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FAST Globular Cluster Pulsar Survey: Twenty-four Pulsars Discovered in 15 Globular Clusters

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Abstract

We present the discovery of 24 pulsars in 15 globular clusters (GCs) using the Five-hundred-meter Aperture Spherical radio Telescope (FAST). These include the first pulsar discoveries in M2, M10, and M14. Most of the new systems are either confirmed or likely members of binary systems. M53C and NGC 6517H and I are the only three pulsars confirmed to be isolated. M14A is a black widow pulsar with an orbital period of 5.5 hr and a minimum companion mass of 0.016 $M_{\odot}$. M14E is an eclipsing binary pulsar with an orbital period of 20.3 hr. With the other 8 discoveries that have been reported elsewhere, in total 32 GC pulsars have been discovered by FAST so far. In addition, We detected M3A twice. This was enough to determine that it is a black widow pulsar with an orbital period of 3.3 hr and a minimum companion mass of 0.0125 $M_{\odot}$.

Unified Astronomy Thesaurus concepts: Binary pulsars (153); Globular star clusters (656); Radio pulsars (1353); Radio telescopes (1360)

1. Introduction

Globular clusters (GCs) harbor a large population of millisecond pulsars (MSPs). Some of these can be quite exotic, e.g., the fastest spinning pulsar J1748-2446ad (Hessels et al. 2006). This system is part of a large population of eclipsing binary pulsars, most with orbital periods less than one day (see, e.g., Ridolfi et al. 2021 for some recent examples), and even a triple system of a pulsar together with a white dwarf and a planet companion (Thorsett et al. 1999). The exotic systems in globular clusters also include the millisecond pulsars with eccentric orbits, in particular of the systems with very massive companions: these clearly result from exchange encounters that happened after the pulsars were fully recycled in low-mass X-ray binaries (LMXBs), while nothing like them exists in the Galactic disk. Some examples are NGC 1851A (orbital eccentricity 0.89, companion mass $1.22^{+0.06}_{-0.05}$ $M_{\odot}$; Ridolfi et al. 2019), NGC 6544B (orbital eccentricity 0.75, companion mass 1.2064(20) $M_{\odot}$; Lynch et al. 2012), NGC 6652A (orbital eccentricity 0.97, companion mass 0.74 $M_{\odot}$; DeCesar et al. 2015) NGC 6624G (orbital eccentricity 0.38, companion mass $0.53^{+1.30}_{-0.09}$ $M_{\odot}$; Ridolfi et al. 2021), and M15C (orbital eccentricity 0.68, companion mass 1.345 ± 0.010 $M_{\odot}$; Jacoby et al. 2006). The total 225 pulsars in 36 GCs[9] until 2021 May are the result of GC surveys made with the largest existing radio telescopes such as Parkes (e.g., tens of pulsars discovered in 47 Tucanae; Manchester et al. 1991; Robinson et al. 1995; Camilo et al. 2000; Pan et al. 2016; Ridolfi et al. 2021), Arecibo (e.g., 11 new pulsars discovered in a survey of 22 GCs; Hessels et al. 2007), the Green Bank Telescope (e.g., the jackpot Terzan 5; Ransom et al. 2005; Prager et al. 2017), MeerKAT,[10] and Giant Metrewave Radio Telescope (GMRT; Freire et al. 2004).

Since the commissioning of Five-hundred-meter Aperture Spherical radio Telescope (FAST; Nan et al. 2011; Jiang et al. 2019), GCs have been important targets for pulsar searches with FAST. Pan et al. (2020) reported an eclipsing binary discovered in M92. This pulsar was discovered in a 500–700 MHz subband of the single-beam ultra-wide-band receiver covering 270–1620 MHz with a 0.5 hr observation. With the same receiver, Wang et al. (2020) reported the FAST discovery of M13F, which might be an extremely faint and scintillating pulsar, recently shown to be a high-mass neutron star (Cadelano et al. 2020); they also confirmed that M13E is a back widow system. More GC pulsar discoveries were made with the 19-beam *L*-band receiver that replaced the single-beam ultra-wide-band receiver on 2018 May. Pan et al. (2021) discovered three faint isolated millisecond pulsars in NGC 6517. The detection of short-orbit binaries with acceleration search (Ransom et al. 2002) benefits from FAST's high sensitivity, too. For example, NGC 6712A (Yan et al. 2021), a black widow with an orbital period of 0.15 days, was discovered in a 4 minutes segment from the FAST data with the acceleration search. We believe that it is bright enough to be detected by GBT, but may have been missed due to its short orbit.

