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The Analyses of Globular Cluster Pulsars and Their Detection Efficiency

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Abstract

Up to 2022 November, 267 pulsars had been discovered in 36 globular clusters (GCs). In this paper, we present our studies on the distribution of GC pulsar parameters and the detection efficiency. The power law relation between average dispersion measure ($\overline{\mathrm{DM}}$) and dispersion measure difference (ΔDM) of known pulsars in GCs is $\lg\Delta\mathrm{DM} \propto 1.52\lg\overline{\mathrm{DM}}$. The sensitivity could be the key to finding more pulsars. As a result, several years after the construction of a large radio telescope facility, the number of known GC pulsars will likely be increased accordingly. We suggest that currently GCs in the southern hemisphere could have higher possibilities for finding new pulsars.

Key words: (stars:) pulsars: general – (Galaxy:) globular clusters: general – stars: statistics

1. Introduction

As of 2021, 170 globular clusters (GCs) had been discovered in the Milky Way (Vasiliev & Baumgardt 2021). Since the discovery of the first GC pulsar in M28 (Lyne et al. 1987), until 2022 November, 267 pulsars had been discovered in 36 GCs.[7] Terzan 5 and 47 Tucanae harbor the largest known GC pulsar populations, with 40 and 29 pulsars, respectively. Among all GC pulsars, 147 are members of binary systems, while 120 are isolated. The distance of GCs with known pulsars ranges from 2.2 kpc (M4, one pulsar; Lyne et al. 1988) to 17.9 kpc (M53, five pulsars, e.g., Kulkarni et al. 1991).

There are many exotic objects in GC pulsars, including the fastest spinning pulsar (J1748-2446ad, with the spin frequency $\sim$716 Hz, Hessels et al. 2006), the triple system with a white dwarf and a Jupiter-mass companion in M4 (B1620-26, Sigurdsson et al. 2003), binaries with highly eccentric orbits (e.g., NGC 6652A, with eccentricity $e \sim 0.968$, DeCesar et al. 2015; NGC 1851A, with $e \sim 0.888$, Freire et al. 2004), 17 redbacks and 26 black widows. These pulsars can be used to constrain the stellar evolution, and to study the intrinsic dynamics of GCs (e.g., Pooley et al. 2003; Papitto et al. 2013).

By the end of 2004, only 100 pulsars were detected in 24 GCs (Camilo & Rasio 2005). The GCs with the largest numbers of pulsars were Terzan 5 (with 23 pulsars) and 47 Tucanae (with 22 pulsars). Between 2004 and 2007, 38 more GC pulsars were discovered while the number of GCs with pulsar discoveries only increased slightly, from 24 to 25. At that moment, the only two factors related to the number of pulsars in a GC were the total mass and the distance. However, there are exceptions, such as ω Centauri (NGC 5139), one of the nearest and most massive GCs in the Milky Way (Ransom 2008). In the following decade, the number of GC pulsars increased slowly.

Most GC pulsars have been discovered by large radio telescopes. These telescopes include Lovell ($\sim$5 pulsars; e.g., Lyne et al. 1987), Giant Metrewave Radio Telescope (GMRT) ($\sim$2 pulsars; e.g., Swarup 1991), Parkes ($\sim$48 pulsars; e.g., Morris et al. 2002), Arecibo ($\sim$28 pulsars; e.g., Hessels et al. 2007), Green Bank Telescope (GBT) ($\sim$82 pulsars; e.g., Prestage et al. 2009), MeerKAT ($\sim$51 pulsars; e.g., Ridolfi et al. 2022; TRAPUM project[8]) and the Five-hundred-meter Aperture Spherical radio Telescope (FAST, Nan et al. 2011) ($\sim$41 pulsars; e.g., Pan et al. 2021; FAST GC survey[9]).

In this work, we analyzed the 267 GC pulsars and estimated the detection efficiency. The detection efficiency of radio telescopes and the spatial distribution of GC pulsars are described in Sections 2 and 3 respectively. The distribution of physical parameters is presented in Section 4. Section 5 is for the summary.

