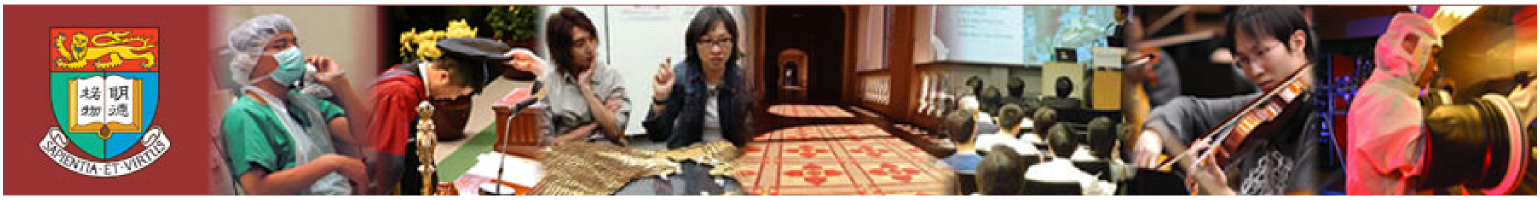

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SEARCH FOR PULSED γ-RAY EMISSION FROM GLOBULAR CLUSTER M28

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ABSTRACT

Using the data from the Large Area Telescope on board the *Fermi Gamma-ray Space Telescope*, we have searched for γ-ray pulsations from the direction of the globular cluster M28 (NGC 6626). We report the discovery of a signal with a frequency consistent with that of the energetic millisecond pulsar (MSP) PSR B1821−24 in M28. A weighted H-test test statistic of 28.8 is attained, which corresponds to a chance probability of $\sim 10^{-5}$ (4.3σ detection). With a phase-resolved analysis, the pulsed component is found to contribute ∼25% of the total observed γ-ray emission from the cluster. However, the unpulsed level provides a constraint for the underlying MSP population and the fundamental plane relations for the scenario of inverse Compton scattering. Follow-up timing observations in radio/X-ray are encouraged to further investigate this periodic signal candidate.

Key words: gamma rays: stars – globular clusters: individual (M28, NGC 6626) – pulsars: individual (PSR B1821−24, PSR J1824−2452A)

Online-only material: color figure

1. INTRODUCTION

The first millisecond pulsar (MSP), which is a rejuvenated old neutron star through accreting matter from its companion, was discovered 30 years ago (Backer et al. 1982). It has long been suggested that they are descendants of low-mass X-ray binaries (LMXBs; Alpar et al. 1982). In comparison with the Galactic field, the formation rate per unit mass of LMXBs in globular clusters (GCs) is orders of magnitude higher because of frequent stellar encounters (Katz 1975; Clark 1975; Pooley et al. 2003; Hui et al. 2010). Therefore, it is not surprising that GCs should host a large population of MSPs. Since the first cluster MSP, PSR B1821−24, was discovered in M28 (Lyne et al. 1987), dedicated radio pulsar surveys toward different clusters have resulted in the currently known population of 144 MSPs in 28 GCs.[5]

Since the launch of the *Fermi Gamma-ray Space Telescope*, a new population of γ-ray emitting GCs have been detected (Abdo et al. 2010a; Tam et al. 2011). As MSPs are the only known steady γ-ray sources in GCs, they are suggested to be the contributors for the observed emission. The γ-rays from a GC are interpreted as the collective contribution from the entire pulsar population that resides in it (Abdo et al. 2010a; Cheng et al. 2010; Hui et al. 2011). For most of the cluster MSPs, detecting the γ-ray pulsations is very challenging as the γ-ray flux of individual pulsar is weak. To exacerbate the situation, the spatial resolution of the *Fermi* Large Area Telescope (LAT) does not allow individual MSPs in a GC to be resolved. This results in a high background that makes the pulsation search for any individual MSP very difficult. However, there are two notable exceptions, namely, the GCs NGC 6624 and M28. Both of these GCs contain a very energetic and young MSP and thus they can possibly stand out from the background.

For PSR J1823−3021A in NGC 6624 ($P = 5.44$ ms), its large spin-down rate, $\dot{P} = 3.38 \times 10^{-18}$ s s^{-1}, implies that it is the youngest MSP ($\tau \sim 25$ Myr) ever detected (Freire et al. 2011). Its spin-down luminosity is $\dot{E} = 8.3 \times 10^{35}$ erg s^{-1}, which is ∼1–2 orders of magnitude greater than the typical MSPs in GCs (Bogdanov et al. 2006). Due to the accurate timing model provided by the dedicated radio observations, its γ-ray pulsations have been revealed by *Fermi* (Freire et al. 2011). Through a phase-resolved analysis, it has been shown that this single pulsar dominates all the observed γ-rays from NGC 6624 (Freire et al. 2011). The γ-ray conversion efficiency of PSR J1823−3021A, $L_\gamma/\dot{E} \sim 0.1$, is found to be comparable with other γ-ray detected MSPs (Abdo et al. 2010b), where L_γ is the γ-ray luminosity.

