

## A Fermi-LAT Study of Globular Cluster Dynamical Evolution in the Milky Way: Millisecond Pulsars as the Probe postprint

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### Abstract

Using archival Fermi-LAT data with a time span of 12 yr, we study the population of Millisecond Pulsars (MSPs) in Globular Clusters (GICs) and investigate their dependence on cluster dynamical evolution in the Milky Way. We show that the  $\gamma$ -ray luminosity ( $L_\gamma$ ) and emissivity (i.e.,  $= L_\gamma/M$ , with  $M$  the cluster mass) are good indicators of the population and abundance of MSPs in GICs, and they are highly dependent on the dynamical evolution history of the host clusters. Specifically speaking, the dynamically older GICs with more compact structures are more likely to have larger  $L_\gamma$  and  $\epsilon$ , and these trends can be summarized as strong correlations with cluster stellar encounter rate  $\Gamma$  and the specific encounter rate ( $\Lambda = \Gamma/M$ ), with  $L_\gamma \propto \Gamma^{0.70 \pm 0.11}$  and  $\epsilon \propto \Lambda^{0.73 \pm 0.13}$  for dynamically normal GICs. However, as GICs evolve into deep core collapse, these trends are found to exhibit  $L_\gamma \propto \Gamma^{1.0(0.57 \pm 0.1)}$ , decreasing tidal radius ( $r_t$ ) and distances from the Galactic Center (GC,  $R_{GC}$ ). These correlations indicate that, as GICs losing kinetic energy and spiral in toward the GC, tidal stripping and mass segregation have a preference in leading to the loss of normal stars from GICs, while MSPs are more likely to concentrate to cluster center and be deposited into the GC. Moreover, we gauge of GICs is  $10$ - $1000$  times larger than the Galactic bulge, the latter is thought to reside thousands of unresolved MSPs and may be responsible for the GC  $\gamma$ -ray excess, which supports that GICs are generous contributors to the population of MSPs in the GC.

### Full Text

### Preamble

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## A Fermi-LAT Study of Globular Cluster Dynamical Evolution in the Milky Way: Millisecond Pulsars as the Probe

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### Abstract

Using archival Fermi-LAT data with a time span of 12 yr, we study the population of Millisecond Pulsars (MSPs) in Globular Clusters (GCs) and investigate their dependence on cluster dynamical evolution in the Milky Way. We show that the  $\gamma$ -ray luminosity ( $L_\gamma$ ) and emissivity (i.e.,  $\eta_\gamma = L_\gamma/M$ , with  $M$  the cluster mass) are good indicators of the population and abundance of MSPs in GCs, and they are highly dependent on the dynamical evolution history of the host clusters. Specifically, the dynamically older GCs with more compact structures are more likely to have larger  $L_\gamma$  and  $\eta_\gamma$ , and these trends can be summarized as strong correlations with cluster stellar encounter rate  $\Gamma$  and the specific encounter rate ( $\Lambda = \Gamma/M$ ), with  $L_\gamma \propto \Gamma^{0.70 \pm 0.11}$  and  $\eta_\gamma \propto \Lambda^{0.73 \pm 0.13}$  for dynamically normal GCs. However, as GCs evolve into deep core collapse, these trends are found to be reversed, implying that strong encounters may have led to the disruption of Low-Mass X-ray Binaries and ejection of MSPs from core-collapsed systems. Besides, the GCs are found to exhibit larger  $\eta_\gamma$  with increasing stellar mass function slope ( $\eta_\gamma \propto 10^{(0.57 \pm 0.1)\alpha}$ ), decreasing tidal radius, and distances from the Galactic Center (GC). These correlations indicate that, as GCs lose kinetic energy and spiral in toward the GC, tidal stripping and mass segregation have a preference in leading to the loss of normal stars from GCs, while MSPs are more likely to concentrate to the cluster center and be deposited into the GC. Moreover, we gauge  $\eta_\gamma$  of GCs is 10–1000 times larger than the Galactic bulge, the latter is thought to reside thousands of unresolved MSPs and may be responsible for the GC  $\gamma$ -ray excess, which supports that GCs are generous contributors to the population of MSPs in the GC.

**Key words:** (Galaxy:) globular clusters: general -(stars:) pulsars: general - Galaxy: kinematics and dynamics -Galaxy: center -Galaxy: bulge -gamma-rays: stars -gamma-rays: diffuse background -gamma-rays: galaxies

## 1. Introduction

Globular Clusters (GCs) are self-gravitating systems that evolve with dynamical timescale (i.e., two-body relaxation timescale) much smaller than their age (Heggie & Hut 2003), and the binary burning process (i.e., extraction of binary binding energy via dynamical encounters) is the “heating mechanism” that supports the cluster against gravothermal collapse (Fregeau et al. 2003), which also makes GCs promising breeding grounds for exotic objects, such as blue straggler stars (BSS, Fregeau et al. 2004; Chatterjee et al. 2013), coronal active binaries (ABs), cataclysmic variables (CVs; Ivanova et al. 2006; Shara & Hurley 2006; Belloni et al. 2016, 2017, 2019), low-mass X-ray binaries (LMXBs; Rasio et al. 2000; Ivanova et al. 2008; Kremer et al. 2018), millisecond pulsars (MSPs; the offspring of LMXBs; Ye et al. 2019; Kremer et al. 2020b; Ye & Fragione 2022), and gravitational-wave sources made up of compact objects (Clausen et al. 2013; Rodriguez et al. 2015, 2016; Askar et al. 2017; Arca Sedda 2020; Ye et al. 2020; Kremer et al. 2021).

Depending on their distances from the Galactic Center (GC), the dynamical evolution of GCs is also subjected to the gravitational tidal field of the Milky Way (Baumgardt & Makino 2003). The expanding cluster halo could be truncated by the external tidal field, and tidal stripping may lead to the loss of stars from GCs, enhance the energy outflow of GCs and thereby accelerating the dynamical evolution of the cluster (Gnedin & Ostriker 1997; Gnedin et al. 1999). Besides, dynamical friction between GCs and Galactic background stars may lead to the spiral in of GCs toward the deep potential well of the Galaxy (Tremaine et al. 1975; Moreno et al. 2022), where tidal stripping would eventually lead to the full dissolution of the clusters. GCs therefore can take their binary burning products into the Inner Galaxy (Fragione et al. 2018a; Arca-Sedda et al. 2018b), and contribute the cluster mass to the growing Galactic nuclei (Antonini et al. 2012; Antonini 2013; Gnedin et al. 2014).

Thanks to their exclusive formation process and emission properties, the binary burning products are proved to be superb tracers for studying stellar dynamical interactions and cluster evolution. For example, compared with normal stars, the emission of LMXBs, MSPs, CVs, ABs and BSS are found to be much more luminous either in optical, X-ray,  $\gamma$ -ray or radio band and can be detected and picked out from the dense core of GCs, making them ideal tracers for studying stellar dynamical encounters (Verbunt & Hut 1987; Pooley et al. 2003; Verbunt 2003; Pooley & Hut 2006), two-body relaxation and mass segregation effect of GCs (Ferraro et al. 2012; Cheng et al. 2019b, 2019a). The cumulative cluster X-ray luminosity  $L_X$  and emissivity  $\eta_X$  ( $L_X$  per unit stellar mass), proxies of population and abundance of weak X-ray sources (mainly CVs and ABs) in GCs (Cheng et al. 2018; Heinke et al. 2020), are also shown to be effective indicators for diagnosing cluster binary burning process (Cheng et al. 2018, 2020).

Among all the binary burning products in GCs, MSPs are outstanding for many reasons. First, compared with BSS, CVs and ABs that can be formed through

both primordial binary evolution and dynamical formation channels, it is widely recognized that LMXBs, the progenitors of MSPs, are dynamically formed in GICs (Verbunt & Hut 1987; Pooley et al. 2003; Verbunt 2003), and the abundances (number per unit stellar mass) of LMXBs and MSPs are more than 100 times higher in GICs than in the Galactic field (Clark 1975; Katz 1975; Camilo & Rasio 2005; Ransom 2008). Besides, unlike other tracers that could be contaminated by fore- and background sources, MSPs are mainly detected via either radio or  $\gamma$ -ray observations, in which contamination is negligible. Moreover, the lifetime of MSPs is very long ( $10^{10}$  yr) and their luminosities are observed to be very stable. Taking these aspects together, it is safe to say that MSPs are the best probe of cluster dynamical evolution, especially in tracing the tidal dissolution of GICs in the Milky Way.

In  $\gamma$ -ray astronomy, both MSPs and GICs are recognized as important  $\gamma$ -ray emitters in the Galaxy (Abdo et al. 2010; Tam et al. 2011), and 30 GICs have been identified as point sources in the fourth Fermi Large Area Telescope catalog (4FGL, Abdollahi et al. 2020). The  $\gamma$ -ray emission of GICs is widely assumed to originate from MSPs that reside in the clusters (Cheng et al. 2010; Bednarek & Sobczak 2013), and the detection of pulsed gamma-ray emission from two GICs has further strengthened the case for this connection (Freire et al. 2011; Wu et al. 2013). In concert with LMXBs, a strong correlation between  $\gamma$ -ray luminosity  $L_\gamma$  and the stellar encounter rate  $\Gamma$  has been established among GICs (Abdo et al. 2010; Hui et al. 2011; Hooper & Linden 2016; Tam et al. 2016; Zhang et al. 2016; Lloyd et al. 2018; de Menezes et al. 2019), which lends support to the dynamical origin of MSPs in GICs.

