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Gamma-ray emission from globular clusters 2MS-GC01, IC 1257, FSR 1735, NGC 5904 and 6656

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ABSTRACT

Globular clusters (GCs) are the oldest stellar systems in the Galaxy, in which millisecond pulsars are widely believed to be the only steady γ-ray emitters. So far, nine γ-ray GCs have been identified and a few candidates, such as 2MS-GC01 and IC 1257, have been suggested. In this work, after analysing the publicly available *Fermi* Large Area Telescope data, we confirm the significant γ-ray emission from 2MS-GC01 and IC 1257 and report the discovery of γ-ray emission from NGC 5904 and 6656 within their tidal radii. Also, strong evidence of significant γ-ray emission is found from FSR 1735. From the observed γ-ray luminosities, we estimate the numbers of millisecond pulsars that are expected to be present in these GCs.

Key words: gamma-rays: general – globular clusters: individual: NGC 5904 – globular clusters: individual: NGC 6656 – globular clusters: individual: FSR 1735 – globular clusters: individual: 2MS-GC01 – globular clusters: individual: IC 1257.

1 INTRODUCTION

Globular clusters (GCs) are spherical stellar systems in which stars are tightly bound by gravity. They are the oldest and also the most dense stellar systems in the Galaxy. On average, the stellar density is ∼0.4 star per cubic parsec, increasing to 100 or 1000 stars per cubic parsec in their cores. The dynamical interactions with high stellar encounter rate are expected to form low-mass X-ray binaries (LMXBs). The formation rate per unit mass of LMXBs in GCs is known to be greater than in other places of the Galaxy (Clark 1975; Katz 1975) and millisecond pulsars (MSPs) are generally believed to be the descendants of LMXBs (Alpar et al. 1982). It is also widely accepted that MSPs contribute almost all γ-ray emissions of GCs. Before 2008, no GCs had been known to be γ-ray emitters. The situation changed dramatically after the successful launch of the *Fermi* Gamma-ray Space Telescope (Atwood et al. 2009) because the Large Area Telescope (LAT) onboard the *Fermi* satellite, a pair-production telescope, can detect γ-rays at energies between ∼20 MeV and >300 GeV with unprecedented sensitivity. The discovery of γ-ray emission from GCs was made in 47 Tucanae (NGC 104; Abdo et al. 2009), in which at least 23 MSPs have been discovered by radio/X-ray observations. As suggested by Abdo et al. (2010), the γ-ray emission from GCs is not due to a single MSP but to all the MSPs as a population.

More than 150 GCs have been identified in the optical band (Harris 1996, 2010 edition), but most of them are not significant γ-ray emitters. Nine 2FGL sources are doubtless associated with GCs, including 47 Tuc (Abdo et al. 2009), Omega Cen (NGC 5139), Terzan 5, NGC 6266, 6388, 6440, 6626 and 6652 (Abdo et al. 2010), and M80 (NGC 6093; Tam et al. 2011). Moreover, there are a few candidates, such as 2MS-GC01 and IC 1257 (Nolan et al. 2012). The non-detection of significant γ-ray emission from most GCs is likely to be a result of their low luminosities of GeV emission and the strong background emission for the GCs superposed in the Galactic disc.

In this work, we analyse the latest *Fermi* LAT data, aiming to identify more γ-ray emitters of GCs. This work is structured as follows. In Section 2, we present our data analysis. We introduce our results in Section 3. In Section 4, we give our summary with some discussion.

2 DATA ANALYSIS

2.1 Data preparation

We use more than 6 yr of *Fermi* LAT data (Pass 7 Reprocessed data; total covering 2191 d from 2008 August 4) with energy ranges from 100 MeV to 100 GeV. The *Fermi* Science Tools `v9r33p0`

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package is used to analyse the data, which is available from the *Fermi* Science Support Center.[1] The P7REP_SOURCE (evclass=2) photons for point source analysis are selected in this work. To reduce the contribution from Earth albedo γ-rays, we only use events with zenith angles $\leq 100^\circ$. The P7REP_SOURCE_V15 instrument response functions (IRFs) are used.