PSR B1821−24 in M28 (hereafter M28A) is very similar to PSR J1823−3021A in many aspects. Its period ($P = 3.05$ ms) and spin-down rate ($\dot{P} = 1.61 \times 10^{-18}$ s s^{-1}) imply its age and spin-down power to be $\tau \sim 30$ Myr and $\dot{E} = 2.2 \times 10^{36}$ erg s^{-1}, respectively, which makes it the most energetic MSP that has been found so far (Bogdanov et al. 2011). Together with its non-thermal X-ray spectrum, its sharp and narrow X-ray pulse profile strongly indicates that most of the observed X-rays from M28A have originated from the magnetosphere. γ-ray emission from M28 has been detected by *Fermi* LAT (Abdo et al. 2010a). As its L_γ is only a fraction of the spin-down power of M28A, it is possible that this pulsar could significantly contribute to the observed γ-rays. Together with its relatively short distance, 5.5 kpc (cf. Harris 1996, 2010 version), the cluster M28 is a promising target for searching γ-ray pulsation. In this Letter, we report our recent search for the possible pulsation from this GC by using *Fermi* LAT data.

2. DATA ANALYSIS AND RESULTS

In this work, we used the *Fermi* LAT data between 2008 August 4 and 2012 January 31. For the data analysis, the *Fermi* Science Tools v9r23p1 package, available from the *Fermi* Science Support Center,[6] was used. We used Pass 7 data and

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[5] See http://www.naic.edu/~pfreire/GCpsr.html for updated information.

[6] http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/

Table 1
Ephemeris of PSR J1824−2452A Adopted from Ray et al. (2008)

Parameter	
Pulsar name	J1824−2452A
Right ascension, α	18:24:32.00790550
Declination, δ	−24:52:10.8076448
Pulse frequency, ν (s^{-1})	327.4056060517495439
First derivative of pulse frequency, $\dot{\nu}$ (s^{-2})	$-1.735361869603 \times 10^{-13}$
Epoch of frequency determination (MJD)	53800
Epoch of position determination (MJD)	53800
Solar system ephemeris model	DE405
Time system	TDB

selected events in the "Source" class (i.e., event class 2) only. In addition, we excluded the events with zenith angles larger than 100° to greatly reduce the contamination by Earth albedo γ-rays. The instrumental response functions (IRFs) "P7SOURCE_V6" were adopted throughout the study. Events were selected within a circular region-of-interest (ROI) with a diameter of 10° centered at the optical center of M28. Photon energies are restricted in the range of 200 MeV–300 GeV. This set of cuts is adopted throughout this work.

To investigate the spectral characteristic of M28 with the updated IRFs and background model, we performed an unbinned likelihood analysis with the aid of *gtlike* by assuming a point source with power law with exponential cutoff (PLE) of the form $dN/dE \propto E^{-\Gamma} \exp(-E/E_{\mathrm{cutoff}})$ at the nominal position of M28, where Γ and E_{cutoff} are the photon index and the cutoff energy, respectively. To model the background, we included the Galactic diffuse model (`gal_2yearp7v6_v0.fits`), the isotropic background (`iso_p7v6source.txt`), as well as all point sources reported in the 2FGL catalog within 10° from the center of the ROI. All of these 2FGL sources were assumed to be point sources which have specific spectrum suggested by the 2FGL catalog (Nolan et al. 2012). While the spectral parameters of the 2FGL sources located within the ROI were set free, we kept the parameters for those lying outside our adopted ROI fixed at the values given in 2FGL (Nolan et al. 2012). We allowed the normalizations of the diffuse background components to be free. The best-fit PLE model is characterized by $\Gamma = 0.96 \pm 0.22$ and $E_{\mathrm{cutoff}} = 1.41 \pm 0.3$ GeV with a test-statistic (TS) value of 825 which is highly significant. We have tested the robustness of the spectral results by repeating the analysis with different sizes of ROI. The fitted parameters from the independent analysis are consistent within 1σ uncertainties. In this model the photon flux between 200 MeV and 300 GeV was found to be $(2.39 \pm 0.22) \times 10^{-8}$ cm^{-2} s^{-1}. The corresponding integrated energy flux is $f_\gamma = (3.17 \pm 0.29) \times 10^{-11}$ erg cm^{-2} s^{-1}. The spectral results are consistent with those reported by Abdo et al. (2010a) within 1σ uncertainties.