On the other hand, the Fermi Large Area Telescope (Fermi-LAT) has discovered an unexpected  $\gamma$ -ray excess around the GC, peaking at a few GeV, with an approximately spherical density profile  $\propto r^{-2.4}$  and extending to  $10^\circ$ - $20^\circ$  (1.5-3 kpc) from the GC (Goodenough & Hooper 2009; Hooper & Goodenough 2011a; Hooper & Linden 2011b; Di Mauro 2021). The nature of this “Galactic Center Excess” (GCE) is still not clear, and many promising models have been proposed over the past decade, including dark matter annihilation (Abazajian & Kaplinghat 2012; Daylan et al. 2016), emission of thousands of unresolved MSPs (Abazajian 2011; Yuan & Zhang 2014; Bartels et al. 2016), or cosmic rays injected at the GC (Carlson & Profumo 2014; Petrović et al. 2014; Cholis et al. 2015; Gaggero et al. 2015). In the MSP scenario, Galactic GICs fallen into the GC are expected to deposit their population of MSPs, which are then inherited by the Galactic nuclear star cluster and nuclear bulge, and contribute to the observed  $\gamma$ -ray excess (Bednarek & Sobczak 2013; Brandt & Kocsis 2015; Fragione et al. 2018a; Arca-Sedda et al. 2018b; Abbate et al. 2018).

In the present work, we perform a  $\gamma$ -ray study of the Galactic GICs based on the archival Fermi data. Unlike previous works that only focus on the cumulative GIC  $\gamma$ -ray luminosity  $L_\gamma$  (Abdo et al. 2010; Hooper & Linden 2016; de Menezes et al. 2019), we also measure the  $\gamma$ -ray emissivity  $\eta_\gamma$  ( $L_\gamma$  per unit stellar mass) of the GICs, and explore their dependence on various cluster parameters. The

cumulative cluster  $\gamma$ -ray luminosity offers us a chance to study the population of MSPs at the Inner Galaxy, where single MSP is hard to be detected via radio or  $\gamma$ -ray observation. On the other hand, as demonstrated by Cheng et al. (2018) and Heinke et al. (2020) in the X-ray band, the emissivity has been proved to be a reliable indicator of exotic objects abundance in GICs, which is insensitive to the luminosity function (LF) and can be applied to a large cluster sample in a highly uniform fashion. More importantly, the derived GIC  $\gamma$ -ray emissivity can be directly compared to the stellar  $\gamma$ -ray emissivity of the Galactic nuclear star cluster and nuclear bulge, which are crucial to evaluating the relative abundance of putative MSPs in these environments, thus estimating the possible stellar origins and contribution to the GCE by dissolved GICs.

The limitation of our approach is that we assume the measured cluster  $\gamma$ -ray luminosity is a good proxy of the population of hosted MSPs, which may not be true for all clusters, especially for GICs containing few MSPs. However, as we will show below, although the uncertainty of small counts of MSPs in individual GICs may introduce large scatter to our cluster sample, it is unlikely to create the correlations and trends observed in this work.

The paper is organized as follows. Section 2 describes the data reduction and analysis that lead to the detection and the measurement of the  $\gamma$ -ray luminosity  $L_\gamma$  and emissivity  $\eta_\gamma$  of individual GICs. Section 3 explores the dependence of  $L_\gamma$  and  $\eta_\gamma$  on various cluster physical properties. A discussion and a summary of our results are presented in Sections 4 and 5, respectively. Throughout this work we quote  $1\sigma$  errors, unless otherwise stated.

## 2. $\gamma$ -Ray Data Analysis

### 2.1. Data Reduction and Analysis

We analyzed the archival Fermi-LAT data of the 157 GICs presented in the catalog of Harris (1996). The Fermi data were observed from 2008 August 8 to 2020 November 8 (MET: 239,846,401–626,486,405), with a time span of 12 yr. We used the Fermi tools release 2.0 to analyze the data, with the energy band restricted to 100 MeV–300 GeV and divided into 15 logarithmically spaced energy bins. We selected events with source class (evclass = 128, evtype = 3) and filtered the data with DATAQUAL > 0, LATCONFIG == 1. A zenith angle cut of  $<90^\circ$  and a satellite rocking angle cut of  $<52^\circ$  were applied to avoid contamination from the Earth limb.

The region of interest (ROI) of each target was restricted to a  $14^\circ \times 14^\circ$  rectangular box centered on the optical center of the GICs. We used the Make4FGLxml.py tool and the 4FGL DR2 catalog to generate the background source list within the ROI. For diffuse background modeling, we adopted the most recent Galactic interstellar emission model `gll_{{iem}}_{{v07}}.fits` and the isotropic spectral template `iso_{{P8R3}}_{{SOURCE}}_{{V3}}_{{v1}}.txt`. The instrument response function (IRF) was set as `P8R3_{{SOURCE}}_{{V3}}`.

All targets were investigated by means of binned likelihood analysis (gtlike tool). To search for the  $\gamma$ -ray emission from the GICs, we added a putative point source at the optical center of the cluster, and used the gttsmmap tool to derive the TS maps. From the TS maps, one can visually inspect the detections of unknown sources located within the ROI. We then removed the new sources by adding them to the background source lists and refit the data again. The spectral models of GCs were set as either a power-law (PL), a PL plus exponential cut-off (PL+Expcut), or a logparabola (LP) model. During the fitting, all the GIC parameters (i.e., coordinates, photon index, cut-off energy and normalization) were set as free, whereas for diffuse backgrounds and point sources located within  $5^\circ$  of the ROI, only the normalization parameter was left free to vary. To quantify the significance of the detection, a test statistic (TS) was calculated, defined as  $TS = 2(\log L_1 - \log L_0)$ , where  $L_1$  ( $L_0$ ) is the maximum likelihood value of the model with (without) the putative source. The chosen criterion for detection was  $TS > 25$ , corresponding to a significance slightly above  $4\sigma$ .

## 2.2. Data Analysis Results

For the 157 GICs tabulated in the catalog of Harris (1996), about 25% (39/157) of them are found to be  $\gamma$ -ray bright ( $TS > 25$ ) in this work, with two clusters, HP-1 ( $TS = 44.3$ ) and Terzan 9 ( $TS = 42.1$ ), first identified as  $\gamma$ -ray emitters. Cross-checking the 39 clusters with the 4FGL-DR3 catalog (Abdollahi et al. 2022), five clusters (NGC 362 with  $TS = 16$  and NGC 6304 with  $TS = 21.7$ ) are found to have a smaller significance than our detection threshold. Besides, Liller 1 was found to be  $\gamma$ -ray bright by Tam et al. (2011), while our data fitting suggests that the detection is marginal ( $TS = 21.6$ ). All the 39 GICs are located within a distance of  $D < 15$  kpc from the Earth (Figure 1(a) [Figure 1: see original paper]), and there is no evident observation bias for GICs near the GC (Figure 1(b)) and the Galactic disk (Figure 1(c)), or significant dependence on cluster metallicity (Figure 1(d)). However, it seems that GICs are more likely to be identified as  $\gamma$ -ray emitters, provided that they are more massive (Figure 1(e)) or have larger stellar encounter rate (Figure 1(f)). Interestingly, the  $\gamma$ -ray detection rate of core-collapsed GICs (12/29) is found to be 2 times higher than the dynamically normal GICs (27/128), which suggests that the dynamical evolution history is also an important factor influencing the  $\gamma$ -ray luminosity of GICs.

The  $\gamma$ -ray data analysis results are summarized in Table 1, which is segmented into two panels according to the core collapse flag in the catalog of Harris (1996). The likelihood fit parameters, arranged from left to right, are: cluster name, test statistic (TS) values, PL photon index, spectral models, exponential cut-off energy  $E_c$  and measured GIC energy flux  $f_\gamma$ . Adopting the cluster distance ( $D$ ) presented in the catalog of Baumgardt & Hilker (2018), we also calculated the cumulative GIC  $\gamma$ -ray luminosity with function  $L_\gamma = 4\pi D^2 f_\gamma$ . We define the GIC  $\gamma$ -ray emissivity as  $\eta_\gamma = L_\gamma/M$ , with  $M$  being the cluster mass given in the catalog of Baumgardt & Hilker (2018).  $L_\gamma$  and  $\eta_\gamma$  are listed in Columns 7

and 8 of Table 1. The errors are given at  $1\sigma$  standard deviation level.