2. The Detection Efficiency of Large Radio Telescopes

About 2 yr after the construction of a large radio telescope facility, the number of GC pulsars tends to be increased accordingly

[7] Paulo Freire's GC Pulsar Catalog, https://www3.mpifr-bonn.mpg.de/staff/pfreire/GCpsr.html.
[8] http://trapum.org/discoveries/
[9] https://fast.bao.ac.cn/cms/article/65/

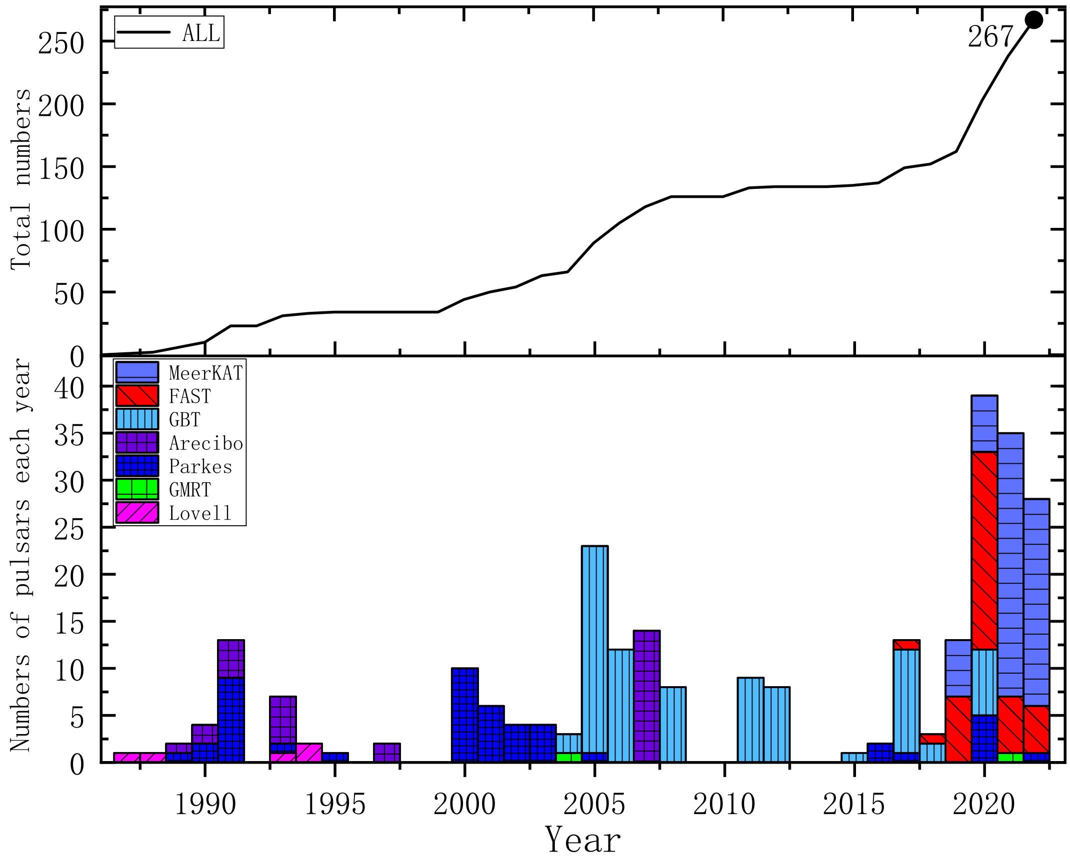

Figure 1. Cumulative number of known pulsars in GCs. (Top) All GC pulsars; (bottom) the numbers of GC pulsars discovered by different radio telescopes represented as colored bars. For the definition of discovery time: the discovery dates of pulsars from FAST and MeerKAT are listed on their websites, while pulsars discovered by other telescopes are the "publication" time, based on the time of the first reference as listed by Paulo Freire's GC pulsar catalog.