Assuming that M28A is major contributor for the γ-rays from M28, we searched for the possible γ-ray pulsation from this GC. We began by adopting the timing ephemeris determined for M28A from a long-term observation with the *Rossi X-ray Timing Explorer* (Ray et al. 2008), which are tabulated in Table 1. For barycentric correction, we used the updated planetary ephemeris JPL DE405 throughout this analysis. Following the method proposed by Kerr (2011), we used the best-fit model which resulted from the phase-averaged likelihood analysis as described above for assigning weight to each γ-ray photon by computing the probability that it originates from M28. This enables us to alleviate the problem of source confusion with a more efficient background rejection. We then assign a pulsar spin phase to every γ-ray photon with energies >0.2 GeV and within 5° from M28A's direction (see Table 1). A promising signal with a weighted H-test TS of 28.8 has been found by directly folding the data with this ephemeris (de Jager & Büsching 2010). The folded γ-ray pulse profile and the phaseogram (i.e., pulse phase as a function of time) with the weighted photons are shown in the upper panel and the lower panel of Figure 1, respectively.

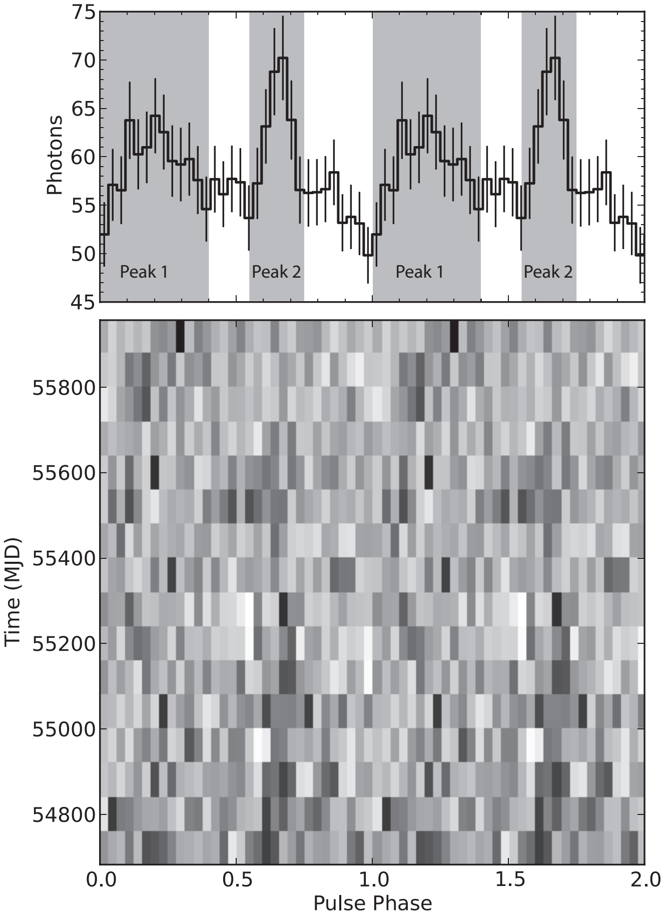

Figure 1. *Fermi* LAT γ-ray weighted light curve (upper panel) and the phaseogram (lower panel) of M28A. A weight was assigned to each photon with the probability that it comes from M28 by using the task *gtsrcprob* in the *Fermi* Science Tool. Two periods of rotation with a resolution of 40 phase bins per period are shown for clarity. The error bars of the light curve represent 1σ Poisson uncertainties. The shaded regions define the on-pulse intervals for Peak 1 and Peak 2.

According to Figure 1, it appears to have two peaks, with one broader than the other. We then define the phase intervals for peak 1 and peak 2 to be 0–0.4 and 0.55–0.75, respectively. The rest is defined as the off-pulse component. With this definition, we show the *Fermi* LAT count maps of the sky region around M28 at different phases in Figure 2. During the on-pulse intervals, a point-like γ-ray source can be clearly seen at the pulsar position, which is illustrated by the yellow cross. On the other hand, a faint diffuse excess is found in the off-pulse phase (i.e., $0.40 < \phi < 0.55$ and $0.75 < \phi < 1.0$). However, the limited photon statistic does not allow us to constrain the extent of this putative feature.