To check the spatial consistency between the  $\gamma$ -ray emission and the optical centers of GICs, we plot in Figure 2 [Figure 2: see original paper] the TS maps of the 39 clusters. For each GIC, the image was restricted to a  $5^\circ \times 5^\circ$  box, with the central green circle indicating the tidal radius of the cluster. All maps show evidence for good coincidence between the  $\gamma$ -ray emission and the GIC centroids, except for NGC 1904, where the offset between the optical center and the peak of the  $\gamma$ -ray emission (cyan ellipse) is  $0.3^\circ$ . Besides the coincidence of spatial coordinates, it is possible that the  $\gamma$ -ray emission is associated with a fore/background source rather than the cluster. We estimated this probability with function  $P_{\text{random}} = (R_t^2/S_{\text{ROI}}) \times N$ , where  $R_t$  is the GIC tidal radius,  $S_{\text{ROI}}$  is the area of the ROI, and  $N$  is the number of  $\gamma$ -ray sources detected within  $S_{\text{ROI}}$ . The values of  $P_{\text{random}}$  are presented in the last column of Table 1. In most clusters, the  $P_{\text{random}}$  value is less than 10%; the exceptions are NGC 104 (16.9%), NGC 5139 (34.5%), NGC 6624 (18.1%), NGC 6752 (32.1%) and NGC 6656 (40.1%), where the random detection probability is over ten percent. However, as illustrated in Figure 2,  $R_t$  of these clusters are also found to be very large, thus the larger  $P_{\text{random}}$  is more likely to result from the larger tidal radius rather than being associated with a fore/background source.

### 3. Statistical Relations

As discussed in Section 1, the measured GIC  $\gamma$ -ray luminosity ( $L_\gamma$ ) arises from a collection of MSPs residing in the cluster. Generally speaking, there are two dominant factors that may influence the number of MSPs of a given GIC: (i) the population (thus the cluster mass  $M$ ) of neutron stars (NS) hosted by the cluster, and (ii) the stellar dynamical interactions that transform NS into LMXBs and MSPs. The second factor also refers to the binary burning process, which is thought to be the essential internal energy source of cluster dynamical evolution. In this regard, the  $\gamma$ -ray emissivity ( $\eta_\gamma = L_\gamma/M$ ) is better than  $L_\gamma$  in tracing the formation efficiency of MSPs in GICs, and both  $L_\gamma$  and  $\eta_\gamma$  may serve as sensitive probes to study the dynamical evolution of GICs. With this in mind, we examine the dependence of  $L_\gamma$  and  $\eta_\gamma$  on various cluster physical parameters in this section. If tidal stripping has played an important effect in the dynamical evolution of GICs, significant correlations between GIC  $\gamma$ -ray emission and the Galactic environment parameters are also expected. The GIC parameters are mainly taken from Baumgardt & Hilker (2018) or Harris (1996), unless specific references are quoted. Throughout the paper, we also classify the GICs into two subgroups (i.e., the dynamically normal and core-collapsed GICs) according to their labels in Harris (1996). The core-collapsed GICs are generally considered to be in the late phase of cluster dynamical evolution, and thus are dynamically older than the normal GICs.

### 3.1. Correlations with Cluster Mass

In Figure 3(a) [Figure 3: see original paper], we first explore  $L_\gamma$  versus  $M$  for all GICs. The GIC mass is adopted from the online catalog of Baumgardt & Hilker (2018), which is derived by comparing the observed cluster velocity dispersion, surface density, and stellar mass function profiles against N-body simulations. Although the scatter is substantial, a moderate positive correlation between  $L_\gamma$  and  $M$  is observable, from which we find the Spearman' s rank coefficient  $r = 0.454$  and  $r = 0.464$  for the total and dynamically normal GICs, with  $p = 0.004$  and  $p = 0.017$  for random correlation. We fit a power-law function to the correlations and obtained  $L_\gamma \propto M^{0.53 \pm 0.17}$  and  $L_\gamma \propto M^{0.51 \pm 0.20}$  for total and the dynamically normal GICs, respectively. The best-fitting functions are shown as the blue and the olive lines in Figure 3(a), and the dotted curves mark the 95% confidence range.

Compared with the dynamically normal GICs, the dependence of  $L_\gamma$  on  $M$  is marginal for core-collapsed GICs, with Spearman' s rank coefficient  $r = 0.259$  and random correlation  $p$ -value of  $p = 0.417$ . The minimum and median  $\gamma$ -ray luminosity of dynamically normal GICs is measured to be  $L_{\gamma, \min} = 1.0 \times 10^{33}$  erg s $^{-1}$  and  $L_{\gamma, \text{med}} = 4.1 \times 10^{34}$  erg s $^{-1}$ , which is comparable to that of the core-collapsed GICs (i.e.,  $L_{\gamma, \min} = 1.0 \times 10^{33}$  erg s $^{-1}$  and  $L_{\gamma, \text{med}} = 3.22 \times 10^{34}$  erg s $^{-1}$ ). The exception is for the most luminous GICs (i.e.,  $L_\gamma \gtrsim 10^{35}$  erg s $^{-1}$ ), which are dominated by dynamically normal GICs and thus are responsible for the much larger scatter of  $L_\gamma$  in dynamically normal GICs than the core-collapsed ones.

In Figure 3(b), we examine the dependence of  $\eta_\gamma$  on  $M$ . It can be seen that  $\eta_\gamma$  has a substantial scatter ranging over two orders of magnitude. Nevertheless, a marginally significant negative correlation between  $\eta_\gamma$  and  $M$  is suggested by the Spearman' s rank coefficient, with  $r = -0.396$ ,  $r = -0.343$  and  $r = -0.359$ , and random correlation  $p$ -value of  $p = 0.045$ ,  $p = 0.276$  and  $p = 0.027$  for the dynamically normal, core-collapsed and total sample of GICs, respectively. A power-law function fitting gives  $\eta_\gamma \propto M^{-0.49 \pm 0.22}$  (olive lines) and  $\eta_\gamma \propto M^{-0.48 \pm 0.29}$  (blue lines) for the dynamically normal and total GICs. These negative correlations are consistent with the sub-linear correlations found in Figure 3(a). The average  $\gamma$ -ray emissivity and standard deviation of all GICs is measured to be  $\langle \eta_\gamma \rangle = (1.0 \pm 1.5) \times 10^{30}$  erg s $^{-1} M_\odot^{-1}$ , and no significant difference between the dynamically normal GICs ( $\langle \eta_\gamma \rangle = (1.1 \pm 1.6) \times 10^{30}$  erg s $^{-1} M_\odot^{-1}$ ) and core-collapsed GICs ( $\langle \eta_\gamma \rangle = (0.8 \pm 1.1) \times 10^{30}$  erg s $^{-1} M_\odot^{-1}$ ) are found. The dependence of  $L_\gamma$  on  $M$  is consistent with the work of Hooper & Linden (2016), where massive GICs are also found to have larger  $\gamma$ -ray luminosities. This trend is also in agreement with Figure 1(e), supporting a  $\gamma$ -ray detection preference for massive GICs. However, the negative  $\eta_\gamma - M$  correlation suggests that the cluster mass is not the decisive factor influencing the abundance (or formation efficiency) of MSPs in GICs. We note that a similar  $\eta_\gamma - M$  relationship has also been reported by Fragione et al. (2018a) in their Figure 3.

### 3.2. Correlations with Stellar Encounter Rates

Traditionally, there are two parameters in literature to describe the stellar encounter rate of GICs. The first is the total stellar encounter rate,  $\Gamma \propto \int \rho^2 / \sigma$ , an integral of stellar encounters over the cluster volume, with  $\rho$  the stellar density and  $\sigma$  the cluster velocity dispersion (Verbunt & Hut 1987; Verbunt 2003). The second is the specific encounter rate, defined as  $\Lambda \equiv \Gamma / M$ , and measures the chance that a particular star (or binary) undergoes dynamical encounters in GICs (Pooley & Hut 2006). For this reason,  $\Gamma$  is thought to be a reasonable indicator of the total amount of exotic objects that can be dynamically produced in GICs (Pooley et al. 2003; Cheng et al. 2018), while  $\Lambda$  is considered to be highly correlated with the abundance (or the formation efficiency) of exotic objects in GICs (Pooley & Hut 2006; Cheng et al. 2018).

In Figure 4(a) [Figure 4: see original paper], we plot  $L_\gamma$  versus  $\Gamma$  for each GIC. The values of  $\Gamma$  are adopted from Bahramian et al. (2013), which are integrated over the cluster and normalized to a value of 1000 for NGC 104 (Table 2). It is clear that  $L_\gamma$  is highly correlated with  $\Gamma$  for dynamically normal GICs. The Spearman's correlation coefficient is  $r = 0.697$ , with a random correlation  $p$ -value of  $p = 1.1 \times 10^{-4}$ . If core-collapsed GICs are taken into account, this correlation is still significant, with  $r = 0.583$  and  $p = 1.5 \times 10^{-4}$  for total GICs. The best-fitting functions can be written as  $L_\gamma \propto \Gamma^{0.71 \pm 0.11}$  and  $L_\gamma \propto \Gamma^{0.73 \pm 0.11}$  (blue curves) for the dynamically normal and total GICs, respectively. These correlations are consistent with the finding of de Menezes et al. (2019), where the possible number of MSPs ( $N$ ) of GICs is found to be proportional to  $\Gamma$ , with  $N \propto \Gamma^{0.64 \pm 0.15}$  in a sample of 23 GICs.

