

# Gamma-ray emission from globular clusters

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## Abstract

Over the last few years, the fruitful data provided by the Large Area Telescope aboard the Fermi Gamma-ray Space Telescope has revolutionized our understanding of high-energy processes in globular clusters, particularly those involving compact objects like millisecond pulsars (MSPs). Gamma-ray emission between 100 MeV to 10 GeV has been detected from more than a dozen globular clusters in our Galaxy, most notably 47 Tucanae and Terzan 5. Based on a sample of known gamma-ray globular clusters, empirical relations between the gamma-ray luminosity and properties of globular clusters such as stellar encounter rate, metallicity, as well as optical and infrared photon energy density in the cluster, have been derived. The gamma-ray spectra are generally described by a power law with a cut-off at a few GeV. Together with the detection of pulsed  $\gamma$ -rays from a millisecond pulsar in a globular cluster, such spectral signature gives support that  $\gamma$ -rays from globular clusters are collective curvature emission from magnetospheres of MSPs within the cluster. Alternative models in which the inverse-Compton emission of relativistic electrons accelerated close to MSPs or the pulsar wind nebula shocks have also been suggested. Observations at  $>10$  GeV by Fermi/LAT and atmospheric Cherenkov telescopes like H.E.S.S.-II, MAGIC-II, VERITAS, and CTA will help to settle some questions unanswered by current data. We also discuss TeV observations of globular clusters, as well as observational prospects of gravitational waves from double neutron stars in globular clusters.

*Keywords:* gamma-ray observations, clusters: globular

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## 1. Introduction

Globular clusters are the oldest gravitationally-bounded stellar systems in the Galaxy. Nearly 160 globular clusters are known nowadays (Harris, 1996, 2010 edition). They fill a spherical halo around the Galaxy, many of them are located within the Galactic bulge. Due to the high concentration of stars within the globular clusters, they host a large number of compact objects including neutron stars and white dwarfs; many of them are found in binary systems, forming for example low-mass X-ray binaries (LMXBs) and Cataclysmic variables.

Since 1970s, it has been known that the formation rate per unit mass of LMXBs (Alpar et al. 1982) is orders of magnitude greater in globular clusters than in the rest of the Galaxy (Katz 1975; Clark 1975). As millisecond pulsars (MSPs) are generally believed to be descendants of LMXBs, it becomes natural that  $\sim 80\%$  of the known MSPs are detected in globular clusters (cf. Manchester et al. 2005). Theoretical arguments have long asserted that the formation of LMXBs (and therefore their decedents MSPs) is made efficient through frequent stellar encounters. Using the X-ray populations in various globular clusters unveiled by the Chandra X-Ray Observatory, Pooley et al. (2003) and Gendre et al. (2003)

found a positive correlation between the number of LMXBs in globular clusters and the stellar encounter rate,  $\Gamma_c$ , putting the dynamical formation scenario of LMXBs in globular clusters on an observational ground.

Using the cumulative luminosity distribution functions of radio millisecond pulsars (MSPs) in globular clusters as a probe of the resided MSPs in the clusters, Hui et al. (2010) found that the number of MSPs in a globular cluster is correlated with its stellar encounter rate, as well as its metallicity. This finding provides the first observational evidence of the dynamical origin of MSPs. This is easy to understand since MSPs are descendants of LMXBs.

In this paper we review main results revealed by high-energy  $\gamma$ -ray observations of Galactic globular clusters, which were mainly contributed by data taken using the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope since its launch in June 2008. Towards the end of the paper we also discuss the recent TeV observations as well as observational prospects related to gravitational wave experiments of globular clusters. The readers are referred to an earlier review by Bednarek (2011) from a more theoretical aspect.

## 2. GeV $\gamma$ -ray observations

### 2.1. Pre-Fermi era

Observations by EGRET in the 1990s did not result in any positive detection from a couple of globular clusters, including 47 Tucanae that hosts the largest number of known MSPs at that time (Michelson et al., 1994; Manandhar et al., 1996). Later LAT observations found that the EGRET upper limit for 47 Tucanae is only a factor of two higher than the measured flux.

### 2.2. First discoveries: 47 Tucanae and Terzan 5

The launch of the Fermi Gamma-ray Space Telescope has enabled the detection of  $\gamma$ -ray emission from a number of globular clusters. The first discovery is made on 47 Tucanae by the Fermi/LAT collaboration (Abdo et al., 2009b, see Fig. 1). By the time this discovery was announced, MSPs as a class had already been established as  $\gamma$ -ray emitters (Abdo et al., 2009c), and they are believed to be the only stable  $\gamma$ -ray sources in globular clusters. The observed  $\gamma$ -rays from the direction of 47 Tucanae are naturally attributed to the MSPs in the cluster (Abdo et al., 2009b). This assertion is strengthened by the measured cutoff at  $\sim 2.5$  GeV in the spectrum (Fig. 1) that is close to the average cutoff energy obtained for nearby,  $\gamma$ -ray emitting MSPs in the Galactic field (Abdo et al., 2009c). From the average  $\gamma$ -ray luminosity of individual MSPs in the Galactic field, i.e.,  $\sim 5 \times 10^{33}$  erg s $^{-1}$  (Abdo et al., 2009c), they would not be detected at distances of several kpc (the very luminous PSR J1823–3021A is an exception; Freire et al., 2011, see Sect. 2.4). It is therefore generally believed that the  $\gamma$ -rays from globular clusters do not come from a single MSP, but are collective emission originated from the entire MSP population in a cluster. Assuming that the average  $\gamma$ -ray efficiencies of MSPs in 47 Tucanae are similar to nearby MSPs, the number of MSPs needed to give rise to the observed flux from 47 Tucanae ( $\sim 2.5 \times 10^{-11}$  erg cm $^{-2}$ s $^{-1}$  (Abdo et al., 2010b)) is about 50, a factor of  $\sim 2$  higher than 23 MSPs in 47 Tucanae detected in radio survey. Such discrepancy can be understood as incomplete radio surveys of MSPs, e.g., due to viewing angle effect.