Table 1
Parameters of GC Pulsar Surveys

Telescope	β	T_{sys} (K)	Gain (K Jy^{-1})	Bandwidth (MHz)	S_{min} (μJy)	η	Visible Sky (Decl./degree^{-1})	Visible-GCs ($R_{Sun} \leqslant 30$ kpc)
Parkes(1)	1.5	35	0.7	288	122.8	0.38	(−87, 10)	127
Arecibo(2)	1.2	40	10.5	250	8.0	1.33	(−1.5, 38.5)	21
GBT(3)	1.05	22.8	1.9	700	13.6	0.70	(−46, 90)	117
FAST(4)	1	24	16	400	2.1	1.17	(−14, 65)	35
MeerKAT(5)	1.1	26	2.8	700	10.7	0.44	(−90, 45)	140
uGMRT(6)	1	102.5	4.2	200	47.9	0.01	(−71, 90)	136

Note. (1). Parkes: 13 beam receiver package at a central radio frequency of 1374 MHz (Camilo et al. 2000); (2). Arecibo: using the Gregorian L-band wide receiver, the central observing frequency was either 1175 MHz (DM $\lesssim$ 100 pc cm^3) or 1475 MHz (DM $\gtrsim$ 100 pc cm^3) (Hessels et al. 2007); (3). GBT: the Green Bank Ultimate Pulsar Processing Instrument (GUPPI) backend at S band (2 GHz) (DeCesar et al. 2015); (4). FAST: The FAST 19 beam receiver with a frequency range of 1.0–1.5 GHz (Pan et al. 2021); (5). MeerKAT: used the L-band (856-1712 MHz) receivers and up to 42 of the 44 antennas with central frequency 1284 MHz (Ridolfi et al. 2021), $G = (N_{ant}/64) \times 2.8$ K Jy^{-1} and N_{ant} the number of antennas used in the observation (Abbate et al. 2022); (6). uGMRT: the upgraded Giant Metrewave Radio Telescope (uGMRT), observed the low-DM clusters at 400 MHz and the others at 650 MHz with the digital GMRT wideband backend system. T_{sys} is 130 K for 400 MHz and 102.5 K for 650 MHz (Gautam et al. 2022). We take $\alpha = 10$, $n_{pol} = 2$, $t_{int} = 2$ hr and $W = 0.1P$.

as illustrated in Figure 1. For example, FAST and MeerKAT have been the main facilities for GC pulsar discoveries in recent years. The first GC pulsar discoveries by FAST were reported in 2020 (e.g., Pan et al. 2020; Wang et al. 2020). Till now, a total of 41 pulsars have been found. MeerKAT started observation in 2018, and the first GC pulsar discovery was reported in 2021 (Ridolfi et al. 2021). In total, 61 pulsars have been detected by MeerKAT. As a result, the number of GC pulsars increased steeply since 2020.

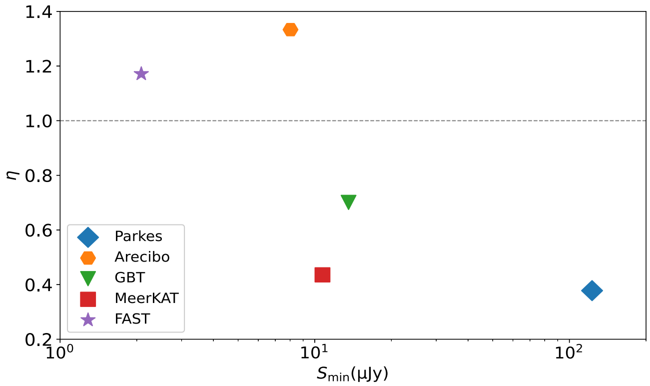

Figure 2. The detection efficiencies of radio telescopes. The uGMRT was not included.

The possibility to discover GC pulsars is mainly related to the sensitivity and the number of visible clusters within the sky covered by a telescope. The achievement of higher sensitivity would increase the number of GC pulsar discoveries. The minimum detectable flux density for a pulsar can be calculated with the radiometer equation (e.g., Dewey et al. 1985)

$$S_{\min} = \frac{\alpha\beta T_{\rm sys}}{G\sqrt{n_{\rm pol}\Delta\nu t_{\rm int}}}\sqrt{\frac{W}{P - W}}, \tag{1}$$

where α is the minimum signal-to-noise ratio (S/N), β is the factor accounting for losses from the digitization and other processing, $T_{\rm sys}$ is the system temperature, G is the gain of the telescope, $n_{\rm pol}$ is the number of polarizations, $\Delta\nu$ is the observing bandwidth (in the unit of MHz), $t_{\rm int}$ is the integration time in the unit of seconds, W is the pulse width and P is the pulse period. Here, we take $\alpha = 10$, $n_{\rm pol} = 2$, $t_{\rm int} = 2$ hr and $W = 0.1P$.