According to the Spearman's rank correlation coefficients, it is clear that  $L_\gamma$  depends on  $\Gamma$  better than  $M$ , which suggests that stellar dynamical interactions are the fundamental influence on the population of MSPs in GICs. To minimize the dependence on cluster mass, we also examine  $\eta_\gamma$  versus  $\Lambda$  in Figure 4(b). The value of  $\Lambda$  was calculated with equation  $\Lambda = \Gamma / M_6$ , with  $M_6$  being the cluster mass in units of  $10^6 M_\odot$ . Since  $\Gamma$  was estimated based on the V-band luminosity (Bahramian et al. 2013), here we calculated  $M_6$  using the V-band-based magnitude for consistency, following an empirical mass-to-magnitude relation described in Cheng et al. (2018). From Figure 4(b), it is obvious that the dynamically normal GICs have a larger  $\eta_\gamma$  with increasing  $\Lambda$ . The Spearman's rank correlation coefficient is  $r = 0.616$ , with  $p = 1.0 \times 10^{-3}$  for random correlation. This correlation becomes less significant when taking the core-collapsed GICs into account, with  $r = 0.368$  and  $p = 0.025$  for the total GICs. A power-law fitting yields a function of  $\eta_\gamma \propto \Lambda^{0.78 \pm 0.15}$  (olive curves) for the dynamically normal GICs. Compared with dynamically normal GICs, the core-collapsed GICs are found to have much larger scatter in  $\eta_\gamma$ .

The difference may arise from the rapid change of cluster structure in these systems. Once GICs are running out of binary systems and undergo deep core collapse, their structure is not stable anymore and the cluster core may suf-

fer from gravothermal oscillations (Fregeau et al. 2003). Core-collapsed GICs therefore may create extremely frequent stellar encounter environments. Indeed, some core-collapsed GICs (e.g., NGC 6624 and NGC 7078) are proved to be clusters with the highest stellar encounter rates in Table 2, supporting a currently deep core collapse in these systems. While some clusters (e.g., HP-1 and Terzan 1) are found to have the smallest values of  $\Gamma$  and  $\Lambda$ , which may indicate a core bounce phase after the deep core collapse. On the other hand, with extremely large  $\Lambda$ , it is possible for LMXBs to be dynamically disrupted during deep core collapse (Verbunt & Freire 2014), and strong encounters from the clusters may lead to the ejection of MSPs (Section 4.2). These processes may introduce uncertainties to the  $L_\gamma - \Gamma$  and  $\eta_\gamma - \Lambda$  correlations for core-collapsed GICs.

### 3.3. Correlations with Cluster Structure Parameters

To find out the dependence of GIC  $\gamma$ -ray emission on the cluster structure and dynamical evolution history, we sort parameters and investigate their correlations with  $L_\gamma$  and  $\eta_\gamma$  in Figures 5 and 6. Generally speaking, MSPs are prone to be dynamically formed in the dense core of GICs. Therefore, we first plot  $L_\gamma$  versus GIC core radius  $R_c$ , core density  $\rho_c$ , core relaxation time  $t_{rc}$  and central velocity dispersion  $\sigma_c$  in the upper panels of Figure 5 [Figure 5: see original paper]. No clear correlation exists for the total GIC sample, except that  $L_\gamma$  is highly correlated with  $\sigma_c$  ( $r = 0.574$ ,  $p = 2.0 \times 10^{-4}$ ) in Figure 5(d). When only the dynamically normal GICs are considered, this correlation is still evident, with Spearman's  $r = 0.672$  and random correlation  $p$ -value of  $p = 2.4 \times 10^{-4}$ . We fit this correlation with power-law function, which gives  $L_\gamma \propto \sigma_c^{2.36 \pm 0.44}$  (blue lines) and  $L_\gamma \propto \sigma_c^{2.18 \pm 0.61}$  (olive lines) for the total and dynamically normal GICs, respectively. However, it seems that the cluster mass is the more fundamental parameter underlying the  $L_\gamma - \sigma_c$  relation, since the dependence of  $\eta_\gamma$  on  $\sigma_c$  is less significant in Figure 6(d) [Figure 6: see original paper], and  $\sigma_c$  is highly correlated with  $M$  in GICs (Table 3).

Unlike the linear relations reported in Sections 3.1 and 3.2, the Spearman's rank correlation coefficients suggest dynamically normal GICs and core-collapsed GICs are statistically different in Figures 5(a)-(c). As GICs evolve to older dynamical age (i.e., with decreasing  $t_{rc}$ ) and become more compact (i.e., with smaller  $R_c$  and larger  $\rho_c$ ), the dynamically normal GICs are more likely to exhibit larger  $L_\gamma$ . Whereas for core-collapsed GICs, this trend is reversed. When the influence of cluster mass is eliminated, this tendency still holds in Figures 6(a)-(c), where the dynamically normal GICs are measured to have larger  $\eta_\gamma$  with increasing dynamical age, which then reverses to smaller values as clusters evolve into core-collapsed GICs. We suggest these features may indicate an episodic ejection of MSPs from GICs. Namely, during the deep core collapse and subsequent core bounce, a significant number of MSPs may have been dynamically ejected from the host clusters. The implication of this effect will be addressed in Section 4.2. Here, we find the significant correlations of dynamical

cally normal GICs can be expressed as  $\eta_\gamma \propto R_c^{-0.93 \pm 0.27}$ ,  $\eta_\gamma \propto \rho_c^{0.39 \pm 0.14}$ , and  $\eta_\gamma \propto t_{rc}^{-0.61 \pm 0.11}$ . They are plotted as olive lines in the figures.

In the middle panels of Figures 5 and 6, we test the dependence of  $L_\gamma$  and  $\eta_\gamma$  on the GIC half-mass radius  $R_h$ , stellar density ( $\rho_h$ ) inside  $R_h$ , half-mass relaxation time  $t_{rh}$  and central escape velocity  $v_{esc}$ . It is obvious that the dynamically normal GICs have a larger  $L_\gamma$  with increasing  $\rho_h$  and  $v_{esc}$ , and the best-fitting functions (olive lines) can be written as  $L_\gamma \propto \rho_h^{0.63 \pm 0.15}$  and  $L_\gamma \propto v_{esc}^{2.18 \pm 0.61}$ . If core-collapsed GICs are included, these correlations are still evident, with  $L_\gamma \propto \rho_h^{0.58 \pm 0.13}$  and  $L_\gamma \propto v_{esc}^{2.25 \pm 0.48}$  for the total GICs (blue lines). However, the dependence of  $\eta_\gamma$  on  $R_h$  and  $v_{esc}$  are not significant in Figures 6(f) and (h), reflecting again that cluster mass is the more fundamental parameter underlying these relations. On the other hand, GICs with smaller  $R_h$  appear to have larger  $L_\gamma$ , as indicated by the mild anti-correlation coefficients in the figures. This trend is still evident in Figure 6(e), where the best-fitting functions between  $\eta_\gamma$  and  $R_h$  can be expressed as  $\eta_\gamma \propto R_h^{-1.12 \pm 0.91}$ ,  $\eta_\gamma \propto R_h^{-2.09 \pm 0.61}$ , and  $\eta_\gamma \propto R_h^{-1.76 \pm 0.48}$  for the dynamically normal, core-collapsed and total samples of GICs, respectively. Besides, although the dependence of  $L_\gamma$  on  $t_{rh}$  is not apparent in Figure 5(g),  $\eta_\gamma$  is found to decrease with increasing  $t_{rh}$  in Figure 6(g), with the best-fitting functions written as  $\eta_\gamma \propto t_{rh}^{-0.65 \pm 0.38}$ ,  $\eta_\gamma \propto t_{rh}^{-0.85 \pm 0.20}$ , and  $\eta_\gamma \propto t_{rh}^{-0.80 \pm 0.17}$  for dynamically normal, core-collapsed and total GICs, respectively.

By and large, the dependence of  $\gamma$ -ray emission on GIC half-mass parameters is in agreement with that on the core parameters. That is, as GICs evolve to older dynamical age and become more compact, GICs are more likely to exhibit larger  $L_\gamma$  and  $\eta_\gamma$ . The discrepancy may arise from the core collapse, in which the cluster core structure may change dramatically during the gravothermal oscillations. Whereas for the half-mass parameters, their response to core collapse will be more moderate (Fregeau et al. 2003), thus both dynamically normal and core-collapsed GICs are found to exhibit similar correlations in Figures 5(e)-(h) and 6(e)-(h).

In the bottom panels of Figures 5 and 6, we examine the dependence of  $L_\gamma$  and  $\eta_\gamma$  on the cluster tidal radius  $R_t$ , stellar mass function (MF) slope  $\alpha$ , concentration parameter  $c$  and metallicity [Fe/H].  $L_\gamma$  is found to be independent of  $R_t$ ,  $\alpha$  and  $c$  in Figures 5(i), (j) and (k). However, it is clear that GICs with smaller  $R_t$  and larger  $\alpha$  are more likely to have larger  $\eta_\gamma$  (Figures 6(i) and (j)). The  $\eta_\gamma$ - $R_t$  relation yields  $\eta_\gamma \propto R_t^{-1.08 \pm 0.28}$ ,  $\eta_\gamma \propto R_t^{-0.98 \pm 0.37}$ , and  $\eta_\gamma \propto R_t^{-1.00 \pm 0.22}$  for the dynamically normal, core-collapsed and total GICs, respectively. While for the  $\eta_\gamma$ - $\alpha$  relation, which can be expressed as  $\log \eta_\gamma = a\alpha + b$  in Figure 6(j), the best-fitting parameters are  $a = (0.57 \pm 0.10)$  and  $b = (29.24 \pm 0.07)$  for total GICs,  $a = (0.67 \pm 0.14)$  and  $b = (29.26 \pm 0.09)$  for dynamically normal GICs, and  $a = (0.41 \pm 0.15)$  and  $b = (29.22 \pm 0.11)$  for core-collapsed GICs, respectively.