The second globular cluster that is found to emit  $\gamma$ -rays is Terzan 5 (Kong et al., 2010, see Fig. 1). Terzan 5 hosts the largest number of detected MSPs by now (i.e., 33). Its spectrum also shows cutoff

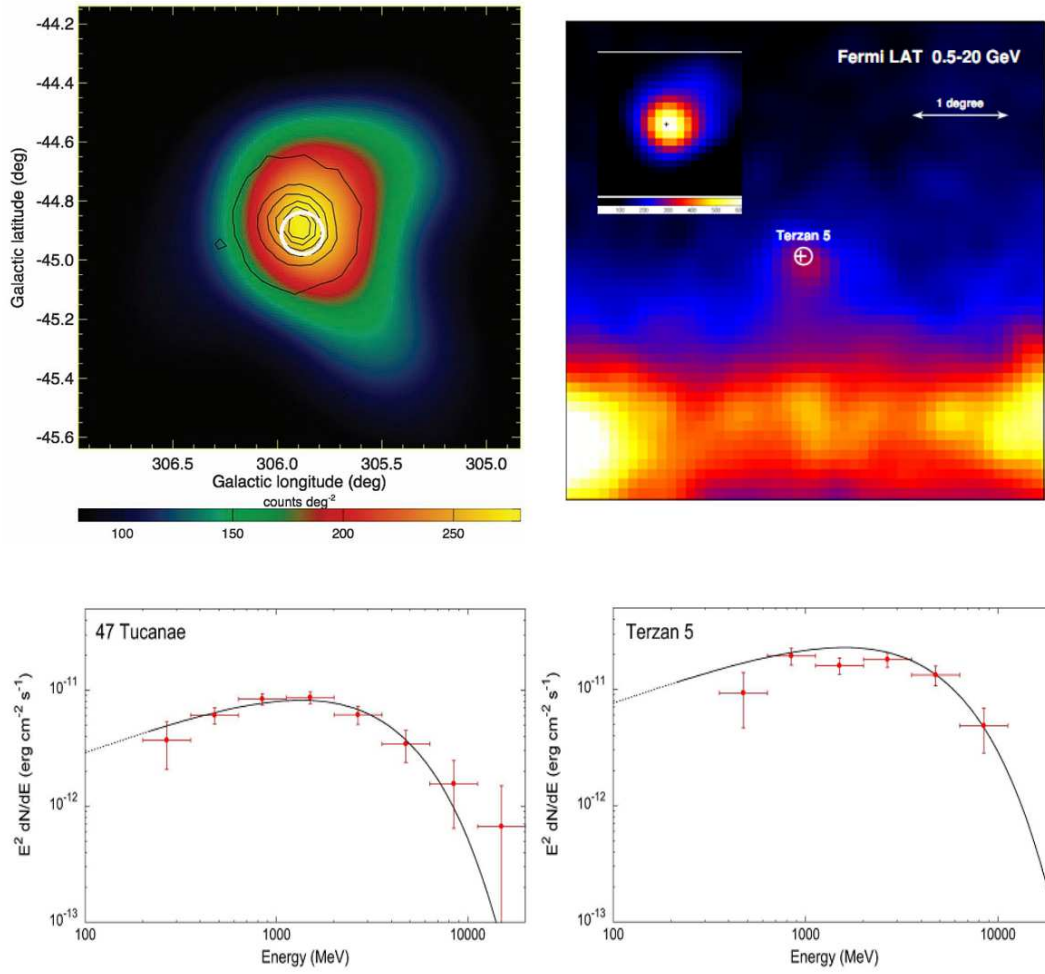


Figure 1: Photon count maps of 47 Tucanae (upper left; Abdo et al., 2009b) and Terzan 5 (upper right; Kong et al., 2010). Their  $\gamma$ -ray spectra are also shown (Abdo et al., 2010b).

which is at  $\sim 3$  GeV (Kong et al., 2010; Abdo et al., 2010b, see Fig. 1). The observed energy flux above 100 MeV is given by  $\sim 7.1 \times 10^{-11}$  erg cm $^{-2}$ s $^{-1}$  (Abdo et al., 2010b)<sup>1</sup>. Taking the distance estimates of 47 Tucanae and Terzan 5 to be 4.0 kpc (McLaughlin et al., 2006) and 5.5 kpc (Ortolani et al., 2007), respectively, the  $\gamma$ -ray luminosity of Terzan 5 is roughly five times that of 47 Tucanae, indicating that either the actual number of MSPs is higher in Terzan 5 than 47 Tucanae, or the average  $\gamma$ -ray efficiency of the underlying MSPs in Terzan 5 is higher than 47 Tucanae, or a combination of both. There are some indications from cumulative radio luminosity distributions that Terzan 5 may indeed contain more MSPs than 47 Tucanae (Hui et al., 2010). If the number of MSPs resided in Terzan 5 is smaller than  $\sim 5$  times that of 47 Tucanae, environmental factors such as the background soft photons (whose number is much higher in Terzan 5 than in 47 Tucanae), as suggested by Bednarek & Sitarek (2007) and Cheng et al. (2010), may explain the higher  $\gamma$ -ray luminosity of Terzan 5.

Kong et al. (2010) report a marginal detection ( $3.7\sigma$ ) for  $\gamma$ -ray emission between 10 GeV and 20 GeV for Terzan 5 and no sign for emission in the same energy band for 47 Tucanae. However, this may not necessarily indicate a substantial difference between 47 Tucanae and Terzan 5 in their  $>10$  GeV spectra. The energy flux of Terzan 5 is higher than 47 Tucanae by a factor of  $\sim 3$ , which might explain the apparent discrepancies in the 10–20 GeV band for these two globular clusters.