The data used to calculate the minimum detectable flux density for each radio telescope are displayed in Table 1. Here, we define that the detection efficiency (η) is the number of pulsars found by each radio telescope ($N_{\rm p}$) divided by the number of visible GCs in its sky ($N_{\rm gc}$)

$$\eta = N_{\rm p}/N_{\rm gc}. \tag{2}$$

The most distant GC with known pulsars is M53 (17.9 kpc). Accordingly, we use 30 kpc as the limit for detecting GC pulsars for current radio telescopes. For 157 GCs, 141 are in this range. Figure 2 shows the relation between the minimum detection flux density and the pulsar detection efficiency of each radio telescope.

With higher sensitivity, it is possible to detect pulsars missed by previous surveys. The total discovery rate of pulsars in GCs is $\eta = 267/141 \sim 1.89$. This is due to the accumulation of all GC pulsar discoveries. The detection efficiency with FAST or Arecibo is higher than that with other radio telescopes. This can be explained by their higher sensitivities. Similarly, Parkes is limited by its relatively low sensitivity (64 m single dish). With the ultra-wide-bandwidth, low-frequency receiver (UWL) (Hobbs et al. 2020) installed, it may have a chance to find more. GBT has a large sky coverage and an intermediate sensitivity. Its detection efficiency is improved mainly due to the 35 pulsars from Terzan 5 (e.g., Ransom et al. 2005). It is worth noting that FAST, Arecibo and GBT are located in the northern hemisphere, while more than half of the GC pulsars discovered by them are located in the southern sky. MeerKAT is located in South Africa (southern hemisphere) and has already discovered a number of GC pulsars. The number of visible GCs in the FAST and MeerKAT skies is ∼45 and 140, respectively. MeerKAT will definitely produce more discoveries in the near future. Assuming that the detection efficiency of MeerKAT is 1, the total number of GC pulsars discovered can reach ∼140.

The next stage is the era of the Square Kilometre Array (SKA), which will revolutionize detection of the population of GC pulsars. The SKA will provide unprecedented sensitivity (e.g., ∼4 μJy in 2 hr integrations operating from 1.4 to 2.0 GHz of SKA1-MID) for GC search of targets in the southern sky and can cover about ∼154 GCs (Hessels et al. 2015). Considering the integration time of 2 hr, we assume that the detection efficiency of SKA is 1, and about 150 GC pulsars will be detected. For SKA1-MID, tracking observation times of up to 8 hr (∼2 μJy) are possible; the SKA can possibly detect more GC pulsars (e.g., Hessels et al. 2015).

3. Spatial Distribution of GCs with Known Pulsars

The most distant GC pulsars were located in M53, and 35 GCs are farther away than M53 (Harris 1996, 2010 edition). Figure 3 depicts the spatial distribution of all GCs in Galactic coordinates. GCs with known pulsars do not exhibit an obvious distribution trend or selection deviation when compared with other GCs. The details of pulsars in each GC are provided in Table 2.

The fraction of GCs with known pulsars in all sky regions is $\Gamma_{\rm all} = 36/141 \approx 26\%$. In the northern and southern sky, pulsars were found in 9 out of 19 GCs ($\Gamma_{\rm decl.>0^\circ} = 9/19 \approx 47\%$) and 27 out of 122 GCs ($\Gamma_{\rm decl.<0^\circ} = 27/122 \approx 20\%$), respectively (see Figure 4). Since 130 of the 157 GCs are located at declinations below 0°, radio telescopes covering more southern sky would have a significantly greater prospect of discovering more GC pulsars; 9 of 15 GCs with $D_{\rm Sun} \leqslant 5$ kpc have known pulsars, while 27 of 126 with $D_{\rm Sun} \geqslant 5$ kpc and $D_{\rm Sun} \leqslant 17.9$ kpc have known pulsars. The corresponding proportions are $\Gamma_{D_{\rm Sun}\leqslant 5} = 9/15 = 60\%$ and $\Gamma_{D_{\rm Sun}>5} = 27/126 = 21\%$, respectively. Thus, higher sensitivity would still result in more GC pulsar discoveries.