Observationally, many authors argued that LMXBs are more likely to be de-

tected in old, metal-rich GICs, rather than in young, metal-poor ones (Sivakoff et al. 2007; Li et al. 2010; Kim et al. 2013). As the offspring of LMXBs, Figure 5(1) also suggests that MSPs are more likely to be found in metal-rich GICs. We fit the  $L_\gamma$ -[Fe/H] relation with the function  $\log L_\gamma = a[\text{Fe}/\text{H}] + b$ , with best-fitting parameters  $a = (0.53 \pm 0.18)$  and  $b = (35.16 \pm 0.21)$  for dynamically normal GICs,  $a = (0.47 \pm 0.14)$  and  $b = (35.09 \pm 0.17)$  for total GICs, respectively. When the influence of cluster mass was eliminated, we find this tendency is still evident in Figure 6(1). The best-fitting function gives parameters of  $a = (0.58 \pm 0.17)$  and  $b = (29.71 \pm 0.20)$  for dynamically normal GICs,  $a = (0.54 \pm 0.18)$  and  $b = (29.88 \pm 0.26)$  for core-collapsed GICs, and  $a = (0.53 \pm 0.13)$  and  $b = (29.73 \pm 0.13)$  for total GICs, respectively. We note that a similar  $L_\gamma$ -[Fe/H] relation was also obtained by de Menezes et al. (2019) with 23 GICs.

### 3.4. Correlations with the Galactic Environment

Contrary to the contraction of cluster cores, the outskirts of GICs are driven to expand and may be truncated by the tidal force of the host galaxy. The tidal radius, defined as the boundary where a GIC may lose its stars to the Galaxy, is subject to its coordinates in the Milky Way (Baumgardt & Makino 2003). The independence of  $L_\gamma$  on  $R_t$  in Figure 5(i), and the negative  $\eta_\gamma$ - $R_t$  relation in Figure 6(i), suggests that tidal stripping is another important factor influencing the abundance of MSPs in GICs. Indeed, this tendency can also be confirmed by the positive  $\eta_\gamma$ - $\alpha$  correlation, since mass segregation and tidal stripping effects have a preference for the depletion of low-mass stars from GICs, thus tidally stripped clusters are more likely to exhibit larger stellar MF slope  $\alpha$  (Vesperini & Heggie 1997; Baumgardt & Makino 2003).

Therefore, we also investigate the dependence of GIC  $\gamma$ -ray emission on the Galactic environment parameters in Figures 7 and 8. The coordinates of GICs are adopted from the online catalog of Baumgardt et al. (2019), with  $X$  pointing from the Galactic center toward the Sun,  $Y$  pointing in the direction of Galactic rotation at the Solar position, and  $Z$  pointing toward the North Galactic pole, respectively. In Figures 7(a) and 8(a), both  $L_\gamma$  and  $\eta_\gamma$  are found to decrease moderately with increasing  $X$ . However, these features may reflect an observational selection effect of GIC  $\gamma$ -ray detection by Fermi-LAT at the position of Sun (i.e., with  $X \approx 8$  kpc,  $Y = 0$  kpc and  $Z = 0$  kpc), rather than a physical dependence of GIC  $\gamma$ -ray emission on  $X$ . Nevertheless, it seems that  $L_\gamma$  tends to reach the maximum values near the GC in  $Y$  and  $Z$  direction (Figures 7(b) and (c)), and this tendency is still evident when the influence of cluster mass is considered in Figures 8(b) and (c). We further plot in Figures 7(d)-(f)  $L_\gamma$  as a function of cluster distance to the GC ( $R_{\text{gc}}$ ), the perigalactic distance ( $R_{\text{gc,per}}$ ) and apogalactic distance ( $R_{\text{gc,apo}}$ ) of GIC orbit in the Milky Way. Although with large scatter, the mild anti-correlations between  $L_\gamma$  and the GIC distances to GC are in agreement with the finding of Figures 7(b) and (c), suggesting that more MSPs tend to be dynamically formed in GICs closer to the GC. This tendency is

even more significant in Figures 8(d)-(f), where the best-fitting functions can be expressed as  $\eta_\gamma \propto R_{\text{gc}}^{-1.13 \pm 0.21}$ ,  $\eta_\gamma \propto R_{\text{gc,per}}^{-0.74 \pm 0.13}$  and  $\eta_\gamma \propto R_{\text{gc,apo}}^{-1.21 \pm 0.20}$  for total GICs,  $\eta_\gamma \propto R_{\text{gc}}^{-1.06 \pm 0.15}$ ,  $\eta_\gamma \propto R_{\text{gc,per}}^{-0.78 \pm 0.34}$  and  $\eta_\gamma \propto R_{\text{gc,apo}}^{-1.43 \pm 0.28}$  for dynamically normal GICs, and  $\eta_\gamma \propto R_{\text{gc}}^{-1.00 \pm 0.22}$ ,  $\eta_\gamma \propto R_{\text{gc,per}}^{-0.73 \pm 0.16}$  and  $\eta_\gamma \propto R_{\text{gc,apo}}^{-0.73 \pm 0.16}$  for core-collapsed GICs, respectively.

For comparison, it will be interesting to mark in Figures 8(d)-(f) the  $\gamma$ -ray emissivity of stars in the Inner Galaxy, since tidally disrupted GICs are thought to contribute to at least part of the stars therein. With a total mass of  $(1.4 \pm 0.6) \times 10^9 M_\odot$  for nuclear bulge stars and  $(0.91 \pm 0.7) \times 10^{10} M_\odot$  for boxy bulge stars, Bartels et al. (2018) showed that the emission profile of GCE can be better fitted by stellar mass in the boxy and nuclear bulge rather than dark matter profiles, and the  $\gamma$ -ray emissivity of the Galactic boxy bulge and nuclear bulge is measured to be  $\eta = (1.0 \pm 0.5) \times 10^{29} \text{ erg s}^{-1} M_\odot^{-1}$  and  $\eta = (1.5 \pm 0.7) \times 10^{29} \text{ erg s}^{-1} M_\odot^{-1}$  separately. We mark the boxy bulge and nuclear bulge with blue and olive rectangles in Figures 8(d)-(f), with vertical ranges indicating  $\gamma$ -ray emissivity errors and the horizontal ranges roughly denoting the extent of the boxy bulge ( $10^\circ$ ) and nuclear bulge (200 pc). We also display the best fit of GCE emission per unit stellar mass as a red dashed horizontal line ( $\eta = 1.0 \times 10^{29} \text{ erg s}^{-1} M_\odot^{-1}$ , Bartels et al. 2018) in the figures.

From Figures 8(d)-(f), it can be seen that GICs have a  $\gamma$ -ray emissivity 10-1000 times higher than the Galactic boxy bulge and nuclear bulge, which indicates that tidally disrupted GICs may enhance the  $\gamma$ -ray emissivity of the Inner Galaxy greatly. More importantly, as GICs inspiral toward the GC, it seems that normal stars are more likely to be stripped off the clusters by Galactic tidal force, while MSPs are preferentially deposited to the Inner Galaxy, thus resulting in a negative dependence of  $\eta_\gamma$  on  $R_{\text{gc}}$ ,  $R_{\text{gc,per}}$  and  $R_{\text{gc,apo}}$  in GICs. These features suggest that, in addition to tidal stripping, mass segregation may also play an important role in allocating the objects that can be delivered to the GC. Therefore, an estimation of GIC contribution to the GCE must take these effects into account. We leave the implication of this problem to be addressed in Section 4.4.

We end this section by emphasizing that the GIC parameters are not independent of each other. For example, there is a significant correlation between  $\Gamma$  and  $M$  in GICs (Cheng et al. 2018), and massive GICs are usually found to have larger central velocity dispersion  $\sigma_c$ , escape velocity  $v_{\text{esc}}$ , core density  $\rho_c$ , and smaller half-mass (core) relaxation time  $t_{rh}$  ( $t_{rc}$ ). On the other hand, significant dependence of cluster parameters on  $R_c$  and  $R_{\text{gc}}$  has been reported in literature (Djorgovski & Meylan 1994). These mutual relations suggest that the GIC parameters are highly coupled with each other, and they are closely connected with the dynamical evolution of GICs in the Milky Way tidal field (Meylan & Heggie 1997). In Table 3, we summarize the Spearman's rank coefficients of  $L_\gamma$ ,  $\eta_\gamma$ ,  $M$  and  $R_{\text{gc}}$  on various GIC parameters; the corresponding random correlation  $p$ -values are also listed in the table.