### 2.3. Globular clusters as a population of $\gamma$ -ray sources

After these two initial discoveries, Abdo et al. (2010b) and Tam et al. (2011) have reported detailed analyzes of a total of 16 globular clusters. These include 12 cases for which the  $\gamma$ -ray detection is significant: Terzan 5, Liller 1, 47 Tucanae, NGC 6440, M 62, M 28, NGC 6388,  $\omega$  Centaurus, NGC 6624, NGC 6652, NGC 6441, and NGC 6752 (in descending order of reported  $>100$ MeV energy flux in the best-fit spectral model), and four cases for which the  $\gamma$ -ray detection is not significant enough yet: NGC 6139, NGC 6541, M 15, and M 80. There are two more detections in the second Fermi/LAT catalog (Nolan et al., 2012): IC 1257 and 2MS–GC01. The  $\gamma$ -ray properties for these 18 globular clusters are shown in Table 1. No variability has been found for any reported detection, indicating that the  $\gamma$ -ray emission is stable.

In the original analyzes, for almost all of the cases (except Liller 1 and NGC 6624) where the  $\gamma$ -ray emission is significant enough, the nominal cluster position is within  $R_{95}$  from the best-fit  $\gamma$ -ray centroid positions. For NGC 6624, Freire et al. (2011) has refined the  $\gamma$ -ray position, which is consistent with the core of the cluster. In the case of Liller 1, no strong radio and X-ray counterpart is found near the  $\gamma$ -ray emission region and therefore the MSP population in the respective clusters are the only known potential source of the observed  $\gamma$ -ray emission. In the context of magnetospheric origin of  $\gamma$ -rays, the offset requires that most MSPs in these clusters are located outside the core, a possibility which is unlikely. In the inverse-Compton model, relativistic electrons diffuse gradually outward from the cluster core (Bednarek & Sitarek, 2007; Cheng et al., 2010). If the diffusion time scale of the accelerated particles is much shorter than the cooling time scale, the emission from these particles may be offset from the cluster cores if they diffuse unevenly into different directions.

Abdo et al. (2010b) report that the  $\gamma$ -ray emission region is consistent with a point source for almost all globular clusters that they analyzed, except possibly M 28. The upper limit of the angular size of the emission ranges from  $4.8'$  (for 47 Tucanae) to  $15.6'$  (for M 28).

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<sup>1</sup>The energy flux over 0.1–10 GeV derived in Kong et al. (2010) is  $\sim 1.2 \times 10^{-11}$  erg cm $^{-2}$ s $^{-1}$ , which is a factor of  $\sim 2$  higher. This may be due to the differences in the choices of region-of-interest (ROI) and energy range in the two publications. Here we quote the results in Abdo et al. (2010b) for both 47 Tucanae and Terzan 5 to better compare their  $\gamma$ -ray properties.

Table 1: The 18 reported  $\gamma$ -ray emitting globular clusters and candidates (whose  $\gamma$ -ray detection significance  $<7.0\sigma$ ) until end of 2011. References: Abdo et al. (2010b); Nolan et al. (2012); Tam et al. (2011)

Cluster Name	$\gamma$ -ray position (J2000)		Offset ( $'$ )	Core Radius ( $'$ )	Half-mass Radius ( $'$ )	Significance of		Photon Flux ( $10^{-8}\text{cm}^{-2}\text{s}^{-1}$ )	Energy Flux ( $10^{-11}\text{erg cm}^{-2}\text{s}^{-1}$ )	
	R.A. ( $^{\circ}$ )	Dec. ( $^{\circ}$ )				$R_{95}$ ( $'$ )	Detection ( $\sigma$ )			Cutoff ( $\sigma$ )
47 Tucanae	5.95	-72.07	3.3	1.7	0.36	3.17	24.6	5.6	$2.9^{+0.6}_{-0.5}$	$2.5^{+0.2}_{-0.2}$
$\omega$ Centaurus	201.63	-47.48	7.5	3.2	2.37	5.00	7.1	4.0	$0.9^{+0.5}_{-0.4}$	$1.0^{+0.2}_{-0.2}$
M 62	255.28	-30.13	4.4	1.6	0.22	0.92	10.4	2.5	$2.7^{+1.0}_{-0.9}$	$2.1^{+0.3}_{-0.3}$
Liller 1	263.20	-33.39	5.9	7.5	0.06	...	10.3	...	$6.9^{+2.3}_{-2.3}$	$5.3^{+1.8}_{-1.8}$
NGC 6388	263.98	-44.68	5.7	5.7	0.12	0.52	9.3	3.3	$1.6^{+1.0}_{-0.6}$	$1.6^{+0.3}_{-0.3}$
Terzan 5	266.98	-24.80	2.9	2.4	0.15	0.52	18.5	7.1	$7.6^{+1.7}_{-1.5}$	$7.1^{+0.6}_{-0.5}$
NGC 6440	267.20	-20.35	5.2	1.3	0.14	0.48	8.1	1.4	$2.9^{+2.7}_{-1.3}$	$2.2^{+0.9}_{-0.5}$
NGC 6441	267.63	-36.89	13.2	10.6	0.13	0.57	10.0	5.3	$1.0^{+0.2}_{-0.2}$	$0.8^{+0.1}_{-0.1}$
2MS-GC01	272.15	-19.85	4.8	3.8	0.85	1.65	7.8	...	...	$5.4^{+0.8}_{-0.8}$
NGC 6624	275.93	-30.34	10.3	1.4	0.06	0.82	11.0	...	...	$1.1^{+0.1}_{-0.1}$
M 28	276.10	-24.85	8.0	1.6	0.14	1.00	8.8	4.3	$2.6^{+1.3}_{-1.0}$	$2.0^{+0.4}_{-0.3}$
NGC 6652	278.93	-33.02	7.5	1.7	0.10	0.48	7.4	3.2	$0.7^{+0.5}_{-0.3}$	$0.8^{+0.2}_{-0.1}$
NGC 6752	287.57	-59.96	13.2	4.7	0.17	1.91	7.0	...	$0.6^{+0.3}_{-0.3}$	$0.6^{+0.3}_{-0.3}$
M 80	244.23	-23.02	8.8	3.3	0.15	0.61	5.2	...	$0.6^{+0.3}_{-0.4}$	$0.7^{+0.4}_{-0.5}$
NGC 6139	246.83	-38.90	10.3	5.1	0.15	0.85	5.6	...	$1.0^{+0.5}_{-0.5}$	$0.9^{+0.5}_{-0.5}$
IC 1257	261.80	-7.08	10.8	1.3	0.25	1.40	4.1	...	...	$1.2^{+0.3}_{-0.3}$
NGC 6541	272.04	-43.85	16.2	8.9	0.18	1.06	4.4	...	$1.0^{+0.4}_{-0.5}$	$0.7^{+0.3}_{-0.3}$
M 15	322.15	12.10	6.9	9.3	0.14	1.00	2.3	...	$< 0.6$	$< 0.7$