Up until 2021 December, we searched 15 GCs with 24 new pulsars discovered and updated timing solutions for several previously discovered pulsars. In Section 2, we describe the observation and the pulsar searching method. Timing results

[9] http://www.naic.edu/~pfreire/GCpsr.html

[10] http://trapum.org/discoveries.html

Table 1
Observation and Data Reduction Details

GC Name	R.A. (J2000)	Decl. (J2000)	Observation Date	Observation Length (hr)	DM Range from Known Pulsars	Sensitivity μJy
M2 (NGC 7089)	21:33:27	−00:49:23.5	2020 Jan 4	2.0	43.3–44.1	0.76
M3 (NGC 5272)	13:42:12	+28:22:38.2	2019 Dec 14	4.5	26.1–26.5	0.51
M5 (NGC 5904)	15:18:33	+02:04:51.7	2019 Dec 11	4.0	29.3–30.1	0.54
M10 (NGC 6254)	16:57:09	−06:04:01.1	2020 Jan 5	3.0	43.4–43.9	0.62
M13 (NGC 6205)	16:41:41	+36:27:35.5	2020 Dec 27	5.0	30.1–30.5	0.16
M14 (NGC 6402)	17:37:36	−03:14:45.3	2019 Jul 17	2.0	78.8–82.1	0.76
M15 (NGC 7078)	21:29:58	+12:10:01.2	2020 Dec 21	5.0	65.5–67.7	0.48
M53 (NGC 5024)	13:12:55	+18:10:05.4	2019 Nov 30	5.0	24.0–26.1	0.48
M71 (NGC 6838)	19:53:46	+18:46:45.1	2019 Dec 12	5.0	117.4	0.48
M92 (NGC 6341)	17:17:07	+43:08:09.4	2020 Mar 12	3.6	35.45	0.57
NGC 6517	18:01:51	−08:57:31.6	2020 Jan 23	2.5	174.7–185.3	0.68
NGC 6539	18:04:50	−07:35:09.1	2021 Feb 10	2.2	186.38	0.72
NGC 6712	18:53:04	−08:42:22.0	2019 Jul 21	2.0	155.2	0.76
NGC 6749	19:05:15	+01:54:03.0	2019 Dec 10	3.0	192.0–193.7	0.62
NGC 6760	19:11:12	+01:01:49.7	2019 Dec 6	4.0	196.7–202.7	0.54

Note. The observation date and length are for the longest observation done with the corresponding GC.

and discussion are presented in Section 3. Conclusions are provided in Section 4.

2. Observation and Data Reduction

As a part of the SP^2 project,[11] the FAST GC pulsar survey[12] was started in 2018. The FAST 19-beam receiver, which covers a frequency range of 1.0–1.5 GHz, was used for these observations. Because GC pulsars are close to the centers normally, the data from the center beam were only recorded. The data were channelized into 4096 channels, corresponding to 0.122 MHz channel width. The signals were 8-bit sampled from two polarizations that are from two orthogonal dipoles. The sampling time is 49.152 μs. The system temperature is ∼24 K (Jiang et al. 2020), and the beam size is ∼2.′9 at 1.4 GHz. There are 45 GCs in the FAST sky. All 11 GCs with previously known pulsars were observed first. In order to maximize the search sensitivity, these GCs were observed with the longest allowed integration time. The other four GCs, M14, M10, M2, and NGC 6712, in which we also found new pulsars during FAST commissioning, were also included. Table 1 shows more details of these observations. The search sensitivities in Table 1 were calculated using the radiometer equation as follows (e.g., Lynch et al. 2011):

$$S_{\rm min} = \beta \frac{({\rm S/N_{min}}) T_{\rm sys}}{G\sqrt{n_{\rm p} t_{\rm int}\,\Delta f}} \sqrt{\frac{W}{P - W}}, \tag{1}$$

in which β is the sampling efficiency and is equal to 1 for our 8-bit recording system. W is the width of the pulsar profile, and we used 10% of the pulse. The minimum signal-to-noise ratio $({\rm S/N})_{\rm min}$ in our search is 10. The system temperature ($T_{\rm sys}$) is 24 K. The antenna gain, G, is 16 K $\rm Jy^{-1}$. The number of polarizations (n_p) is 2. The $t_{\rm int}$ is the integration time in the unit of seconds. The Δf is the bandwidth in the unit of MHz, here it is 300 MHz; as in our radio-frequency interference (RFI) masking, ∼25% channels were masked as RFIs and will not be used in further processes.