The on-and-off nature of the γ-ray emission from M28 provides strong support for the presence of a periodic signal and leads us to a more detailed investigation. To investigate the possible spectral variations among peak 1, peak 2, and the unpulsed

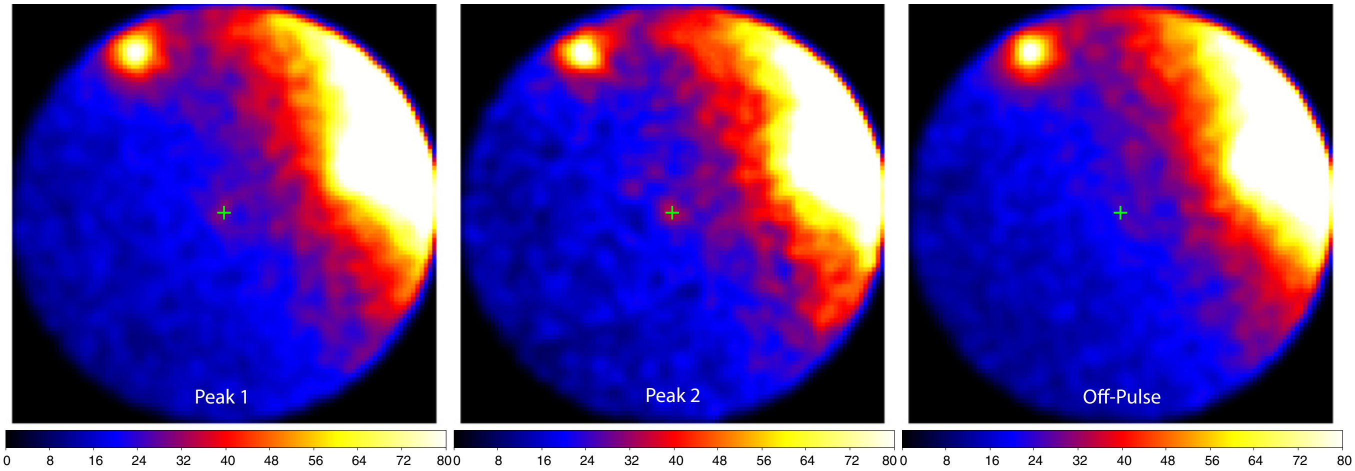

Figure 2. *Fermi* LAT phase-resolved γ-ray count maps for events >0.2 GeV within 5° of the timing position of M28A (illustrated by the yellow cross). Top is north and left is east. The scale bar below shows the color scale of counts pixel^{-1} divided by the relevant phase interval. Left panel: Peak 1 region (i.e., $0.0 < \phi < 0.4$). Middle panel: Peak 2 region (i.e., $0.55 < \phi < 0.75$). Right panel: off-pulse region (i.e., $0.4 < \phi < 0.55$ and $0.75 < \phi < 1$). The point source in the northeast of these maps is 2FGL J1833.6−2104 and the bright extended emission in the northwest is due to the diffuse γ-ray emission from the Galactic plane.

(A color version of this figure is available in the online journal.)

Table 2
Phase-resolved Spectroscopy of M28A

	Peak 1	Peak 2	Off-pulse Component
		PL Fit	
Γ	2.20 ± 0.06	2.18 ± 0.09	2.17 ± 0.07
f_{ph} [a]	$(1.45 \pm 0.14) \times 10^{-8}$	$(9.77 \pm 1.20) \times 10^{-9}$	$(1.02 \pm 0.13) \times 10^{-8}$
TS	330	303	192
		PLE Fit	
Γ	0.68 ± 0.32	0.96 (fixed)	1.26 ± 0.27
E_{cutoff} [b]	1.16 ± 0.27	1.21 ± 0.12	2.05 ± 0.71
f_{ph} [a]	$(1.01 \pm 0.14) \times 10^{-8}$	$(8.29 \pm 0.79) \times 10^{-9}$	$(8.42 \pm 1.24) \times 10^{-9}$
TS	403	368	219

Notes.

[a] Photon flux in units of photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ measured in the range of 0.2–300 GeV.