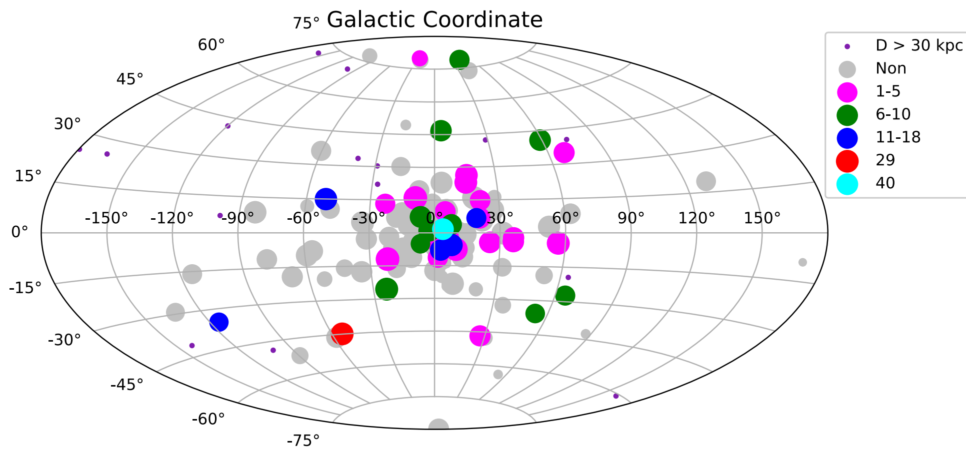

Figure 3. Distribution of GCs in Galactic coordinates. The circles in different colors represent the different numbers of known pulsars in GCs. The size of the circles represents the distances from Earth to GCs. Larger circles indicate closer distances. The same sizes of circles are for clusters with a distance greater than 30 kpc. The distances of GCs are from Harris (1996, 2010 edition).

4. Dispersion Measures and Dispersion Measure Differences

For a blind pulsar search, the time cost directly relates to the range of dispersion measure (DM). Once the DM of any pulsar in a GC is known, the search time will be largely reduced, since the DM values of such pulsars are similar.

The differing column density of interstellar medium along the line of sight leads to different DM values of pulsars in the same GC. It is not easy to tell whether a pulsar is a member of the GC when it is the only known pulsar. For GCs that host two or more pulsars, their close DM values can be the deciding factor. In the 36 GCs with known pulsars, 31 GCs host at least two pulsars. Among these GCs, the three with the largest ΔDM values are 10.9 cm^{-3} pc for NGC 6517, 10.5 cm^{-3} pc for NGC 6624 and 9.9 cm^{-3} pc for Terzan 5, respectively. Figure 5 features the relation between the average dispersion measures ($\overline{\mathrm{DM}}$) and the differences of the dispersion measures ($\Delta\mathrm{DM} \equiv \mathrm{DM}_{\mathrm{max}} - \mathrm{DM}_{\mathrm{min}}$ in each GC) for the pulsars in these 31 GCs. It seems that the relation between ΔDM and $\overline{\mathrm{DM}}$ is a power law. With M53 and NGC 6624, the equation for the maximum ΔDM values is

$$\mathrm{lg}\Delta\mathrm{DM} = 1.52 \times \mathrm{lg}\overline{\mathrm{DM}} - 1.93. \quad (3)$$

For the lower boundary of the maximum ΔDM value, only the data from Terzan 1 pulsars are used. This is due to M30 and NGC 6652 (the two points below the line) only having two pulsars and ΔDM may be increased with new discoveries. Assuming the same slope as Equation (3), the equation for the lower boundary is

$$\mathrm{lg}\Delta\mathrm{DM} = 1.52 \times \mathrm{lg}\overline{\mathrm{DM}} - 3.36. \quad (4)$$

Thus, the pulsars in GCs with higher $\overline{\mathrm{DM}}$ tend to be distributed in a wider DM range. This is similar to previous studies (e.g., Freire et al. 2005). However, the upper limit of DM range can still be too wide when searching for pulsars in high DM GCs.

The upper limit can also be regarded as evidence that a pulsar is associated with the GC or not. For example, Terzan 5B (PSR J17482-2444, 205 cm^{-3} pc, Lyne et al. 1990) was demonstrated to be a foreground pulsar (Ransom et al. 2005). The upper limit of DM difference for Terzan 5 from Equation (3) is 48 cm^{-3} pc ($\overline{\mathrm{DM}}\pm$ 24 cm^{-3} pc), but Terzan 5B is outside of the limit.