The RPPPS package (Yu et al. 2020), which is a parallel pipeline base on PRESTO (Ransom 2001; Ransom et al. 2002, 2003), was used in the search. The data were dedispersed with dispersion measure (DM) ranges (see in Table 1) a few times wider than those from known pulsars in the GC. For GCs without previously known pulsars, the DM ranges were initially set to be twice that of the upper limits of the YMW16 model (Yao et al. 2017) predictions on the direction of GCs. The acceleration search with a summation of up to 32 Fourier harmonics was used for periodic signal search. In order to detect both faint isolated pulsars and binaries, the zmax values were set to be 20 and 1200, respectively. The observations normally lasted for more than 2 hr. Thus, even with a zmax value of 1200, a very limited range of acceleration was searched,[13] and thus the search sensitivity could be significantly reduced for pulsars with orbital period less than one day. Now, we are processing segments for the GC data to redetect these pulsars and search for new pulsars. We will report these results elsewhere. To examine the candidates obtained or rejecting those unlikely to be pulsars and to combine multiple detections of the same signal, both the `ACCEL_sift.py` routine from PRESTO and our sifting code (`Jinglepulsar`[14]; see Pan et al. 2021) were used. For candidates from both `ACCEL_sift.py` and `Jinglepulsar`, we folded the dedispersed time series, filtered out RFI detections, and removed known pulsar harmonics. The DM values, periods and accelerations of the remaining candidates were then used to fold the search data where they were discovered; the resulting plots were visually inspected for pulsar detections. As results, 24 new GC pulsars and all the previously FAST discovered pulsars (M92A, M13F, NGC 5627E to G, and NGC 6712A) were redetected. Figure 1 show the pulse profiles of the 24 new GC pulsars, and Table 2 presents a summary of all 30 GC pulsars discovered by FAST.

[11] Search of Pulsars in Special Population, https://crafts.bao.ac.cn/pulsar/SP2/.
[12] https://fast.bao.ac.cn/cms/article/65/

[13] The average acceleration of the pulsar in the integration can be calculated as $a = zc/(T^2 f_0)$ (Ransom 2001), in which c is the speed of light, T is the total integration time, and f_0 is the pulsar spin frequency. If the total integration time was 5 hr, using 20/1200 as the zmax value corresponded to an acceleration of 0.09/5.5 m $\rm s^{-2}$ for a 200 Hz signal or 0.04/2.2 m $\rm s^{-2}$ for a 500 Hz signal.
[14] https://www.github.com/jinglepulsar