## 4. Discussion

By exploring the dependence of  $L_\gamma$  and  $\eta_\gamma$  on various GIC parameters in Section 3, we have established many correlations and trends between GIC dynamical evolution and their binary burning products. In particular, the measured  $\gamma$ -ray emission is mainly contributed by MSPs, which facilitates us to trace the dynamical formation of MSPs within GICs, their migration with host clusters in the Milky Way, and the final settlement and spatial distribution surrounding the GC. As introduced in Section 1, these processes are particularly important for the MSP interpretation of the GCE. Here we discuss our findings and conclusions as follows.

### 4.1. GIC Dynamical Evolution and Formation of MSPs

As self-gravitating systems, the dynamical evolution of GICs is balanced by the production of energy in the core and the outflow of energy from the cluster, and two-body relaxation is the fundamental process that dominates the transportation of energy and mass in GICs. Stars are driven to reach a state of energy equipartition by two-body relaxation; massive stars (or binaries) therefore tend to lose energy and drop to the cluster center (thus influencing the types of binary burning products), whereas lower-mass stars tend to gain energy and move faster, and they will migrate outward (thus leading to the energy outflow in GICs) and drive the cluster envelope to expand (Heggie & Hut 2003). Binary burning is thought to be the internal energy source that supports the cluster against gravothermal collapse, and the energy production rate of GICs is sensitive to the encounter rate of hard binaries (Cheng et al. 2018):

$$\Gamma_b \propto f_b A_b \Gamma$$

where  $f_b$  is the fraction of stars in binary systems,  $A_b \propto a/\sigma^2$  is the binary encounter cross section, with  $a$  being the orbital separation of the binary. In practice, it is hard to determine the distribution of  $a$  by observation, while  $f_b$  is found to vary not too much among GICs (i.e.,  $f_b \sim 1\%$ -20%; Milone et al. 2012). Therefore,  $\Gamma_b$  is usually simplified as  $\Gamma \propto \int \rho^2/\sigma$  in literature.

As binaries are disrupted or are driven to evolve to harder systems by dynamical encounters, both  $f_b$  and  $A_b$  will become smaller and the energy production rate of GICs may decrease according to Equation (1). However, this may not happen in a real cluster. In fact, GICs contract their cores to increase the stellar density, which enhances the stellar encounter rates (i.e.,  $\Gamma$  and  $\Lambda$ ) and thus the energy production rate. Accordingly, the cluster two-body relaxation time is adjusted to smaller values, to enhance the energy outflow rate and maintain the balance between the energy production in the cores and the outflow of energy from the systems. As a result, the dynamical evolution of GICs will become more and more rapid, until dynamical ejection of close binaries becomes important (see Section 4.2) and the cluster evolves into a core-collapsed GIC.

With larger mass than normal stars, NS are expected to concentrate to the cluster center and take part in the binary burning process, thus leading to the formation of LMXBs and MSPs in GICs. However, recent N-body simulations suggest that many GICs may host a significant population of primordial stellar mass black holes (BHs), even at an age larger than 12 Gyr (Breen & Heggie 2013; Morscher et al. 2013, 2015; Wang et al. 2016). Compared with NS, the BHs are expected to drop to the cluster center first and form a high-density BH subsystem (BHS), where the BH burning process (i.e., the dynamical hardening of BH binaries, Kremer et al. 2020b) may dominate the energy production of GICs and lead to the formation of gravitational wave sources (Rodriguez et al. 2016; Askar et al. 2017; Anagnostou et al. 2020; Antonini & Gieles 2020). The thermal coupling of BHS with GICs is sufficient to reshape the structure of the cluster (Merritt et al. 2004; Mackey et al. 2007, 2008; Giersz et al. 2019) and quench or slow down the mass segregation of less-massive objects (such as NS, binaries and BSS) in GICs (Fragione et al. 2018b; Weatherford et al. 2018). Besides, through exchange encounters involving a BH, binaries are preferentially transformed into BH binaries; BHS therefore may suppress the formation of other binary burning products in GICs, and clusters with a large number of BHs are more likely to have a lower formation efficiency of LMXBs, MSPs, CVs, ABs, and BSS (Fragione et al. 2018b; Ye et al. 2019; Kremer et al. 2020a).

The mass segregation delay of heavy objects in GICs has been confirmed by the radial distribution study of X-ray sources, MSPs and BSS in 47 Tuc and Terzan 5 (Ferraro et al. 2012; Cheng et al. 2019b, 2019a), where massive objects (i.e., MSPs, bright X-ray sources or BSS) are found to drop to the cluster center earlier and be more centrally concentrated than the less massive ones (i.e., faint X-ray sources and normal stars). The exception is M28, where Cheng et al. (2020) reported an abnormal deficiency of X-ray sources in the cluster central region with respect to its outskirts, and argued that an early phase of primordial binary disruption by BHS may have happened in M28 (Cheng et al. 2020). On the other hand, significant evidence of BH burning has been reported in GIC  $\omega$  Centauri, in which the dynamical formation of X-ray sources is found to be highly suppressed, and BHS is the essential internal energy source that supports the cluster against collapse (Cheng et al. 2020). Indeed, with 4.6% of the cluster mass being invisible,  $\omega$  Centauri is thought to be the cluster with the heaviest BHS in the Galaxy (Baumgardt et al. 2019). In Table 1, the  $\gamma$ -ray emissivity of  $\omega$  Centauri is also the smallest among the 39 GICs, suggesting a low formation efficiency of MSPs in this cluster.

The evolution fate of the BHS is beyond the scope of this paper. It is very likely that the majority of the BHs will be ejected from the cluster gradually, and host GICs tend to contract their cores and increase the stellar density (Arca Sedda et al. 2018a). As a consequence, NS start to concentrate to the cluster center and gradually take over the binary burning process, which then results in the formation of a large number of LMXBs and MSPs in GICs. Indeed, we have demonstrated that  $L_\gamma$ , the proxy of the population of MSPs in GICs, is

highly correlated with the cluster stellar encounter rate  $\Gamma$ , with  $L_\gamma \propto \Gamma^{0.71 \pm 0.11}$  in dynamically normal GICs (Figure 4(a)). Besides, the GIC  $\gamma$ -ray emissivity  $\eta_\gamma$ , a proxy of the MSP abundance, is highly correlated with the cluster specific encounter rate  $\Lambda$ , with  $\eta_\gamma \propto \Lambda^{0.78 \pm 0.15}$  in Figure 4(b). These correlations provide strong evidence for the dynamical formation of MSPs in GICs.

On the other hand, by examining the dependence of  $L_\gamma$  and  $\eta_\gamma$  on the cluster structure parameters, we have tested the relationship between MSP formation and the dynamical evolution of GICs. For example, both  $L_\gamma$  and  $\eta_\gamma$  are anti-correlated with GIC core radius  $R_c$  and half-mass radius  $R_h$  in dynamically normal GICs (Figures 5 and 6). In particular, the  $\eta_\gamma$ - $R_c$  and  $\eta_\gamma$ - $R_h$  correlations can be expressed as  $\eta_\gamma \propto R_c^{-0.93 \pm 0.27}$  and  $\eta_\gamma \propto R_h^{-1.12 \pm 0.91}$  in Figures 6(a) and (e), respectively. Furthermore,  $\Gamma$  is strongly dependent on the cluster stellar density  $\rho$ , with  $\Gamma \propto \int \rho^2 / \sigma$ . We have also found strong correlations between  $L_\gamma$  and  $\rho_c$  and  $\rho_h$  in dynamically normal GICs, with  $L_\gamma \propto \rho_c^{0.39 \pm 0.14}$  and  $L_\gamma \propto \rho_h^{0.63 \pm 0.15}$  in Figures 5(b) and (f). These trends are in agreement with the dynamical evolution of GICs, that is, as GICs contract their central regions to smaller radius and become more dense, more MSPs are expected to be dynamically formed in the clusters.

Finally, it is necessary to emphasize that the formation of MSPs is far from finished in many dynamically normal GICs. As confirmed by the radial distribution studies of X-ray sources (Cheng et al. 2019b, 2019a, 2020) and BSS (Ferraro et al. 2012) in GICs, it is possible that there are considerable numbers of primordial binaries and NS existing in the outskirts of the dynamically young GICs. Under the effect of mass segregation, these objects tend to drop to the dense core of the cluster, where they could be transformed into LMXBs and MSPs by the binary burning process, thereby increasing the abundance of MSPs in dynamically normal GICs. As a consequence, dynamically normal GICs with an older dynamical age (i.e., with smaller  $t_{rc}$  or  $t_{rh}$ ) are more likely to exhibit a larger abundance of MSPs, with the  $\eta_\gamma$ - $t_{rc}$  correlation expressed as  $\eta_\gamma \propto t_{rc}^{-0.61 \pm 0.11}$  in Figure 6(c), and the  $\eta_\gamma$ - $t_{rh}$  correlation expressed as  $\eta_\gamma \propto t_{rh}^{-0.85 \pm 0.20}$  in Figure 6(g), respectively.