2.2 Analysis method

We try an overall search of the GCs listed in the catalogue (2010 edition) compiled by Harris (1996). In the analysis of each GC, photons from a $20^\circ \times 20^\circ$ square region of interest (ROI) are selected, and binned into spatial pixels of $0.^\circ1 \times 0.^\circ1$. The first step is to apply standard binned maximum likelihood analysis using gtlike. We modelled the events with components of the target source (with coordinates given in the catalogue) and backgrounds. The background components in this model are composed of all sources in the second *Fermi* LAT catalogue[2] within the ROI and diffuse components, including the Galactic diffuse model (gll_iem_v05_rev1.fit) and isotropic background (iso_source_v05_rev1.txt). As usual, a single power law (PL) is used to model the point source. We also apply an exponential cut-off power law (PLE) for the γ-ray GC candidates, in which radio pulsars have been detected. For both models, the pre-factor and the spectral index are set free. Additionally, the cut off energy is set free in PLE model.

We then choose the GCs with test statistic (TS) values greater than 25 for a further study. The TS is defined as $\mathrm{TS} = 2(\mathcal{L}1 - \mathcal{L}0)$, where $\mathcal{L}0$ is the logarithmic maximum likelihood value for a model without the source (null hypothesis) and $\mathcal{L}1$ for a model with an additional source at a specified location. For those γ-ray GC candidates with $\mathrm{TS} \geq 25$, we created $5^\circ \times 5^\circ$ residual TS maps for them using the tool gttsmap. The TS maps aiming to identify weaker sources are created by moving a putative point source through a grid of locations on the sky and maximizing *−log(Likelihood)* at each grid point.[3] In taking this step, the target source that corresponds to the GC is removed from the model. All point source parameters are fixed while the diffuse components are set free. To reduce the contamination from background emissions due to the point spread function (PSF) at a lower energy band, different energy ranges for each GC are selected in the TS map creation.

From the residual TS maps, we find that NGC 5904 and 6656 have evidence of γ-ray emission within their tidal radii (see Fig. 1). Meanwhile, there is evidence of γ-ray emission from FSR 1735 (see the lower panel in Fig. 3), the separation between the best-fitting position of the emission and core of FSR 1735 is 15.6 arcmin. Furthermore, Nolan et al. (2012) reported two other associations with 2FGL sources in the second catalogue: IC 1257 (2FGL J1727.1–0704) and 2MS-GC01 (2FGL J1808.6–1950c). We also create TS maps for these. We then use gtfindsrc to search for the positions of these γ-ray candidates.

The significance from the corresponding TS values follows the χ^2 distribution with two degrees of freedom (PL model; three degrees for the PLE model). To avoid a fake signal with a number of search positions, a similar estimation of the trial factor is involved (Tam et al. 2011). In total, 35 GCs with TS > 25 are further analysed in this work, so $N_{\rm GC} = 35$. The number of bins, $N_{\rm bin} \sim 15$, is derived by dividing the averaged tidal radius area of all known GCs into $0.^\circ1 \times 0.^\circ1$ pixel, where the average tidal radius is 13 arcmin. We obtain the post-trial significance using $(1 - p)^f = 1 - p'$, where p is the pre-trial p-value, $f = N_{\rm GC} \times N_{\rm bin}$ is the trial factor and p' is the post-trial p-value.

Finally, we obtain the spectral energy distributions (SEDs) of these GCs. We divide the energy range from 200 MeV (100 MeV for 2MS-GC01) to 100 GeV into logarithmically equally spaced energy bins (base = 1.94). The flux is obtained by fitting all model components in each bin using gtlike. In the source model, the normalizations of the Galactic diffuse component and isotropic component are left free.