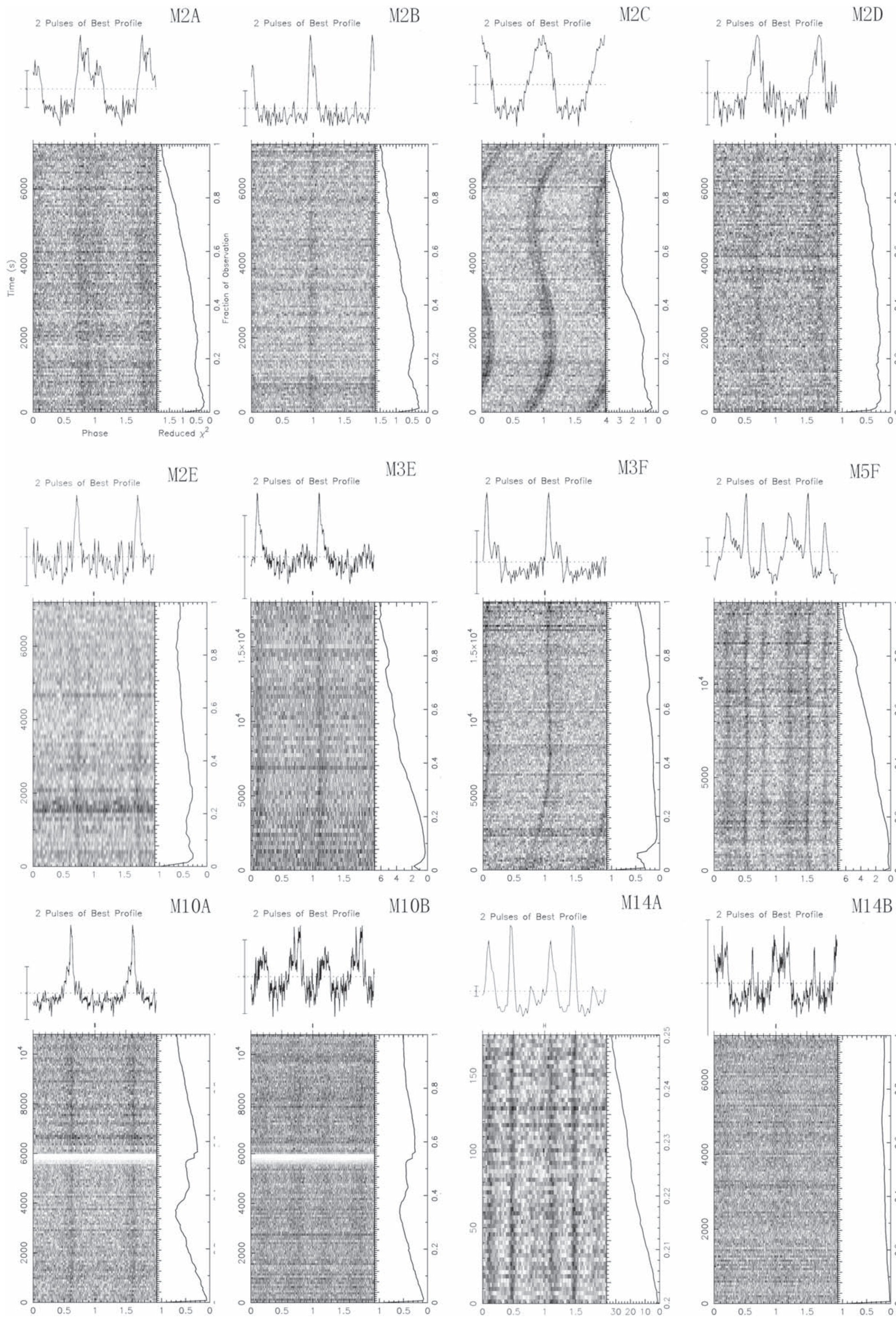

Figure 1. The 24 GC pulsars discovered using FAST. Pulsars from left to right and top to bottom are presented in the same order as in Table 2. M92A, M13F, NGC 6517E to G, and NGC 6712A are previously discovered and not included in these figures.

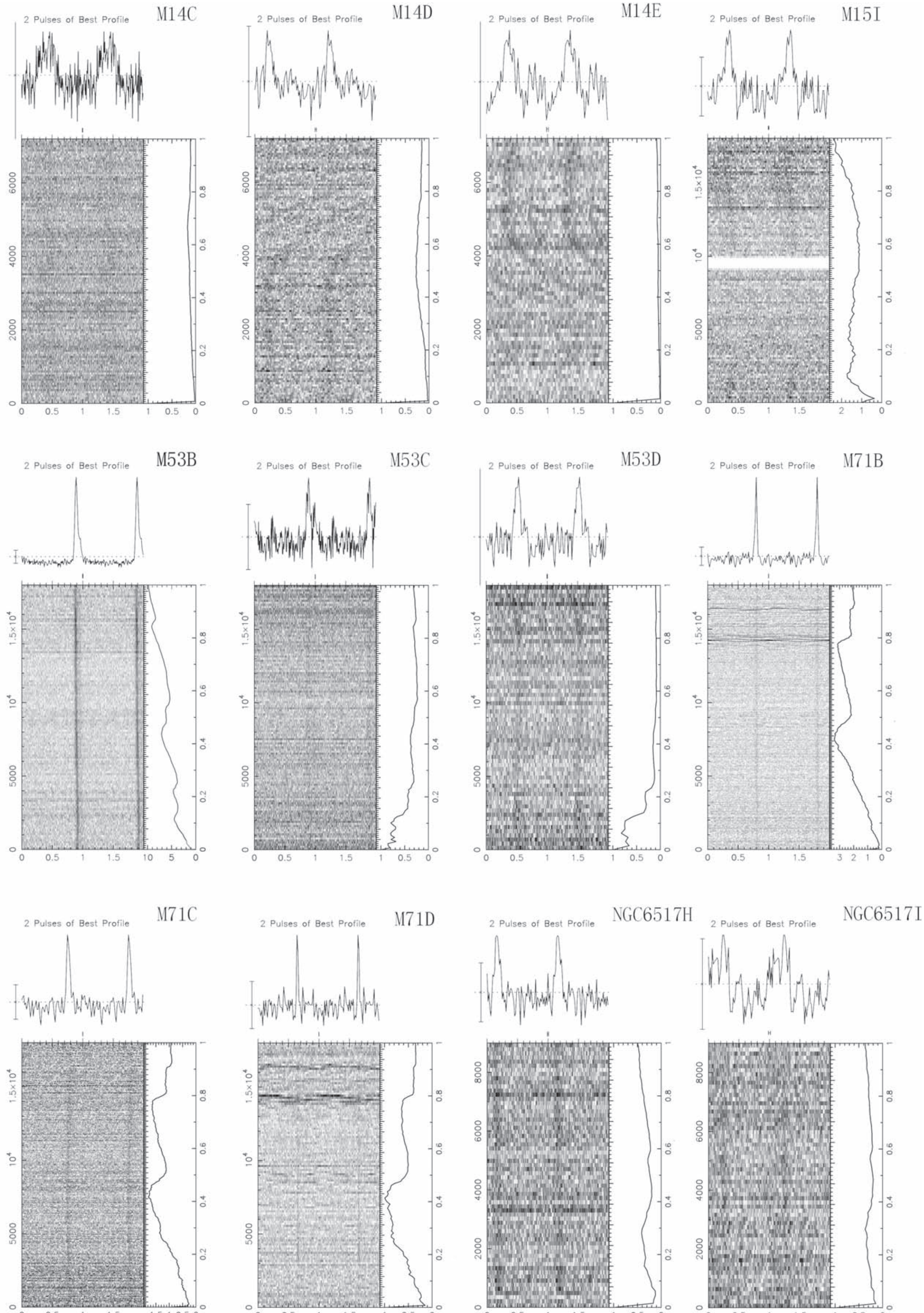

Figure 1. (Continued.)