5. Conclusion

Till 2022 November, 267 pulsars had been detected in 36 GCs. In these pulsars, 147 are in binary systems and 248 are millisecond pulsars with spin periods less than 30 ms. Among GC pulsars, millisecond pulsars and binary pulsar systems account for 93% and 55%, respectively.

We conclude that,

1. The sensitivity can limit the finding of new GC pulsars. GC pulsar discoveries are mainly from large radio telescopes. Based on the detection rate, we suggest that FAST can find many more GC pulsars, while MeerKAT should be able to record many GC pulsar signals in the near future.

Table 2
Information on 267 Pulsars in 36 GCs

GC Name	$N_{\rm ALL}$	$N_{\rm BP}$	$N_{\rm EP}$	$N_{\rm MSP}$	$N_{\rm RB}$	$N_{\rm BW}$	$N_{\rm TBD}$	Γ	C	$\frac{N_{\rm MSP}}{N_{\rm ALL}}$ (%)	$\frac{N_{\rm BP}}{N_{\rm ALL}}$ (%)
Terzan 5	40	21	4	38	3	1		6800		97.50	52.50
47 Tucanae (NGC 104)	29	19	7	29	3	6		1000		100.00	65.52
ω Centauri (NGC 5139)	18	5	1	18	0	1		90.4		100.00	27.78
NGC 6517	15	3	0	14	0	0		338		93.33	20.00
NGC 1851	15	9	0	14	0	0		1530		93.33	60.00
M28 (NGC 6626)	14	10	2	13	2	5		648		92.86	71.43
NGC 6624	12	2	1	9	1	0		1150	c	75.00	16.67
M62 (NGC 6266)	9	9	2	9	1	2		1670	c:	100.00	100.00
NGC 6441	9	3	0	7	0	0		2300		77.78	33.33
NGC 6752	9	1	0	9	0	0		401	c	100.00	11.11
M15 (NGC 7078)	9	1	0	5	0	0		4510	c	55.56	11.11
NGC 6440	8	4	1	7	1	1		1400		87.50	50.00
M5 (NGC 5904)	7	6	1	7	0	1		164		100.00	85.71
Terzan 1	7	0	0	6	0	0		0.292	c	85.71	0.00
M3 (NGC 5272)	6	6	0	6	0	1	1	194		100.00	100.00
M13 (NGC 6205)	6	4	1	6	0	1		68.9		100.00	66.67
M2 (NGC 7089)	6	6	0	6	0	0		518		100.00	100.00
M53 (NGC 5024)	5	4	0	4	0	0		35.4		80.00	80.00
M14 (NGC 6402)	5	5	2	5	2	1		124		100.00	100.00
NGC 6522	5	0	0	5	0	0		363	c	100.00	0.00
M71 (NGC 6838)	5	5	1	3	0	2		2.05		60.00	100.00
M22 (NGC 6656)	4	2	0	4	0	1		77.5		100.00	50.00
NGC 6544	3	3	0	2	0	1		111	c:	100.00	100.00
M12 (NGC 6218)	2	2	0	2	0	0		13		100.00	100.00
M10 (NGC 6254)	2	2	0	2	0	0		31.4		100.00	100.00
NGC 6342	2	1	1	1	0	0		44.8	c	50.00	50.00
NGC 6397	2	2	2	2	2	0		84.1	c	100.00	100.00
NGC 6652	2	2	0	2	0	0		700		100.00	100.00
NGC 6749	2	2	0	2	0	0	1	38.5		100.00	100.00
NGC 6760	2	1	0	2	0	1		56.9		100.00	50.00
M30 (NGC 7099)	2	2	1	2	1	0		324	c	100.00	100.00
NGC 5986	1	1	0	1	0	0		61.9		100.00	100.00
M4 (NGC 6121)	1	1	0	1	0	0		26.9		100.00	100.00
M92 (NGC 6341)	1	1	1	1	1	0		270		100.00	100.00
NGC 6539	1	1	0	1	0	0		42.1		100.00	100.00
NGC 6712	1	1	0	1	0	1		30.8		100.00	100.00
ALL	267	147	28	248	17	26	2			92.88	55.05