3 RESULTS

3.1 2MS-GC01

2MS-GC01 has formally been associated with 2FGL J1808.6–1950c (Nolan et al. 2012; Cholis, Hooper & Linden 2014). Our best-fitting position is RA = 272.18, Dec. = −19.93 (J2000), which is offset by 4.8 arcmin from the GC core (see the TS map, left panel of Fig. 2). We obtain an index of 2.2 ± 0.1 and a cut-off energy $E_{\rm c} = 3.4 \pm 0.2$ GeV in a PLE spectral fitting. A TS value of 241, corresponding to a detection significance of 15.1σ (14.8σ post-trial) is given. If we just take into account the photons above 400 MeV (energy range selection for creating the TS map), the detection significance is $\sim 10\sigma$. Fig. 1 shows the spectrum of the γ-ray emission in $E^2\,{\rm d}N/{\rm d}E$. The integrated photon flux in the energy of 100 MeV–100 GeV is $F_{0.1-100\,{\rm GeV}} = (12.4 \pm 1.2) \times 10^{-8}$ cm^{-2} s^{-1} and the integrated energy flux is $E_{0.1-100\,{\rm GeV}} = (5.7 \pm 0.5) \times 10^{-11}$ erg cm^{-2} s^{-1}. At a distance of 3.6 kpc (Harris 1996, 2010 edition), the γ-ray luminosity is $L_{0.1-100\,{\rm GeV}} = (9.2 \pm 0.8) \times 10^{34}$ erg s^{-1}.

3.2 IC 1257

IC 1257 has formally been associated with 2FGL J1727.1–0704 (Nolan et al. 2012; Cholis et al. 2014). Our best-fitting position is RA = 261.98, Dec. = −7.07 (J2000), which is offset by 10.6 arcmin from the GC core (see the right panel in Fig. 2). Fitting the spectrum with a PLE model, we have an index of 1.2 ± 0.7 with a cut-off energy $E_{\rm c} = 1.6 \pm 0.9$ GeV. We obtained a TS value of 35 and the corresponding detection significance of 5.2σ (4.0σ post-trial). We have TS = 30 if instead just the photons above 400 MeV have been taken into account, corresponding to a significance of 4.7σ (3.4σ post-trial). It is also the energy range selection for TS map creation. The integrated photon flux between 100 MeV and 100 GeV is $F_{0.1-100\,{\rm GeV}} = (5.7 \pm 1.0) \times 10^{-8}$ cm^{-2} s^{-1}, while the integrated energy flux is $E_{0.1-100\,{\rm GeV}} = (5.0 \pm 0.9) \times 10^{-12}$ erg cm^{-2} s^{-1}. The luminosity is $L_{0.1-100\,{\rm GeV}} = (3.7 \pm 0.7) \times 10^{35}$ erg s^{-1} at a distance of 25 kpc. Such a luminosity is high in comparison with other γ-ray GCs, and is actually the largest among all detected γ-ray emitting GCs up to now.

3.3 NGC 5904

In this GC, five radio pulsars[4] have been detected (Anderson et al. 1997; Hessels et al. 2007) but no significant γ-ray emission has been reported. In our analysis, we find some evidence for γ-ray emission from NGC 5904. With the photons in the energy range of

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

[2] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/

[3] http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/likelihood_tutorial.html