The spectra of the  $\gamma$ -ray emission from globular clusters generally show signs of spectral cut-off at energies 1–4 GeV, with different significant levels (see Table 1). On the other hand, possible enhancements at high energies (up to  $\sim 40$  GeV) are reported for Liller 1 and NGC 6624, although in the latter case there may be contamination by a nearby flaring radio source, detected at  $4\text{-}\sigma$  level in the first year of data. Future observations at energies  $>10$  GeV are crucial to probe or rule out a possible enhancement at high energies for globular clusters, thus shedding light on the origin of  $\gamma$ -rays from globular clusters.

#### 2.4. Searching for $\gamma$ -ray pulses from globular clusters

Attempts have been made to detect pulsed  $\gamma$ -rays from individual MSP in globular clusters. In the first three years after the launch of Fermi, no  $\gamma$ -ray pulsation was found using available ephemerides for MSPs in various globular clusters (Abdo et al., 2009b, 2010b).

The first successful effort to detect  $\gamma$ -ray pulsation from an individual MSP in a globular cluster was made by Freire et al. (2011). They found a significant,  $7\text{-}\sigma$  detection of  $\gamma$ -ray pulsations above 100 MeV from pulsar J1823-3021A in the globular cluster NGC 6624 (Fig. 2). The high measured flux in the pulsed component significantly constrain the total number of MSPs in NGC 6624 to be smaller than 32 and provide a strong support to the pulsar magnetospheric emission model of  $\gamma$ -rays at least from this globular cluster.

M 28 hosts 12 MSPs, the third largest among known GCs (Ransom, 2008), after Terzan 5 and 47 Tucanae. The cluster contains the MSP, M28A/PSR J1824–2452A, that is very energetic and is the first MSP discovered in a globular cluster (Lyne et al., 1987). The AGILE collaboration claimed a  $>4\text{-}\sigma$

hint of pulsation at  $>100$  MeV during only a 6-day period in 2007 (Pellizzoni et al., 2009). However, this tentative evidence has not been confirmed by the Fermi/LAT collaboration, who found no pulsation from PSR J1824–2452A since their launch (Abdo et al., 2010b).

### 3. Which properties of globular clusters determine the $\gamma$ -ray luminosity?

#### 3.1. Properties of globular clusters related to the $\gamma$ -ray emission

The two-body stellar encounter rate has long been believed to relate to the binary formation rate and hence the number of MSPs in a GC (see, e.g. Pooley et al., 2003; Hui et al., 2010). The first attempt to search for correlation of  $\gamma$ -ray luminosity with the encounter rate was preformed by Abdo et al. (2010b). Using the first 8 known  $\gamma$ -ray globular clusters and the expression  $\Gamma_c = \rho_0^{\frac{3}{2}} r_c^2$ , where  $\rho_0$  is the central luminosity density and  $r_c$  the core radius (Verbunt & Hut, 1987), they found that the  $\gamma$ -ray luminosity of a globular cluster is correlated to the encounter rate with a linear correlation coefficient 0.7. Assuming that each MSP emits similar amount of  $\gamma$ -rays, the number of MSPs in these  $\gamma$ -ray emitting globular clusters is said to be consistent with the number given by other estimators (Abdo et al., 2010b).

Hui et al. (2011) used the expression  $\Gamma_c \propto \rho_0^2 r_c^3 / \sigma$  where  $\sigma$  is the velocity dispersion at the cluster center calibrated by Gnedin et al. (2002). Using the  $\gamma$ -ray data of 15 globular clusters, they found that the  $\gamma$ -ray luminosity of globular clusters is correlated to the encounter rate at 99% level, as  $L_\gamma \propto \Gamma_c^{0.50 \pm 0.16}$ .

Besides the stellar encounter rate, there are other parameters that are thought to relate to the number of MSPs in a globular cluster. Hui et al. (2010) identified the metallicity of a globular cluster to be another important indicator to the number of MSPs. A binary system in a globular cluster with a higher metallicity is more efficient in orbital shrinkage by magnetic braking. This gives rise to a higher likelihood of a successful Roche-lobe overflow (Ivanova, 2006) and in turn leads to a higher formation rate of MSPs. Hui et al. (2010) found a positive correlation between metallicity and the MSP population. Using the available  $\gamma$ -ray data from 15 globular clusters, Hui et al. (2011) found that the  $\gamma$ -ray luminosity of globular clusters is correlated to the metallicity,  $[\text{Fe}/\text{H}]$ , at 99.9% level, as  $L_\gamma \propto \Gamma_c^{0.59 \pm 0.15}$ .

On the other hand, primordially-formed binaries are not related to stellar encounter rate. If they form the majority of binaries, one would expect the binary population to be correlated to the cluster mass,  $M_{\text{GC}}$ . Assuming a constant mass-to-light ratio,  $M_{\text{GC}}$  can be estimated from the absolute visual magnitude  $M_V$  according to  $M_{\text{GC}} = 10^{-4 M_V}$ . This mass estimate has the advantage of not having any correlation with the encounter rate, thus it serves as an independent parameter in the correlation study. However, no correlation of  $M_V$  with the  $\gamma$ -ray luminosity was found (Hui et al., 2011).

Apart from the above three cluster parameters, the energy densities of optical,  $u_{\text{opt}}$ , and infrared photons,  $u_{\text{IR}}$ , at the cluster location are also important in the predictions of the  $\gamma$ -ray properties as they serve as the seed photons in the inverse Compton models (Cheng et al., 2010). Using the GALPROP code (Strong & Moskalenko, 1998) to estimate the soft photon energy densities, the  $\gamma$ -ray luminosity is found to correlate with them at  $>96\%$  level, as  $L_\gamma \propto u_{\text{opt}}^{0.78 \pm 0.27}$  as well as  $L_\gamma \propto u_{\text{IR}}^{1.29 \pm 0.44}$  (Hui et al., 2011). While the original study was based on the Harris catalog (2003 version), we have re-examined the above correlations with in the revised 2010 Harris catalog (Harris, 1996) and found that the correlations remained robust.