Note. $N_{\rm ALL}$, $N_{\rm BP}$, $N_{\rm EP}$, $N_{\rm MSP}$, $N_{\rm RB}$, $N_{\rm BW}$ and $N_{\rm TBD}$ are the numbers of all pulsars, binary pulsars, millisecond pulsars ($P < 30$ ms), eclipsing pulsars, redback pulsars, black widow pulsars and to be defined pulsars in each GC. Γ, the GC stellar encounter rate catalog (Bahramian et al. 2013). C: King-model central concentration, a "c" signifies a core-collapsed cluster from Harris (1996, 2010 edition). M3C and NGC 6749B are likely real but need confirmation. The pulsar data are from Paulo Freire's GC Pulsar Catalog (http://naic.edu/~pfreire/GCpsr.html, 2022-11 version).

2. With the DM ranges of GC pulsars, we give the equations to estimate the DM ranges of pulsars in a GC. The equations are

$$\lg\Delta{\rm DM} = 1.52 \times \lg\overline{\rm DM} - 1.93,$$

for the upper limit and

$$\lg\Delta{\rm DM} = 1.52 \times \lg\overline{\rm DM} - 3.36,$$

for the lower bound. The upper bound can also be used to judge if a pulsar is a member of the GC or not.

3. Regarding the current spatial distributions of GCs and pulsars in them, we suggest that there are higher chances to find new pulsars in GCs in the southern sky. In order to find more pulsars, large radio telescopes in the southern hemisphere should be employed.

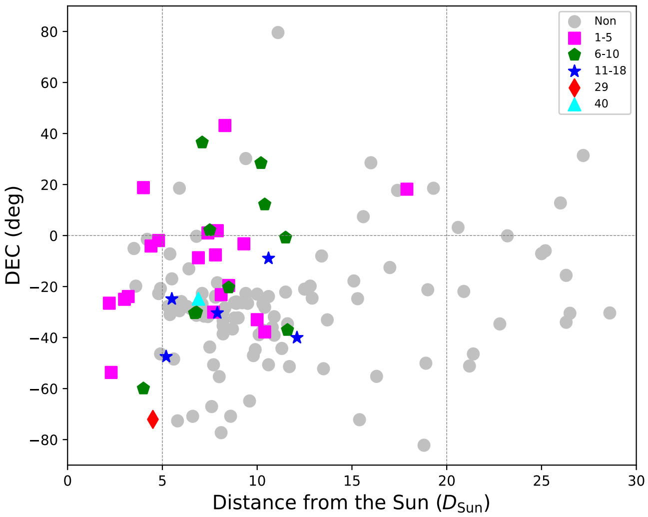

Figure 4. Distributions of GCs with and without pulsars in the distance vs. decl. plane. The different symbols with colors represent the different number ranges of known pulsars in each GCs. Dashed lines are for the decl. 0° (horizontal) and distances from Earth (vertical, for 5 kpc and 20 kpc).

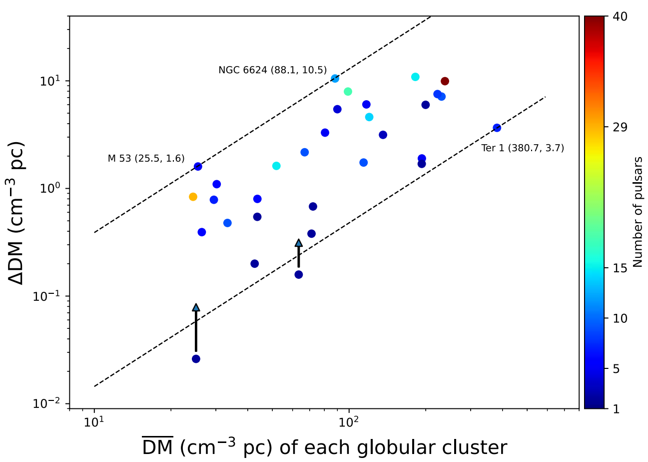

Figure 5. Relationship between the average of dispersion measures ($\overline{\rm DM}$ cm^{-3}pc) and the range of dispersion measure differences ($DM_{max} - DM_{min}$) of pulsars in 31 GCs with known pulsars. The two clusters with arrows are M30 (25.08, 0.03) and NGC 6652 (63.43, 0.16) respectively. These two clusters currently have two known pulsars, and the dispersion measure difference may increase if additional new pulsars are detected.

Acknowledgments

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