[4] http://www.naic.edu/∼pfreire/GCpsr.html

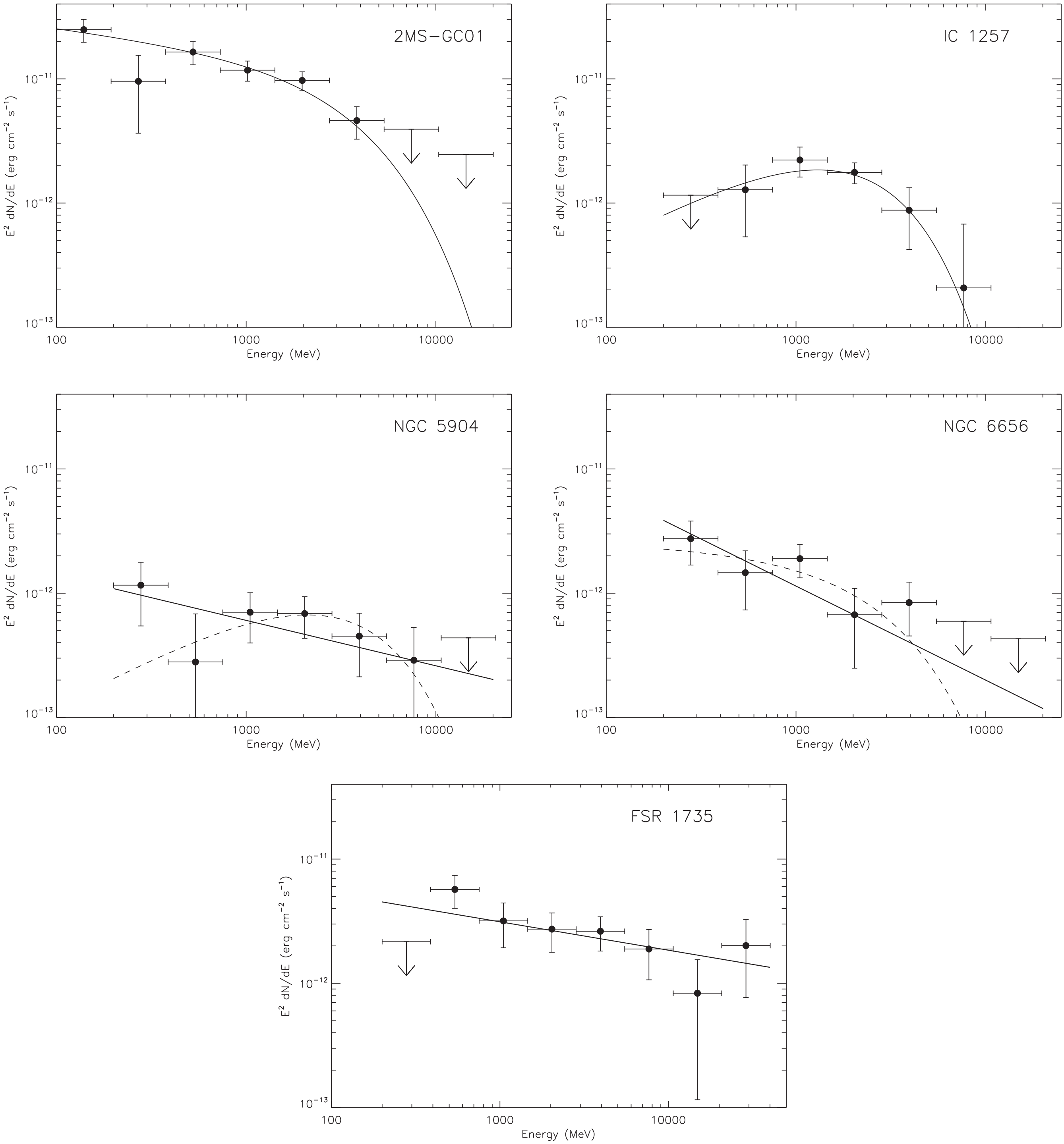

Figure 1. SEDs of GCs. The solid lines indicate the best-fitting spectral model, while the dashed lines indicate spectral fitting with a plausible model.

0.1–100 GeV, the TS value under the PL model is 26, corresponding to a significance of 4.6σ (see the top-left panel in Fig. 3) and the post-trial significance is 3.2σ. To minimize the influence of strong background emission at low energies, we choose the photons at energies of $\geq$500 MeV (for these photons, the PSF is much smaller than that at energies of $\sim$100 MeV and the background pollution can be effectively suppressed) to derive the TS map, which gives a TS value of 21 ($\sim$4.0σ; post-trial 2.4σ). Our best-fitting position is RA = 229.69, Dec. = 2.17 (J2000), 5.9 arcmin from the core position of NGC 5904, well within the tidal radius of NGC 5904 (Harris 1996, 2003 version; see Table 1). The SED can be well fit by a single PL with an index of 2.3 ± 0.2. The integrated photon flux is $F_{0.1-100\,\mathrm{GeV}} = (6.2 \pm 1.4) \times 10^{-9}$ cm^{-2} s^{-1} and the integrated energy flux is $E_{0.1-100\,\mathrm{GeV}} = (3.5 \pm 0.8) \times 10^{-12}$ erg cm^{-2} s^{-1}.