Table 2
The 30 GC Pulsars Discovered Using FAST

Name	P0 (ms)	DM (pc cm^{-3})	Notes	References
M2A	10.15	43.3	Binary	
M2B	6.97	43.8	Binary	
M2C	3.00	44.1	Binary	
M2D	4.22	43.6	Binary	
M2E	3.70	43.8	Binary	
M3E	5.47	26.541	Binary	
M3F	4.40	26.467	Binary	
M5F	2.65	29.4	Binary	
M10A?	4.73	43.9	Need Confirmation	
M10B	7.35	43.355	Possible Binary	
M13F	3.00	30.366	Binary	Wang et al. (2020)
M14A	1.98	82.10	Black Widow	
M14B	8.52	81.0	Binary	
M14C	8.46	80.0	Binary	
M14D	2.89	78.8	Redback	
M14E	2.28	80.4	Eclipsing Redback	
M15I	5.12	67.3	Possible Binary	
M53B	6.07	25.959	Binary	
M53C	12.53	26.106	Isolated	
M53D	6.07	24.6	Binary	
M71B	79.90	119.0	Possible Binary	
M71C	28.93	116.2	Possible Binary	
M71D?	100.67	119.038	Need Confirmation	
M92A	3.16	35.45	Eclipsing Redback	Pan et al. (2020)
NGC 6517E	7.60	183.29	Isolated	Pan et al. (2021)
NGC 6517F	24.89	183.71	Isolated	Pan et al. (2021)
MGC6517G	51.59	185.3	Isolated	Pan et al. (2021)
NGC 6517H	5.64	179.6	Isolated	
NGC 6517I	3.25	177.8	Isolated	
NGC 6712A	2.15	155.2	Black Widow	Yan et al. (2021)

Note. The DM values come from DM searching and optimizing results during pulsar search. The pulsars M10A and M71D (with question marks) are very good candidates but need more observations to confirm.

We will discuss these discoveries in Section 3. Note that the most recent discoveries of M5G and M12A will be reported in separate papers and thus not listed here.

3. Results and Discussions

In total, 32 GC pulsars have been discovered with FAST up to now, which doubles the number of known GC pulsars in the FAST sky (from 31 to 63). Below we discuss the 24 new discoveries made in this work. Because the M5G was discovered by others (even it was also redetected by us) and M12A was just discovered, the discussion on M5G and M12A will be presented in other papers.

3.1. Timing Results

After the new discoveries were made, we searched the FAST archival data to confirm and time these pulsars. With enough archived data, the phase-connected timing solutions of M14A and NGC 65117H were obtained (see Table 3).

M3A were detected twice in observations with lengths of 4.5 and 5 hr, respectively. While its orbital period is shorter than the length of any of the two observations, we successfully determined its previously unknown orbital parameters with the data obtained on 2019 December 14, showing that it is a black widow system with an orbital period of 0.1359 days (3.26 hr) and a minimum companion mass of 0.0125 $M_{\odot}$. Because the

Table 3
Timing Solutions of Two Newly Discovered Pulsars

Pulsar Name	M14A	NGC 6517H
MJD range	58458–59154	58659–59105
Data span (days)	697	446
Number of TOAs	19	35
Timing residuals rms (μs)	0.67	49.95
Measured quantities		
R.A. (J2000)	17:37:35.88794(3)	18:01:52.5895(9)
decl. (J2000)	−03:14:34.775(1)	−08:57:53.15(5)
Spin frequency (Hz)	505.05656417562(4)	177.2193886845(2)
Spin frequency derivative (s^{-2})	−2.4376(3)e-14	−1.210(7)e-14
Orbital Period, P_b (days)	0.2278292041(9)	⋯
Epoch of Periastron passage, T_0 (MJD)	58681.7064745(9)	⋯
Projected Semimajor Axis, χ_p (lt-s)	0.047110(1)	⋯
Set quantities		
Reference epoch (MJD)	58900	58868
DM (cm^{-3} pc)	82.1	179.6
Orbital eccentricity, e	0	⋯
Longitude of periastron, ω (deg)	0	⋯
Solar System ephemeris	DE200	DE200
Binary model	BT	⋯