#### 3.2. Fundamental planes of $\gamma$ -ray emission from globular clusters

We have shown that the total energy output in  $\gamma$ -rays indeed scales with the two factors that are related to the formation of MSPs: encounter rate and metallicity. This places an intimate relationship between

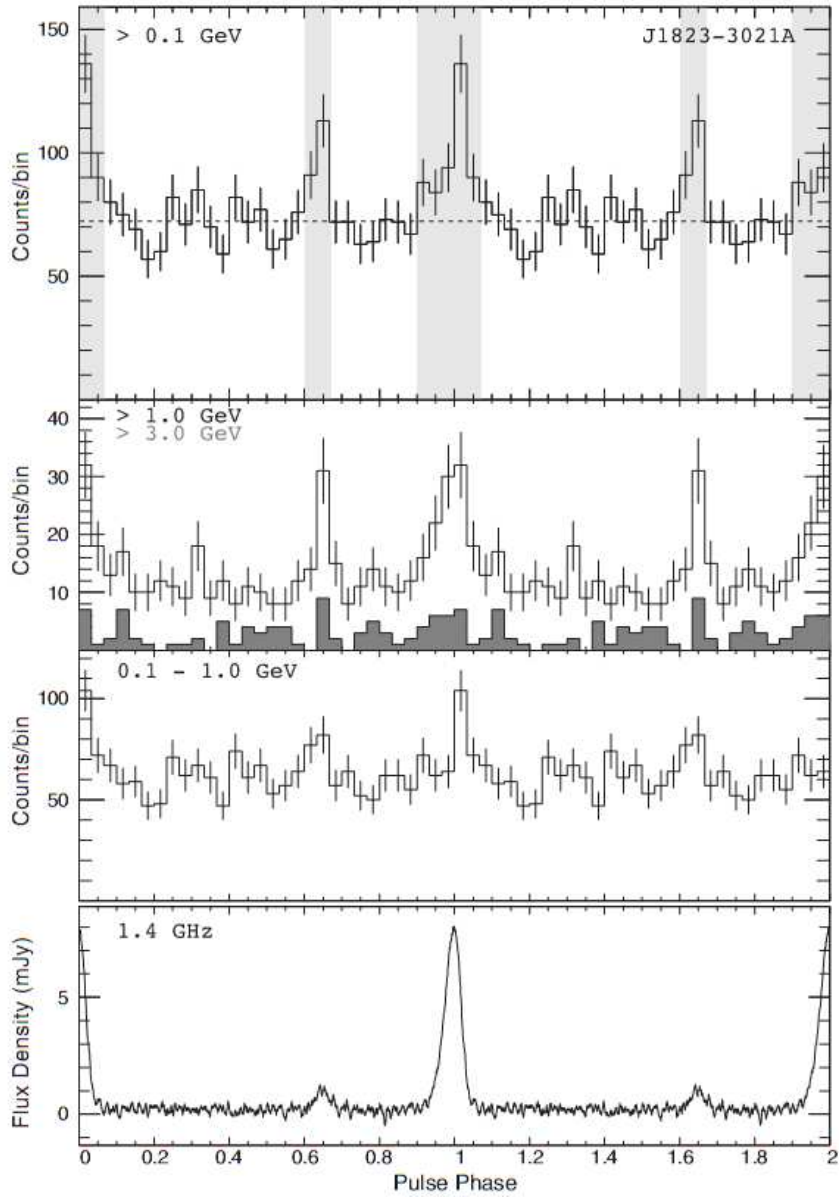


Figure 2: Gamma-ray and radio pulse profiles of PSR J1823–3021A in the globular cluster NGC 6624 (Freire et al., 2011).

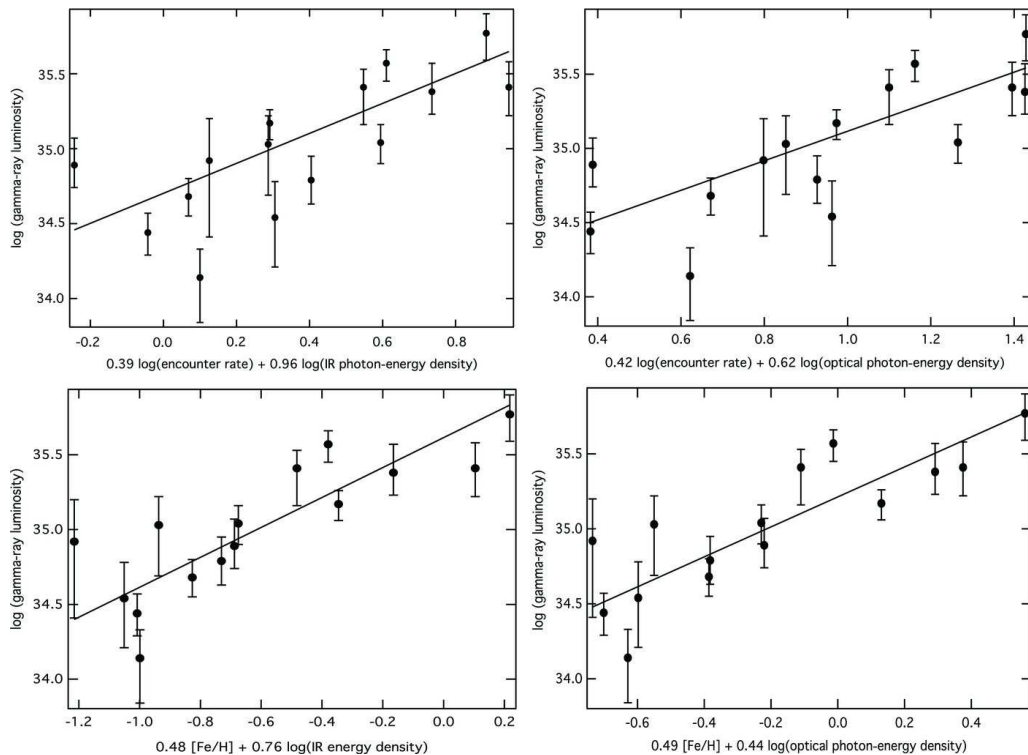


Figure 3: The edge-on views of the fundamental-plane relationships published in Hui et al. (2011).