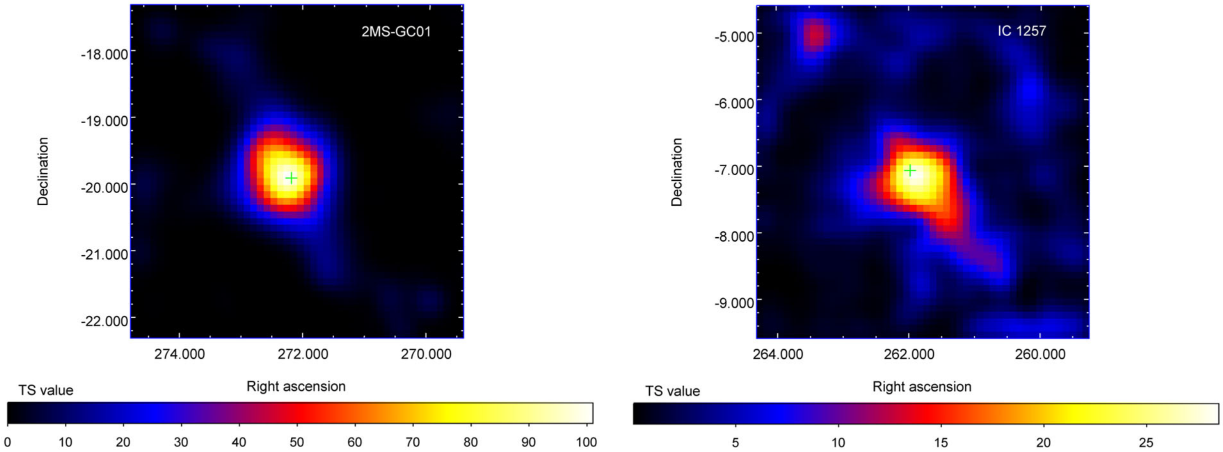

Figure 2. 5° × 5° TS maps of the ROIs for 2MS-GC01 and IC 1257. Both tidal radii are unknown. The cross represents the best-fitting centriod of their γ-ray emission.