Table 4
Updated Timing Solutions for Previous Discovered Pulsars M3A, M92A, and NGC 6712B

Pulsar Name	M3A	M92A	NGC 6517B
MJD range	58830–58831	58351–58991	58659–59105
Data span (days)	<1	641	447
Number of TOAs	29	119	20
Timing residual rms (μs)	20.82	8.01	3.74
Measured quantities			
R.A. (J2000)	13:42:00.67^s	17:17:49640(4)	18:01:50.5642(4)
decl. (J2000)	+28:22:31.4^s	+43:08:03.4806(6)	−08:57:32.87(2)
Pulse Frequency (Hz)	392.967704(6)	316.48368670253(5)	34.5284928861(1)
Pulse Frequency Derivative (s^{-2})	0^s	−6.123(3)e-15	−2.628(7)e-15
Orbital Period, P_b (day)	0.13590(2)	⋯	59.836454(1)
Orbital Frequency, F_b (Hz)	⋯	5.762033487(5)e-5	⋯
Orbital Frequency Derivative, $\dot{F}_b$ (Hz^{-2})	⋯	−5.7(2)e-20	⋯
Epoch of passage at Periastron, T_0 (MJD)	58831.084513(5)	58353.54908181(4)	54757.72304(9)
Projected Semimajor Axis, χ_p (lt-s)	0.025609(6)	0.3987068(7)	33.87543(1)
Set quantities			
Reference epoch (MJD)	58685.702931	58390	58670.000000
Dispersion measure, DM (cm^{-3} pc)	26.5	35.45	182.39
Orbital eccentricity, e	0	0	0.0382258(7)^m
Longitude of periastron, ω (deg)	0	0	−57.8914(6)^m
Timing model assumptions			
Solar System ephemeris model	DE200	DE436	DE200
Binary model	BT	BTX	BT

Note. For M3A, R.A., decl., and pulse frequency derivative are set quantities, labeled by ^{s}. For NGC 6517B, eccentricity and periastron are measured, labeled by ^{m}.

gap between the only two M3A observations is almost one year, we cannot determine a phase-coherent timing solution for this system. The timing solutions of M92A and NGC 6517B were also updated. As a redback system, the orbital frequency and its derivative of M92A were measured. The NGC 6517B solution is consistent with previous ones from Lynch et al. (2011). Table 4 are the timing solutions of these three pulsars.

3.2. M2

In total, five new pulsars were discovered in M2. These are the first pulsars found in this cluster. The DM values of these pulsars fall in the range of 43.3–44.1 pc cm^{-3}, close to the one predicted from YMW16 (34.59 pc cm^{-3}). The variation of their observed spin periods indicates that they are all binary pulsars with orbital periods of several days. Additional observations are required to determine their orbital parameters. The situation of M2 that all discovered pulsars are in binary systems is very similar to that of M3, M5, M14, and M62 where no more than one isolated pulsar has been found in each cluster (Lynch et al. 2012). The very high percentage of binary system in the discovered pulsars of these clusters can be explained by their relatively low encounter rate per binary (Verbunt & Freire 2014), which leaves a high surviving probability of a binary system once formed.

3.3. M3

There were four pulsars discovered in M3 prior to our survey. Of these, M3A did not have a timing solution, or even a known orbit, and M3C has not been confirmed. From our FAST observations of M3, we managed to redetect three of the known pulsars except M3C. M3E was discovered at our first attempt and detected for 6 times out of 10 observations on M3, which is more frequently than the other pulsars in M3. Its spin period is approximately 5.47 ms, close to but still clearly different from that of M3D. M3F was discovered in a later observation, but only seen twice out of 10 epochs. Both pulsars are in binary systems. The flux density of all known pulsars in this cluster shows significant variation, which is likely to be a result of interstellar scintillation.

The detection and timing of M3A was mentioned in the first subsection of this section.

3.4. M5

With one pulsar discovered by us, the number of known pulsars in this cluster is six. The new pulsar, M5F, was found in an ongoing search accounting for the second derivative of the spin period (i.e., jerk; Andersen & Ransom 2018) as an additional check on some of the epoch data to the standard scheme described in Section 2. Its spin period is approximately 2.65 ms, and a DM of 29.5 pc cm^{-3}, which is close to all the other known pulsars. With all the eight epoch observations on M5, we managed to obtain the orbital parameters for M5F. Its orbital period is approximately 1.61 days, and the minimum companion mass is 0.2 $M_{\odot}$, indicating that M5F is likely to have a white-dwarf or low-mass star as the companion.