the observed  $\gamma$ -ray emission from globular clusters and the MSP population. The new findings that optical and infrared photon energy densities are also correlated to  $L_\gamma$  conform with the IC model (Cheng et al., 2010), in which both the number of MSPs in a globular cluster and the soft photon energy densities play important role in the resulted  $\gamma$ -ray output. This prompted Hui et al. (2011) to combine two of the above cluster parameters and to carry out a 2-dimensional regression analysis. The best-fit relations are given by

$$\log L_\gamma = (34.12 \pm 0.29) + (0.42 \pm 0.17) \log \Gamma_c + (0.62 \pm 0.29) \log u_{\text{opt}} \quad (1)$$

$$\log L_\gamma = (34.70 \pm 0.30) + (0.39 \pm 0.18) \log \Gamma_c + (0.96 \pm 0.49) \log u_{\text{IR}} \quad (2)$$

$$\log L_\gamma = (35.21 \pm 0.29) + (0.49 \pm 0.18) [\text{Fe}/\text{H}] + (0.44 \pm 0.31) \log u_{\text{opt}} \quad (3)$$

$$\log L_\gamma = (35.61 \pm 0.16) + (0.48 \pm 0.17) [\text{Fe}/\text{H}] + (0.76 \pm 0.50) \log u_{\text{IR}} \quad (4)$$

The edge-on views of the best-fit fundamental-plane relationships are depicted in Fig. 3.

As discussed, the encounter rate is related to the number of dynamically-formed binaries while metallicity may represent the likelihood of forming MSP in such binary (Ivanova, 2006). Therefore we expect that the number of MSPs in a globular cluster increases as the encounter rate and metallicity in the cluster. Furthermore, soft photons act as seed photons to be up-scattered to  $\gamma$ -ray energies by the relativistic particles originated in MSPs or their surroundings in the IC models. We here attempt to perform a 3-dimensional regression analysis using encounter rate, metallicity, and one of the two soft photon energy densities:

$$\log L_\gamma = A \log \Gamma_c + B [\text{Fe}/\text{H}] + C \log u_{\text{IR}} + D \quad (5)$$



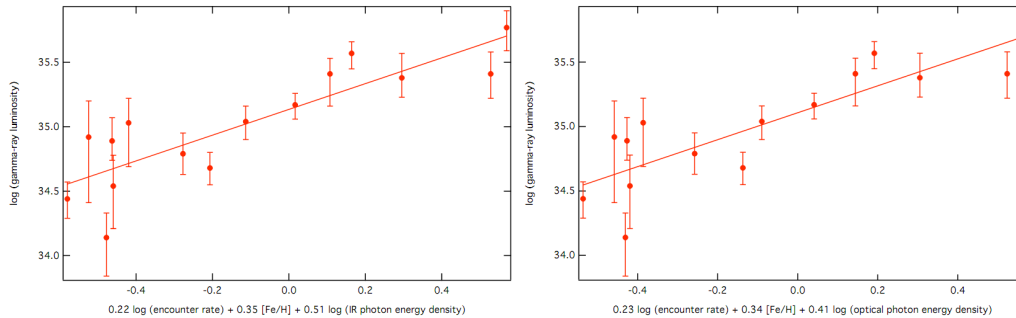


Figure 4: Best-fit fundamental planes using a 3-dimensional regression analysis. Stellar encounter rate, metallicity, and one of the two soft photon energy densities are used.

Table 2: Best-fit parameters in the regression analysis

Equation(5)		Equation(6)	
Parameter	Best-fit value	Parameter	Best-fit value
A	$0.22 \pm 0.15$	A	$0.23 \pm 0.14$
B	$0.35 \pm 0.14$	B	$0.34 \pm 0.13$
C	$0.51 \pm 0.41$	C	$0.41 \pm 0.24$
D	$35.14 \pm 0.31$	D	$34.78 \pm 0.34$

$$\log L_{\gamma} = A \log \Gamma_c + B [\text{Fe}/\text{H}] + C \log u_{\text{opt}} + D \quad (6)$$

The best-fit results are tabulated in Table 2 and the edge-on views on these fundamental-plane relationships are shown in Fig. 4.

#### 4. Models for $\gamma$ -ray emission from globular clusters

Two kinds of models for  $\gamma$ -ray emission from globular clusters have been widely discussed in the literature. In pulsar magnetosphere models,  $\gamma$ -ray emission is produced via curvature radiation within the magnetospheres of MSPs in the clusters (e.g., Venter & de Jager, 2008; Venter et al., 2009). The pulsed emission of a number of MSPs is superposed at different frequencies such that unless a small number of luminous MSPs dominate the combined  $\gamma$ -ray emission, as is the case for NGC 6624, pulsations from individual pulsars cannot be detected.

In another class of models that involve inverse Compton (IC) emission, electrons are accelerated close to the MSPs or (re-)accelerated in colliding wind shocks and scatter off the optical, infrared, or cosmic microwave background photons (Bednarek & Sitarek, 2007; Cheng et al., 2010), giving rise to the observed GeV emission. In this scenario, the  $\gamma$ -rays are intrinsically unpulsed.