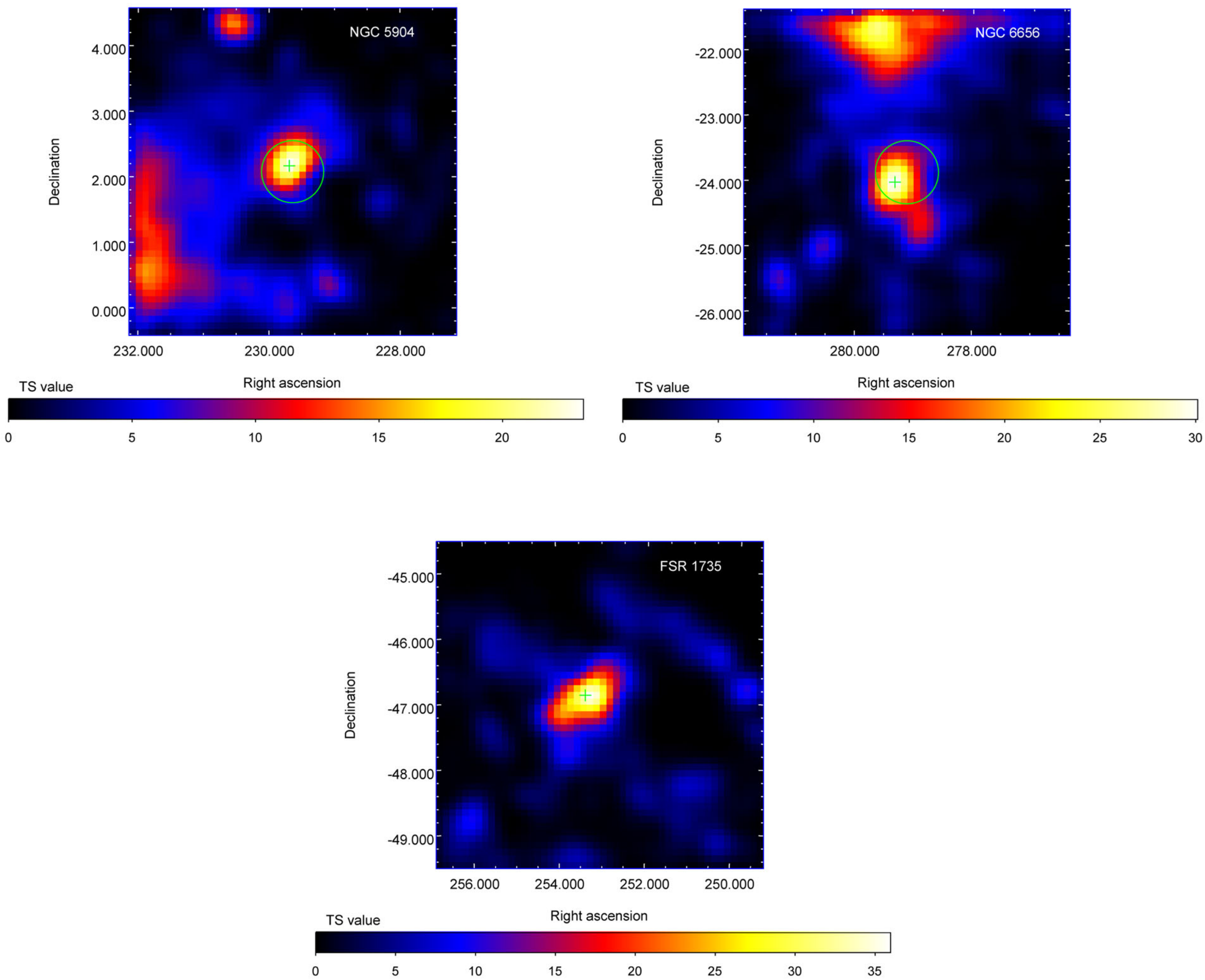

Figure 3. 5° × 5° TS maps of the ROIs for NGC 5904, NGC 6656 and FSR 1735. The cross represents the best-fitting centroid of their γ-ray emission. The circles represent the tidal radii (Harris 1996, 2003 version). The tidal radius of FSR 1735 is unknown.

When deriving the TS map, an additional source (RA = 230.54, Dec. = 4.32) is added to the model, of which the spectrum is set as a single PL and to the ROI centre with a separation of 2°.4. At a distance of 7.5 kpc, the γ-ray emission luminosity is $L_{0.1-100\,\mathrm{GeV}} = (2.4 \pm 0.5) \times 10^{34}$ erg s^{-1}. We also use a PLE model to fit the spectrum, where the photon index $\Gamma = 1.2 \pm 1.3$ and the cut-off energy is (2.6 ± 2.8) GeV. In this model, the significance remains on the same level, 3.1σ post-trial. There is no significance of the PLE model over the PL model, so we consider the PL model to be a better model.

Table 1. Spatial parameters of GCs.

GC name	Position[a] RA	Dec.	l	b	Tidal[b] radius (arcmin)	Position[c] RA	Dec.	Offset (arcmin)
NGC 5904	229.64	2.08	3.86	46.80	28.40	229.69	2.17	5.9
NGC 6656	279.10	−23.90	9.89	−7.55	28.97	279.30	−24.05	14.2
FSR 1735	253.04	−47.06	339.18	−1.85	–	253.37	−46.91	15.6
2MS-GC01	272.09	−19.83	10.47	0.10	–	272.18	−19.93	4.8
IC 1257	261.79	−7.09	16.53	15.14	–	261.98	−7.07	10.6

Notes. [a]Coordinates derived from the catalogue of Harris (1996, 2003 and 2010 versions) and the corresponding Galactic coordinates.
[b]Tidal radii of FSR 1735, 2MS-GC01 and IC 1257 are not given.
[c]Our best-fitting position of γ-ray emission from GCs.

Table 2. Parameters of γ-ray from GCs.