3.5. M10

Two new pulsars were discovered in M10 (one needs further confirmation). They are the first pulsars found in this cluster. The DM values of the two new pulsars, M10A and B, are approximately 43.9 and 43.4 pc cm^{-3}, respectively. These values are inconsistent with the prediction by the YMW16 model, which gives ~107 pc cm^{-3} for the location of M10. This may be a result of the lack of pulsars detected in this region of the sky. M10A was detected with high significance in our first observation as shown in Figure 1, and seen to exhibit period variation probably as a result of acceleration in a binary system. However, it was not detected in the second observation on M10. M10B was detected on both epochs, with significantly different signal-to-noise ratios, which is likely a consequence of interstellar scintillation. Thus, the nondetection of M10A in the second epoch could be attributed to either scintillation or the orbital phase of the pulsar when observed, which may have an impact on the sensitivity of our search.

3.6. M14

We discovered five pulsars in M14. These are the first pulsars found in this cluster. Their DM values range from 78.8 to 82.1 pc cm^{-3}, different from the prediction of 140 pc cm^{-3} by the YMW16 model. M14A has a spin period of approximately 1.98 ms, being the second fastest spinning GC black widow after Terzan 5O (1.68 ms; Ransom et al. 2005). M14B and C have relatively wide pulse profiles, and their spin periods vary slightly in different epochs, indicating they are binaries with orbital periods being of the order of a few days. We cannot obtain the phase-connected timing solutions for M14D and E, but obtained their orbital parameters. M14D has an orbital period of 0.74 days and may exhibit eclipsing phenomena. M14E has an orbital period of 0.85 days and shows clear eclipsing at a particular orbital phase. Considering their circular orbits, low-mass companions, and the eclipsing phenomena, both M14D and E are likely to be redback pulsars.

3.7. M15

Our discovery of M15I is the first newly discovered pulsar in M15 in the past more than 20 yr (Anderson 1993). It was detected in a 5 hr observation, which was interrupted in the middle due to a mechanical issue, and the pulsar signal was seen only before and after the interruption. The DM value of M15I is approximately 67.3 pc cm^{-3}, consistent with those known pulsars of M15. We saw significant period variation during the entire observation, indicating that M15I is likely to be in a binary system.

In our observations, M15A, B, D, E, and F are always detectable even if the observation time is half an hour. M15C was only detected in four observations done on 2018 October and November, 2019 December, and 2020 August. The reason for missing its detections may be the relatively short orbit and/or that it is farther from the GC center than other pulsars. M15G was only detected once, with a very faint signal. The signal is with a DM value of 67.9 pc cm^{-3} and a spin period of 37.660171 ms, which is consistent with previous results. M15H was detected when the length of the observation is 3 hr or longer, indicating that it is too faint so that it cannot be detected in shorter observations.

3.8. M53

M53 is the most distant GC that has known pulsars currently. We managed to redetect M53A and discover three new pulsars, M53B, C, and D, which are all significantly fainter than M53A. The DM values of M53 B, C, and D are 26.0, 26.1, and 24.6 pc cm^{-3}, respectively, all slightly larger than but close to the previously discovered M53A. Now, four pulsars with similar DM values are in the line of sight to M53. As they all have similar DM values, they should be in the GC M53. M53B and D are found to be binary pulsars, while C is likely to be isolated. M53B and C have been detected in all five of the 5 hr observations for M53. Nevertheless, M53D is relatively faint and has been seen in only ~50% of the observation rate. The gaps between the five observations are up to several months, making it difficult to determine the phase-connected timing solution to these pulsars.

3.9. M71

In the FAST sky, M71 is the nearest GC that has known pulsars. From our observations on M71, we redetected M71A, which is an eclipsing black widow pulsar. In addition, we discovered three new pulsars, namely M71B, C, and D. All of them have relatively long spin periods that are 79.9 ms, 28.9 ms, and 100.7 ms, respectively. Judging from their barycentric periods in different observations, M71B and C should be binaries. M71D is the faintest one among them. Though we discovered it in a 5 hr observation, it was not seen in our second M71 observation, which though only lasted for 0.5 hr. Thus, a confirmation of M71D is still needed.

Recently, Han et al. (2021) reported a pulsar discovered 2.5 arcminutes to the center of M71. The DM value of this pulsar is 113 pc cm^{-3} (the DM range of four currently known pulsars is 116.2–119.0 pc cm^{-3}), slightly smaller than all the currently known pulsars in M71. Because this pulsar is far away from our observation center, there is no doubt that such a signal was not detected in our pulsar search. It is possible that this pulsar is at the edge of M71 and thus has a smaller DM value, or is located in the foreground and not related to the cluster. Since Terzan 5B (Lyne et al. 1990, 205 pc cm^{-3}) was proved to be a foreground pulsar due to the significantly different DM value (Ransom et al. 2005, 234–243 pc cm^{-3}), this can be the second example in determining a pulsar as either a member of a GC or just in the line of sight.