The  $\gamma$ -ray spectrum and especially the cutoff energy as observed for a number of GCs are generally similar to nearby MSPs in the Galactic field. Such coincidence may suggest that the observed  $\gamma$ -rays are curvature radiation from pulsar magnetospheres. On the other hand, averaged spectra may not be good discriminators in testing various models, because the IC models can also explain the GeV spectra equally well (Cheng et al., 2010). Moreover, according to Cheng & Taam (2003), MSPs in globular clusters may be very different from those in the Galactic field based on radio and X-ray properties of MSPs in globular clusters. In fact, the former may possess complicated magnetic fields due to frequent

stellar encounter (Cheng & Taam, 2003), thereby strongly affecting the polar/outer gap structures and in particular quench the outer gap. This scenario is supported by the fact that a majority of the MSPs in 47 Tucanae are thermal X-ray emitters (Bogdanov et al., 2006).

The differences in the emission signatures of the two models should provide a diagnostic. In the pulsar magnetosphere model,  $\gamma$ -rays up to a few GeV is emitted, while IC processes may give rise to  $\gamma$ -rays up to TeV energies. A candidate globular cluster reported to emit  $>10$  GeV emission is Liller 1 (Tam et al., 2011). LAT observations above  $\sim 10$  GeV as well as VHE observations by Cherenkov telescopes are crucial in testing both classes of models.

The size of the emission region also differs between the two classes of models. The  $\gamma$ -ray emission from pulsar magnetospheres is more compact and that from the IC model is more extended. The observed  $\gamma$ -ray emission region is consistent with a point source for almost all globular clusters and shows no sign of extended emission based on 1.5 year of data (Abdo et al., 2010b). While it is expected in the pulsar magnetosphere models, IC models predict a certain degree of extension. For example, Cheng et al. (2010) suggests that the IC emission size should be  $>10$  pc, which in the case of 47 Tucanae corresponds to  $\geq 8'$  (see also their Fig. 4), larger than the upper limit imposed in Abdo et al. (2010b). Therefore, unless the actual diffusion coefficients are lower than that assumed in their calculations, the model of Cheng et al. (2010) may not be able to explain the compactness of the emission size.

Current angular resolution of LAT is insufficient to resolve any extended emission significantly smaller than  $10'$ . Observations at energies  $>10$  GeV may better constrain the emission size in the future. This may involve continuous LAT survey observations and targeted observations by current and planned Cherenkov telescopes, such as H.E.S.S.-II, MAGIC-II, VERITAS, and CTA.

Clapson et al. (2011) present radio data taken using Effelsberg 100-m telescope in the vicinity of Terzan 5 which may impose some constraints on the IC models. The measured radio flux at 11 cm in the circle of radius  $0.15^\circ$  around the core of Terzan 5 (region 1 in their Fig. 1) is  $(1.41 \pm 0.21)$  Jy (local background emission contributes about 30–40% of this flux). According to Eq. (27) of Cheng et al. (2010), the modeled radio flux at 11 cm is about 10 Jy and 6.8 Jy within a few arc-minutes when the seed photons in their IC model is infrared and optical photons, respectively. It is also unlikely that the magnetic field is much lower than  $10^{-6}$  Gauss used in their Eq. (27). It may still be possible that low-energy electrons (that is responsible for synchrotron radiation below the peak at  $\sim 44$  GHz) diffuse further out to region 11 in Clapson et al. (2011)'s Fig. 1, thereby explaining the enhanced radio emission in region 11, whose flux is  $(3.86 \pm 0.34)$  Jy, while high-energy electrons having a much shorter diffusion length stay close to the core upscatter ambient photons and give rise to the GeV emission up to 10 GeV. Detailed modeling is needed to understand the astrophysical conditions there.

Recently,  $\gamma$ -ray emission from particles accelerated by non-accreting white dwarfs (WDs) was also suggested (Bednarek, 2012). Due to the large number of WDs, these particles may also contribute to the observed  $\gamma$ -rays from globular clusters. In this scenario, particles are accelerated in the inner magnetosphere of WDs, diffuse out, and produce  $\gamma$ -rays via IC scattering off various soft photon fields, e.g. star light, infrared radiation, and cosmic microwave background radiation (CMBR).

## 5. TeV observations of globular clusters

Gamma-ray emission above 100 GeV can be produced via Inverse Compton scattering off various soft photon fields by relativistic leptons accelerated in the pulsar magnetosphere (Venter et al., 2009),

or leptons re-accelerated in shocks generated by pulsar winds (Bednarek & Sitarek, 2007). The spectrum of  $>100$  GeV emission differs between various models, as illustrated in Fig. 5. These expectations prompted the observations of a couple of globular clusters (i.e., 47 Tucanae, M5, M13, M15, NGC 6388, and  $\omega$  Centauri) by several  $\gamma$ -ray observatories (CANGAROO III, H.E.S.S., MAGIC, and VERITAS) above 100 GeV but they have not resulted in any detection (Kabuki et al., 2007; Aharonian et al., 2009; Abramowski et al., 2011a; Anderhub et al., 2009; McCutcheon et al., 2009).

Recently, the H.E.S.S. collaboration announced the  $7\text{-}\sigma$  detection of  $>0.4$  TeV emission in the vicinity of Terzan 5 (Abramowski et al., 2011b). They estimated the probability of chance coincidence of this new VHE source, HESS J1747–248, with an unknown AGN or PWN to be  $10^{-4}$ . The reported photon flux of  $1.2 \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}$  between 0.44–24 TeV corresponds to 1.5% of the flux of the Crab nebula in this energy range. The spectrum can be fit by a simple power law of photon index  $\Gamma_\gamma = 2.5 \pm 0.3_{\text{stat}} \pm 0.2_{\text{sys}}$ . Unlike the 0.5–20 GeV emission, the TeV emission region is offset from the cluster core (at  $2\text{-}\sigma$  level) and shows sign of extended feature. These morphological features are hard to be reconciled in models where emission is produced directly, either magnetospheric or IC, by the MSP population in Terzan 5. Interestingly, radio emission at 11 cm from the Effelsberg Galactic plane surveys was detected  $0.8^\circ$  towards the north-west of Terzan 5 (Clapson et al., 2011). The authors suggested a PWN scenario in which relativistic leptons are accelerated by the pulsar population, diffuse out, and produce the radio emission and TeV emission by synchrotron and IC emission, respectively. This scenario is supported by the diffuse, non-thermal X-ray emission detected earlier by Eger et al. (2010). A large drawback in this picture is that it cannot explain the different offset directions of radio(north-west)/TeV(south-east) emission from the cluster core. A recent study did not reveal any diffuse X-rays from six  $\gamma$ -ray emitting globular clusters (Eger & Domainko, 2012).