GC name	Spectral model	TS	Significance (post-trial; σ)	Photon index	Cut-off (GeV)	Photon[a] flux	Energy[b] flux	Distance[c] (kpc)	L^d	$N_{\rm MSP}$
NGC 5904	PL	26	3.2	2.3 ± 0.2	–	6.2 ± 1.4	3.5 ± 0.8	7.5	2.4 ± 0.5	16 ± 4
	PLE	28	3.1	1.2 ± 1.3	2.6 ± 2.8	1.6 ± 0.4	1.9 ± 0.4	7.5	1.3 ± 0.3	9 ± 2
NGC 6656	PL	27	3.4	2.7 ± 0.1	–	23.2 ± 5.9	8.6 ± 1.9	3.2	1.1 ± 0.2	7 ± 2
	PLE	30	3.4	2.0 ± 0.5	2.4 ± 1.8	13.1 ± 4.1	6.3 ± 1.4	3.2	0.8 ± 0.2	5 ± 1
FSR 1735	PL	55	6.2	2.2 ± 0.1	–	26.9 ± 4.3	18.4 ± 2.9	9.8	21.1 ± 3.3	147 ± 23
2MS-GC01	PLE	241	14.8	2.2 ± 0.1	3.4 ± 0.2	124.7 ± 11.8	56.8 ± 5.0	3.6	8.8 ± 0.8	61 ± 5
IC 1257	PLE	35	4.0	1.2 ± 0.7	1.6 ± 0.9	5.7 ± 1.0	5.0 ± 0.9	25.0	37.4 ± 6.7	260 ± 47

Notes. [a]Integrated 0.1–100 GeV photon flux in units of 10^{-9} cm^{-2} s^{-1}.
[b]Integrated 0.1–100 GeV energy flux in units of 10^{-12} erg cm^{-2} s^{-1}.
[c]Distance from Harris (1996, 2003 and 2010 versions).
[d]0.1–100 GeV luminosity in units of 10^{34} erg s^{-1}.

3.4 FSR 1735

The γ-ray emission from FSR 1735 (Froebrich et al. 2007) is found with a TS value of 55 and the corresponding significance is $\sim 7.0\sigma$ (6.2σ post-trial). Again, we only take into account the photons above 400 MeV to create the TS map (see the lower panel in Fig. 3), the value of TS is 39 and the corresponding significance is 5.8σ (4.8σ post-trial). Our best-fitting position is RA = 253.37, Dec. = −46.91 (J2000). Although the tidal radius of FSR 1735 is unknown, the best-fitting γ-ray position found in our analysis has an offset ∼15.6 arcmin from the core of FSR 1735. Using a single PL model, we obtained a photon index $\Gamma = 2.2 \pm 0.1$. The integrated photon flux is $F_{0.1-100\,\rm GeV} = (2.7 \pm 0.4) \times 10^{-8}$ cm^{-2} s^{-1} and the integrated energy flux is $F_{0.1-100\,\rm GeV} = (1.8 \pm 0.3) \times 10^{-11}$ erg cm^{-2} s^{-1}. At a distance of 9.8 kpc, the γ-ray luminosity is $L_{0.1-100\,\rm GeV} = (2.1 \pm 0.3) \times 10^{35}$ erg s^{-1}.

3.5 NGC 6656

Two radio pulsars[5] have been discovered (Lynch et al. 2011) in this GC. It also has no association in the second LAT catalogue. Our reduction on this region show evidence of γ-ray emission. The best-fitting position (RA=279.30, Dec. = −24.05; J2000) is well within the tidal radius circle of NGC 6656. Using a single PL model (3.4σ post-trial), we obtained a photon index of $\Gamma = 2.7 \pm 0.1$, and 0.1–100 GeV photon and energy fluxes of $(2.3 \pm 0.6) \times 10^{-8}$ cm^{-2} s^{-1} and $(8.6 \pm 1.9) \times 10^{-12}$ erg cm^{-2} s^{-1}, respectively. The γ-ray luminosity is $L_{0.1-100\,\rm GeV} = (1.1 \pm 0.2) \times 10^{34}$ erg s^{-1} at a distance of 3.2 kpc. The spectrum can also be fitted with a PLE model, where the photon index $\Gamma = 2.0 \pm 0.5$ and cut-off energy $E_{\rm c} = (2.4 \pm 1.8)$ GeV. Because the significance under the PLE model is also 3.4σ post-trial, we consider the PL model to be the better one.