## 4.2. Dynamical Disruption of LMXBs and Ejection of MSPs in Core-Collapsed GICs

From Equation (1), it can be seen that the evolution of GICs to core collapse sensitively depends on the encounter cross section (i.e.,  $A_b \propto a/\sigma^2$ ) of the binaries. With larger  $A_b$ , the primordial binaries are expected to take part in the binary burning process first and are transformed into close binaries, which may lead to the formation of many exotic objects, such as LMXBs (e.g., through exchange encounters involving NS), MSPs, CVs, ABs and BSS in GCs. However, when primordial binaries are exhausted, GICs tend to contract their cores and increase the stellar density, thereby increasing the specific encounter rate ( $\Lambda$ ) of stars in the cluster core. The enhancement of  $\Lambda$  is helpful for extracting energy

from harder binaries, and even very close binary systems, such as LMXBs, MSPs, CVs and ABs, may suffer strong dynamical encounters in core-collapsed GICs. Nevertheless, it is argued that the “burning” of very hard binaries is not sufficient to terminate the deep core collapse of GICs. The cluster cores are expected to contract further, until dynamical interactions between single stars take effect and lead to the formation of new binaries in GICs (i.e., binary formation either via the “two-body binaries” or the “three-body binaries” channels, Heggie & Hut 2003). The sudden introduction of a large number of binaries in an extremely dense core is sufficient to reverse the cluster core collapse to core bounce, and trigger gravothermal oscillations in GICs.

Before discussing the dynamical evolution fate of LMXBs and MSPs in core-collapsed GICs, it is necessary to have an intuitive understanding of the dynamic effects of the binary burning process in GICs. According to the Hills–Heggie law, through binary–single encounters, hard binaries tend to increase their binding energy ( $E_b = Gm^2/2a$ ) and become harder. The average increase of  $E_b$  per encounter is roughly proportional to its initial value, with  $\delta E_b \sim 0.4\text{--}0.5E_b$  for equal-mass encounters (Heggie 1975; Hills 1975). The release of the binding energy is transformed into the kinetic energy of the ejected star, and the remaining binary will receive a recoil velocity as well,  $v_{\text{recoil}} \sim \delta E_b/(m\sigma)$ . Therefore, hard binaries tend to receive larger recoil velocity after strong encounters, which may lead to the recoil of the binaries out of the core into the halo, and sometimes out of the host cluster (Hut et al. 1992). With typical central escape velocity of  $10 \text{ km s}^{-1} \lesssim v_{\text{esc}} \lesssim 100 \text{ km s}^{-1}$ , LMXBs and MSPs may receive a large recoil velocity and escape the core-collapsed GICs after suffering strong encounters. On the other hand, the specific encounter rate  $\Lambda$  of deep core collapse GICs is extremely high; it is possible for LMXBs to be dynamically disrupted (i.e., via binary–binary encounters) or be greatly modified (i.e., exchange encounters, etc.) before they otherwise could evolve into MSPs (Verbunt & Freire 2014). The net effect is that the population of MSPs tends to be gradually exhausted in core-collapsed GICs. Indeed, compared with dynamically normal GICs, the core-collapsed GICs are found to exhibit smaller  $L_\gamma$  and  $\eta_\gamma$  with decreasing  $R_c$ ,  $t_{rc}$ , and increasing  $\rho_c$  in Figures 5(a)–(c) and 6(a)–(c). Two well-known core-collapsed GICs, NGC 6397 and NGC 6752, are proved to be the clusters with the smallest  $L_\gamma$  and  $\eta_\gamma$  in Table 1.

The decreases of MSP populations in core-collapsed GICs have also been reported by de Menezes et al. (2019), which was interpreted as the disruption of LMXBs by the extremely large specific encounter rates in the dense cores. However, these authors have neglected the importance of MSP ejection in deep core collapse clusters. The lifetime of MSPs ( $10^{10}$  yr) is at least one order of magnitude larger than the cluster core relaxation time ( $t_{rc} \sim 10^5\text{--}10^9$  yr), and once MSPs are formed via the recycling process of LMXBs, it is hard to change their properties through direct stellar dynamical interactions. Therefore, the decline of  $L_\gamma$  and  $\eta_\gamma$  from dynamically normal GICs to core-collapsed GICs in Figures 5(a)–(c) and 6(a)–(c) may suggest an episodic ejection of MSPs during the deep core collapse phase, and the injection of MSPs into the Milky Way may play an

important role in shaping the spatial extent of the GCE. Nevertheless, it is also possible for some MSPs to be retained by the host cluster (Hut et al. 1992), and the retention of these MSPs may be responsible for the 2 times larger detection rate of  $\gamma$ -ray emission in core-collapsed GICs than in dynamically normal GICs by Fermi-LAT (Section 2.2).

### 4.3. Tidal Stripping and Deposition of MSPs into the Galactic Center

In addition to the internal effects, the structure of GICs is also subjected to the external influence of the host galaxy, which may affect the dynamical evolution of GICs in two ways. First, the expanding envelopes of GICs are expected to be truncated by the gravitational tidal field of the host galaxy, and compared with clusters in isolation, GICs in the tidal field may suffer an enhanced rate of energy outflow and mass loss. The tidal stripping therefore has a net effect in accelerating the dynamical evolution of the GICs. Second, through dynamical friction with background stars, GICs tend to lose energy and spiral in toward the center of the galaxy, where tidal stripping and interactions with the dense nucleus will eventually lead to the dissolution of the clusters (Tremaine et al. 1975). In particular, during passages close to the Galactic bulge or through the dense disk, GICs may suffer gravitational shocks and these two effects could be enhanced greatly. The bulge shocking and disk shocking tend to heat up the GIC outskirts and increase evaporation of the cluster (Gnedin & Ostriker 1997), which in turn accelerates the core collapse and shortens the destruction time of GICs (Gnedin et al. 1999). Taking these aspects together, it is suggested that GICs are the ancient building blocks of our Galaxy, and the inner galactic structures, such as the nuclear star cluster and the nuclear bulge, are assembled at least in part by the merger of tidally disrupted GICs that spiraled into the deep gravitational well of the GC (Antonini et al. 2012; Antonini 2013; Gnedin et al. 2014).

Observationally, the dynamical evolution of GICs and its coupling with the host galaxy has been widely confirmed in literature, either via the stellar streams of tidal stripping (Leon et al. 2000; Sollima 2020), or the dependence of cluster structure parameters on GIC positions within the Galaxy (Djorgovski & Meylan 1994). As shown in Figure 9 [Figure 9: see original paper], with decreasing distance from the GC, GICs are found to be more concentrated and have smaller and denser cores. These trends are consistent with the dynamical evolution of GICs in the Galactic environment, namely, as GICs undergo orbital decay and spiral in toward the GC, the clusters tend to suffer stronger tidal stripping and will be more dynamically evolved. Besides, it is proposed that mass segregation and tidal stripping effects have a preference in evaporating the low-mass stars from GICs, which is strong enough to turn cluster initially increasing MF into MF that decreases toward the low-mass end (Vesperini & Heggie 1997; Baumgardt & Makino 2003; Lamers et al. 2013), and the global MF slope  $\alpha$  is strongly anti-correlated with the half-mass relaxation time  $t_{rh}$  in GICs (Baumgardt & Sollima 2017; Sollima & Baumgardt 2017).

The relationship of GIC dynamical evolution and its coupling with the Galactic

environment can also be confirmed by our  $\gamma$ -ray data. For example, we showed that there is a mild anti-correlation between GIC  $\gamma$ -ray luminosity  $L_\gamma$  and their current distances  $R_{\text{gc}}$ , perigalactic distances  $R_{\text{gc,per}}$  and apogalactic distances  $R_{\text{gc,apo}}$  from the GC in Figure 7 [Figure 7: see original paper]. Compared with the strong dependence of  $L_\gamma$  on  $\Gamma$  in Figure 4(a), these correlations suggest that tidal stripping is a secondary factor affecting the binary burning process of GICs and the populations of MSPs formed therein. On the other hand, tidal stripping plays a crucial role in diminishing the mass of the GICs and leading to the final dissolution of the clusters, which can be further confirmed by the much stronger anti-correlations between GIC  $\gamma$ -ray emissivity  $\eta_\gamma$  and  $R_{\text{gc}}$ ,  $R_{\text{gc,per}}$  and  $R_{\text{gc,apo}}$  in Figure 8 [Figure 8: see original paper]. In fact, we also showed that there is no evident dependence of  $L_\gamma$  on GIC tidal radius  $R_t$  in Figure 5(i), but  $\eta_\gamma$  is found to be strongly anti-correlated with  $R_t$  in Figure 6(i). Therefore, the loss of cluster mass is the most plausible reason for these anti-correlations.

Finally, it is necessary to emphasize the importance of mass segregation in affecting the tidal stripping and dissolution of GICs. Unlike the low-mass normal stars that tend to migrate outward in GICs and will be stripped off the clusters preferentially, LMXBs and MSPs are more likely to segregate to the GIC center and could be retained by the clusters for much longer time. As a result, GICs with increasing MF slope  $\alpha$  are found to exhibit larger  $\eta_\gamma$  in Figure 6(j), and as GICs undergo orbital decay and spiral in toward the Inner Galaxy, LMXBs and MSPs are more likely to be delivered to the GC, leading to strong anti-correlations between  $\eta_\gamma$  and  $R_{\text{gc}}$ ,  $R_{\text{gc,per}}$  and  $R_{\text{gc,apo}}$  in Figure 8.