Another leptonic scenario that we consider here is that the TeV emission is originated from IC emission by electrons accelerated in colliding shocks between collective pulsar wind from the cluster and the Galactic wind, which can explain the fact that the TeV emission site is on the way between the cluster core and the Galactic centre.

In leptonic scenarios, as noted by Abramowski et al. (2011b) and Domainko (2011), there should be a Klein-Nishina cutoff at a few TeV, which is not observed. However, the lack of a cut-off may simply be a result of low photon statistics at these high energies.

Abramowski et al. (2011b) further discuss two hadronic scenarios: cosmic-rays accelerated by a past supernova or in a short GRB remnant. They have the advantage of being able to explain the observed simple power law spectrum up to 20 TeV. In the supernova interpretation, they argue that given the lack of molecular clouds and thus the low interstellar medium density at this location ( $n \approx 0.1 \text{ cm}^{-3}$  is assumed), the cosmic-ray energy needed to produce the observed TeV flux reaches  $10^{51}$  erg, which is rather high for a supernova. The more exotic short GRB scenario is further developed in Domainko (2011), but a similar energy is required and it is unclear why this particular short GRB can be so energetic (i.e., at least  $10^{51}$  erg, which is at the high end of isotropic-equivalent energy of short GRBs; Nakar, 2007) and efficient in transferring the energy to cosmic-ray particles. In this scenario, thermal X-rays at the flux level of  $10^{-12} \text{ erg cm}^{-2}\text{s}^{-1}$  are produced in shocks caused by sub-relativistic ejecta expelled during the merger event that heat the interstellar medium (Domainko & Ruffert, 2008).

In summary, the origin of HESS J1747–248 is unclear. Future X-ray observations at the centre of the TeV emission, as well as deeper TeV observations, are crucial in tackling the origin of the TeV emission.

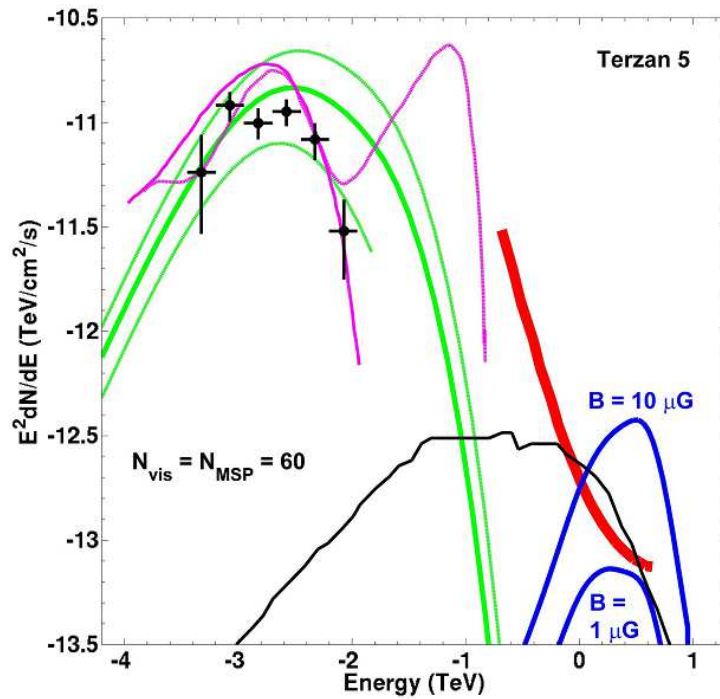


Figure 5: Model comparison for Terzan 5. The green lines represent the curvature radiation spectrum (and errors) from Venter et al. (2009). The magenta lines are IC spectra from Cheng et al. (2010). The black line shows an IC prediction from Bednarek & Sitarek (2007). The blue lines represent IC spectra for different values of magnetic field in the cluster (Venter et al., 2011). Data are taken from Abdo et al. (2010b). The red line shows the H.E.S.S. sensitivity in a 50-h observations. The figure is taken from Venter et al. (2011).

## 6. Gravitational waves from globular clusters?

Double neutron-star (NS) mergers are believed to be progenitors of short gamma-ray bursts (GRBs; Narayan et al., 1992). It is expected that double NS mergers are major sources of gravitational waves, especially shortly before the final coalescence. Gravitational wave detectors, including LIGO<sup>2</sup>, Virgo<sup>3</sup>, GEO-HF<sup>4</sup>, and LCGT<sup>5</sup>, are yet to detect the first signal from these events. In our Galaxy, there are about ten confirmed and candidate double NS binaries (Lorimer, 2008). By adding the estimated coalescence rates derived from each known double NS binary system in our Galaxy, their merger rate is estimated to be  $118_{-79}^{+174} \text{ Myr}^{-1}$ . In this case, the detection rate of advanced LIGO of extragalactic mergers may reach  $265_{-178}^{+390} \text{ yr}^{-1}$  (Lorimer, 2008).

Based on spatial offset distribution of short GRB progenitors from their host galaxies, Grindlay et al. (2006) and Church et al. (2011) have suggested that at least a portion of short GRBs arise from binaries formed dynamically in globular clusters. Of the ten Galactic double NS binaries (or candidates), PSR B2127+11C, itself a dynamically formed one, is the only one situated in a globular cluster, M 15, a  $\gamma$ -ray source candidate (Abdo et al., 2010b). Due to the high encounter rate and high concentration of binaries in globular clusters, there should be a much larger population of double NS binaries in globular clusters that have escaped timing measurements. Therefore, the actual merger rate of Galactic and extragalactic double NS binaries may be even higher, thereby increasing the chance to detect gravitational waves from globular clusters.

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<sup>2</sup><http://www.ligo.caltech.edu/>

<sup>3</sup><http://www.ego-gw.it/>

<sup>4</sup><http://www.geo600.org/>

<sup>5</sup><http://gw.icrr.u-tokyo.ac.jp/lcgt/>

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