[b] Cut-off energy in units of GeV.

component, we performed a phase-resolved likelihood analysis. We fitted their spectra with both a simple power law (PL) of the form $dN/dE \propto E^{-\Gamma}$ and PLE. The results are summarized in Table 2. According to the PL fits, there is no obvious change of the spectral steepness. We note that the likelihood analysis that incorporates the PLE model results in a higher TS for all three components. For peak 2, we found that the spectral parameters for the PLE fit cannot be properly constrained. Therefore, we fixed the photon index at the value inferred in the phase-averaged analysis (i.e., $\Gamma = 0.96$). In the cases of the PL fits, within the tolerance of the statistical uncertainties, we do not find any conclusive evidence for the spectral variation across the phase. Assuming the off-pulse component has a constant contribution across the whole phase, ∼75% of the total observed flux originated from this component.

3. SUMMARY AND DISCUSSION

In this Letter, we report our detection of γ-ray pulsation from the direction of the GC M28. We have found a periodic signal which presumably originated from its energetic MSP M28A. Based on our phase-resolved analysis, the pulsed component contributes ∼25% of the total observed γ-rays. At a distance of $d = 5.5$ kpc, this implies an on-pulse luminosity of $L_\gamma = 4\pi d^2 f_\Omega f_\gamma \sim 3 \times 10^{34} f_\Omega\ \mathrm{erg\ s}^{-1}$, where f_Ω is the fraction of the sky covered by the γ-ray beam. Assuming that the pulsed emission originated from M28A, this suggests a γ-ray conversion efficiency of $L_\gamma/\dot{E} \sim 0.01 f_\Omega$. For some of the MSPs in the Galactic field, such as PSRs J2124−3358 and J0437−4715, we find $L_\gamma/\dot{E}$ at this level (Abdo et al. 2010b). However, this is lower than $L_\gamma/\dot{E} \sim 0.08$ as derived from the nearby MSPs (Abdo et al. 2009). If one adopts this as the intrinsic γ-ray conversion efficiency of M28A, this might suggest that the observed period derivative is largely dominated by the acceleration of a pulsar along the line of sight due to the gravitational field of the cluster.

On the other hand, the off-pulse luminosity is found at the level of $L_\gamma \sim 8 \times 10^{34}\ \mathrm{erg\ s}^{-1}$. This estimate is useful for constraining the collective properties of the rest of the MSP population in M28. There are two main theories to explain the unpulsed γ-ray emission from GCs. One theory proposes that the γ-ray emission from a GC originated from the collection of the magnetospheric radiation from the entire MSP population that resides in it (Abdo et al. 2010a; Venter & de Jager 2008; Venter et al. 2009). Assuming an average spin-down power of $\langle \dot{E} \rangle \sim 2 \times 10^{34}\ \mathrm{erg\ s}^{-1}$ and a characteristic conversion efficiency of ∼0.08, the off-pulse luminosity enables us to estimate the number of the rest MSP population to be $N_{\mathrm{MSP}} \sim 50$. This suggests that about one-fifth of the underlying population has already been uncovered.

Besides the aforementioned standard scenario, inverse Compton scattering (ICS) between the relativistic pulsar wind particles and the ambient soft photons has also been proposed as another possible explanation for the origin of the γ-ray from GCs (Bednarek & Sitarek 2007; Cheng et al. 2010; Hui et al. 2011). Cheng et al. (2010) found that the observed γ-ray spectra of GCs can generally be well modeled by ICS between the e^-/e^+ in the pulsar wind of the whole MSP population in a GC and the Galactic background IR photons or starlight. The two-dimensional regression analysis further suggests L_γ, energy density of the background optical/IR photon field, and the stellar encounter rate/metallicity span a set of fundamental planes (Hui et al. 2011). The unpulsed level inferred for M28 can be used to discriminate which relation(s) can better predict the collective contribution. Using the best-fit parameters for these fundamental plane relations (Equations (1)–(4) and Table 3 in Hui et al. 2011) and the updated GC parameters (Harris 1996, 2010 version), the relations involve metallicity and optical/IR energy densities result in an estimate in a range of $\sim(8\text{–}9)\times 10^{34}$ erg s^{-1}, which is consistent with the observed off-pulse luminosity. On the other hand, the best-fit relations that involve the encounter rate result in an estimate of $\sim 2\times 10^{35}$ erg s^{-1} which apparently overshoots the observed value.

To further investigate this putative periodic signal, multi-wavelength observations are certainly required. In particular, the phase-aligned X-ray/γ-ray pulse profile will provide an important constraint for the high-energy emission model. However, no existing X-ray timing data are available for M28A in the *Fermi* era. As the timing noise of M28A is quite strong in comparison with other MSPs and it possibly exhibited glitches, the phase alignment of multi-wavelength light curves subjects to a lot of uncertainties. Therefore, follow-up timing observations in other wavelengths are encouraged for further investigations.

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