[5] http://www.naic.edu/∼pfreire/GCpsr.html

4 SUMMARY

In this work, we have analysed the *Fermi* LAT data of more than 150 GCs and we detect or find some evidence of γ-ray emission from three GCs (FSR 1735, NGC 5904 and 6656). Another two (2MS-GC01 and IC 1257) have been reported as γ-ray emission candidates by Nolan et al. (2012), of which the associations of significant γ-ray emission have been confirmed here. Among the three newly detected candidates, the evidence of γ-ray emission from FSR 1735 is very significant (the post-trial significance is at a confidence level of $>5\sigma$). Although the tidal radius of such a GC is unknown, the γ-ray source found in our analysis has an offset ∼15.6 arcmin from the core of FSR 1735, which is small enough to allow us to suggest an association of these two sources. The γ-ray emission signals from the other two GCs are weaker (the confidence level is above 3σ but smaller than 5σ) and more data are needed to firmly establish their γ-ray emitting nature. The *Fermi* satellite continues to collect γ-ray data and more γ-ray GCs are expected to be identified. Nevertheless, for the GCs within the Galactic plane, the prospect is not very promising because of the strong background that can effectively minimize the γ-ray signal. More GCs might be detected in the future with a high angular resolution telescope dedicated to sub-TeV (from ∼10 MeV to ∼10 GeV) γ-ray photon detection. For example, the proposed mission *Pair-Production Gamma-Ray Unit* (*PANGU*) aims to have an angular resolution of a factor of ≥5 better than the currently operating *Fermi* Gamma-ray Space Telescope in the sub-GeV range (Wu et al. 2014). The high-quality γ-ray maps will significantly improve the identification of point-like sources from

the extended and complicated diffuse γ-ray background, which is thus very suitable to identify more γ-ray GCs.

As already mentioned in Section 3, no pulsars have been reliably identified in these GCs except NGC 5904 and 6656. The detection of γ-ray emission in turn provides us with the chance to estimate the number of MSPs that are believed to be the unique stable γ-ray emitters in GCs. Our approach follows that of Abdo et al. (2010) and the number of MSPs in each GC is estimated using their equation (1), where $\langle \dot{E} \rangle = (1.8 \pm 0.7) \times 10^{34}$ erg s^{-1} is adopted as the average spin-down power of the pulsar, and the γ-ray luminosity conversion efficiency is set to 0.08. The results are shown in Table 2. For NGC 5904 and 6656, the estimated numbers of MSPs are more than the numbers found currently, implying that in the future more powerful radio telescopes (or arrays) have very promising detection prospects as long as these MSPs also radiate a non-ignorable amount of energy in radio bands.

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REFERENCES

Abdo A. A. et al., 2009, Sci, 325, 845
Abdo A. A. et al., 2010, A&A, 524, 75
Alpar M. A., Cheng A. F., Ruderman M. A., Shaham J., 1982, Nat, 300, 728
Anderson S. B., Wolszczan A., Kulkarni S. R., Prince T. A., 1997, ApJ, 482, 870
Atwood W. B. et al., 2009, ApJ, 697, 1071
Cholis I., Hooper D., Linden T., 2014, preprint (arXiv:1407.5583)
Clark G. W., 1975, ApJ, 199, L143
Froebrich D., Meusinger H., Scholz A., 2007, MNRAS, 377, L54
Harris W. E., 1996, AJ, 112, 1487
Hessels J. W. T., Ransom S. M., Stairs I. H., Kaspi V. M., Freire P. C. C., 2007, ApJ, 670, 363
Katz J. I., 1975, Nat, 253, 698
Lynch R. S., Ransom S. M., Freire P. C. C., Stairs I. H., 2011, ApJ, 734, 89
Nolan P. L. et al., 2012, ApJS, 199, 31
Tam P. H. T., Kong A. K. H., Hui C. Y., Cheng K. S., Li C., Lu T-N., 2011, ApJ, 729, 90
Wu X., Su M., Bravar A., Chang J., Fan Y. Z., Pohl M., Walter R., 2014, Proc. SPIE, 9144, 91440, preprint (arXiv:1407.0710)

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