#### 4.4. Contribution of GIC MSPs to the GCE

As introduced in Section 1, it is proposed that the GCE may arise from a large number ( $10^3$ - $10^4$ ) of unresolved MSPs residing in the GC (Abazajian 2011; Yuan & Zhang 2014; Bartels et al. 2016). The generation of MSPs could arise from in situ star formation and evolution at the GC (Yuan & Zhang 2014; Eckner et al. 2018; Gautam et al. 2022), or be inherited from GICs that were brought to the Inner Galaxy by dynamical friction and assembled the Galactic nuclear star cluster and bulge (Bednarek & Sobczak 2013; Brandt & Kocsis 2015; Fragione et al. 2018a; Arca-Sedda et al. 2018b; Abbate et al. 2018). Compared with the dynamical channel within GICs, the in situ formation of MSPs at the GC is disfavored because LMXBs, the progenitors of MSPs, are observed to be quite rare in the bulge of our Galaxy compared to the prediction of the MSP interpretation (Cholis et al. 2015; Haggard et al. 2017). Besides, Boodram & Heinke (2022) argued that the natal velocity kicks received by newly formed NS during supernova may lead to a lower abundance of MSPs (thus a lower synthetic  $\gamma$ -ray surface brightness) in the central degrees ( $R \lesssim 150$  pc) of the Galactic bulge with respect to its outskirts, which is inconsistent with the measured  $\gamma$ -ray surface brightness profile of the GCE (Boodram & Heinke 2022).

On the other hand, we have demonstrated that the dynamical channel of MSPs is very efficient during cluster dynamical evolution, and as GICs lose kinetic

energy and spiral in toward the GC, MSPs are preferentially deposited into the deep gravitational potential well of the Galaxy, which may avoid the problems reported in the work of Boodram & Heinke (2022). The spatial distribution of GICs is found to be spherically distributed around the GC (Baumgardt & Hilker 2018), and their velocity dispersion is highly isotropic within the central Galaxy (i.e.,  $R \lesssim 10$  kpc; Vasiliev 2019). Therefore, the tidal stripping and ejection of MSPs from GICs to the Milky Way are also expected to create a spherically distributed MSP population in the Inner Galaxy, and the radial distribution profile resembles that of the GCE (Brandt & Kocsis 2015; Fragione et al. 2018a; Arca-Sedda et al. 2018b; Abbate et al. 2018). Moreover, considering the lifetime ( $10^{10}$  yr) of MSPs is much longer than that ( $10^8$  yr) of LMXBs, the very small LMXBs to MSPs ratio observed in the Galactic bulge can be interpreted as the dynamical disruption of LMXBs during the deep core collapse phase of cluster evolution (Section 4.2), and the sudden interruption of the dynamical formation of LMXBs since host GICs were tidally disrupted (Brandt & Kocsis 2015).

To estimate the contribution of Galactic GIC MSPs to the GCE, the knowledge of the luminosity function (LF) of MSPs is particularly important. By utilizing the cluster stellar encounter rate  $\Gamma$  to estimate the formation rate of MSPs in GICs, Hooper & Linden (2016) constrained the  $\gamma$ -ray LF of MSPs in GICs and found that they are as luminous as the Galactic field MSPs, with log-normal LF of  $L_0 \sim 8.8 \times 10^{33}$  erg s $^{-1}$  and  $\sigma \sim 0.62$ . Since MSPs would spin down quickly and fade away in  $\gamma$ -ray luminosity, Hooper & Linden (2016) therefore argued that the GIC MSPs can account for only a few percent or less of the observed GCE. Nevertheless, the LF of Hooper & Linden (2016) also predicts that most of the GICs will be dominated by two MSPs in  $\gamma$ -ray luminosity, which is inconsistent with the radio survey result of MSPs in GICs, where many clusters detected by Fermi are found to host far more than two MSPs. On the other hand, by using the cluster  $\eta_\gamma$  to scale the stellar mass deposited by GICs at the GC, Brandt & Kocsis (2015) showed that a reasonable disrupted GIC mass, such as that calculated in Gnedin et al. (2014), may account for the total  $\gamma$ -ray emission of the GCE. However, both the works of Hooper & Linden (2016) and Brandt & Kocsis (2015) have neglected the influence of cluster dynamical evolution on the formation rate of MSPs in GICs. As discussed in Sections 4.1 and 4.2, the dynamical formation of MSPs is far from finished in dynamically young GICs, while the population of MSPs in core-collapsed GICs is underestimated, since strong encounters may have led to the ejection of many MSPs from these systems. These effects can also be confirmed by the large variance of measured  $\eta_\gamma$  in GICs. From Figures 8(e)-(f), it can be seen that  $\eta_\gamma$  of GICs is 1-3 orders of magnitude larger than that of the Galactic bulge stars; the large variance of  $\eta_\gamma$  suggests that the final population of MSPs created by individual GICs could be more than tens of times higher than that currently hosted in the cluster. Indeed, by assuming a cluster  $\eta_\gamma$ - $M$  relation for GICs, Fragione et al. (2018a) simulated the spiral-in and tidal stripping of GICs in the Milky Way. Although their model has neglected the essential features of cluster dynamical evolution and stellar dynamics (i.e., internal energy sources, stellar mass segregation, core collapse,

etc.) within GICs, the empirical  $\eta_\gamma - M$  relation of Fragione et al. (2018a) is consistent with our results in Figure 3(b), and as GICs spiral in toward the GC and become less massive, the  $\eta_\gamma$  of remaining cluster debris will become larger and larger, as displayed in Figures 8(e)-(f). More importantly, Fragione et al. (2018a) showed that the cluster  $\eta_\gamma$ -derived  $\gamma$ -ray luminosity is about one order of magnitude larger than the observed GCE, and spin-down of MSPs will reproduce a  $\gamma$ -ray luminosity consistent with the GCE.

## 5. Summary

We present a  $\gamma$ -ray study of the 157 Milky Way GICs based on the archival Fermi-LAT data with a time span of 12 yr. By examining the dependence of GIC  $\gamma$ -ray luminosity ( $L_\gamma$ ) and emissivity ( $\eta_\gamma = L_\gamma/M$ ) on various cluster parameters, our main findings are as follows:

1. **39 GICs are found to be  $\gamma$ -ray bright** (i.e., with  $TS > 25$ ) in our work, which corresponds to about 25% (39/157) of the total Milky Way GICs. The detection rate of core-collapsed GICs (12/29) is 2 times higher than that of dynamically normal GICs (27/128).
2. **Compared with cluster mass ( $M$ ), the GIC  $\gamma$ -ray emission is highly correlated with the stellar encounter rate ( $\Gamma$ ) and the specific encounter rate ( $\Lambda = \Gamma/M$ ), with  $L_\gamma \propto \Gamma^{0.71 \pm 0.11}$  and  $\eta_\gamma \propto \Lambda^{0.78 \pm 0.15}$  in dynamically normal GICs. These correlations provide strong evidence for the dynamical formation of MSPs in GICs.**
3. **The formation of MSPs is also highly dependent on the dynamical evolution history of the host GICs.** As GICs evolve to older dynamical age (i.e., with smaller  $t_{rc}$  or  $t_{rh}$ ) and become more compact (i.e., with smaller  $R_c$  or  $R_h$ , and larger  $\rho_c$  or  $\rho_h$ ), the dynamically normal GICs are expected to produce more MSPs, thereby exhibiting larger  $L_\gamma$  and  $\eta_\gamma$  in Figures 5 and 6.
4. **However, compared with dynamically normal GICs, the core-collapsed GICs are found to exhibit decreasing  $L_\gamma$  and  $\eta_\gamma$  as their cores undergo deep core collapse.** This feature may imply that even LMXBs could be dynamically disrupted or be greatly modified in extremely dense cluster cores, and strong encounters may lead to the ejection of MSPs from core-collapsed GICs.
5. **With decreasing tidal radius ( $R_t$ ) and distance ( $R_{gc}$ ) from the GC, GICs are found to have increasing  $\gamma$ -ray emissivity,** with  $\eta_\gamma \propto R_t^{-1.00 \pm 0.22}$  and  $\eta_\gamma \propto R_{gc}^{-1.13 \pm 0.21}$ . Besides,  $\eta_\gamma$  is positively correlated with GIC stellar mass function slope  $\alpha$ , with  $\eta_\gamma \propto 10^{(0.57 \pm 0.1)\alpha}$ . These correlations suggest that both tidal stripping and mass segregation effects are important factors influencing the abundance of MSPs in GICs, and as GICs undergo orbital decay and spiral in toward the GC, MSPs are more likely to be deposited into the GC rather than normal stars.

6. **We gauge the cluster  $\eta_\gamma$  is about 1-3 orders of magnitude larger than that of the Galactic bulge stars**, which implies that GICs may enhance the  $\gamma$ -ray emissivity of the Galactic bulge greatly. The large variance of cluster  $\eta_\gamma$  may arise from the ongoing dynamical formation (or ejection) of MSPs in GICs, and the different degree of tidal stripping among the clusters. More importantly, the  $\eta_\gamma$  relations derived in our paper are in agreement with the empirical relation adopted in the simulation of Fragione et al. (2018a), which states that tidally disrupted GICs may provide a natural astrophysical explanation to the observed GCE.

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