3.10. NGC 6517

As mentioned above, in previous work three isolated pulsars were discovered with the Jinglepulsar pipeline in NGC 6517 (Pan et al. 2021). Afterward, the integration time of the following observations were increased from 30 minutes to 2 hr. This results in the discovery of two more isolated pulsars with both the PRESTO and `Jinglepulsar` pipeline. NGC 6517H is a relatively bright isolated pulsar. It has been detected several times and from those detections we obtained its phase-connected timing solution. NGC 6517I is most likely to be an isolated pulsar as well due to the fact that its barycentric spin period is highly consistent in different observations. However, it is too faint and it was only detected three times, so its phase-connected timing solution is still left to be determined.

3.11. Other GCs without Pulsar Discoveries

We did not discover any new pulsars in other GCs including M13, M92, NGC 6539, NGC 6712, NGC 6749, and NGC 6760, while each of which we observed at least once with the longest possible exposure. M13 has six pulsars and we successfully detected all of them with no additional new pulsar discovered. M92 has been monitored roughly once per month mainly in order to time M92A (Pan et al. 2020), and no additional new pulsars have been discovered from these observations. NGC

6539A is the only pulsar in this GC and that was very clearly seen in our observation, with no additional discovery. There are two pulsars in NGC 6749. NGC 6749A, which is a binary, was detected in a 3 hr observation. NGC 6749B, which is not confirmed, was not confirmed by us either. There is one black widow and one isolated pulsar in NGC 6760. Both of them were detected with no additional candidates obtained. A black widow pulsar has been discovered and timed in NGC 6712 by FAST, the details are reported elsewhere (Yan et al. 2021). However, from more than 10 observations, we did not find any new pulsars. While we also propose to observe these GCs in the future, discoveries on these GCs may come from searching in the larger sky area of these GCs, or more sophisticated acceleration search.

4. Conclusions

Our conclusions are as follows:

1. We present 24 new pulsars discovered using FAST. Up until 2021 March, 32 GC pulsars have been discovered from FAST data. The number of GC pulsars in the FAST sky was doubled (from 31 to 63).
2. These discoveries were possible mainly because of the high sensitivity of FAST. GCs such as M3, M5, M53, and M71, where pulsars had been found before with Arecibo, were observed with FAST for 2 or more hours with several new pulsar discoveries. These discoveries indicate that FAST reaches a significant higher sensitivity than that of the earlier Arecibo surveys.
3. The discoveries from either FAST or other telescopes such as GBT and MeerKAT may affect the GC pulsar number predictions.
4. With our discoveries, all five known pulsars in M2, six in M3, and five in M14 are members of binary systems. NGC 6517 is the only GC where we have discovered only isolated pulsars were discovered.

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References

Anderson, S. B. 1993, PhD thesis, California Institute of Technology, https://labcit.ligo.caltech.edu/~anderson/thesis/thesis.html
Andersen, B. C., & Ransom, S. M. 2018, ApJL, 863, L13
Cadelano, M., Chen, J., Pallanca, C., et al. 2020, ApJ, 905, 63
Camilo, F., Lorimer, D. R., Freire, P., Lyne, A. G., & Manchester, R. N. 2000, ApJ, 535, 975
DeCesar, M. E., Ransom, S. M., Kaplan, D. L., Ray, P. S., & Geller, A. M. 2015, ApJ, 807, 23
Freire, P. C., Gupta, Y., Ransom, S. M., & Ishwara-Chandra, C. H. 2004, ApJ, 606, 53
Han, J. L., Wang, C., Wang, P. F., et al. 2021, RAA, 21, 107
Hessels, J. W. T., Ransom, S. M., Stairs, I. H., et al. 2006, Sci, l311, 1901
Hessels, J. W. T., Ransom, S. M., Stairs, I. H., Kaspi, V. M., & Freire, P. C. C. 2007, ApJ, 670, 363
Jacoby, B. A., Cameron, P. B., Jenet, F. A., et al. 2006, ApJ, 644, 113
Jiang, P., Tang, N.-Y., Hou, L.-G., et al. 2020, RAA, 20, 064
Jiang, P., Yue, Y., Gan, H., et al. 2019, SCPMA, 62, 959502
Lynch, R. S., Freire, P. C. C., Ransom, S. M., & Jacoby, B. A. 2012, ApJ, 745, 109
Lynch, R. S., Ransom, S. M., Freire, P. C. C., & Stairs, I. H. 2011, ApJ, 734, 89L
Lyne, A. G., Manchester, R. N., D'Amico, N., et al. 1990, Natur, 347, 650
Manchester, R. N., Lyne, A. G., Robinson, C., et al. 1991, Natur, 352, 219
Nan, R., Li, D., Jin, C., et al. 2011, IJMPD, 20, 989N
Pan, Z., Hobbs, G., Li, D., et al. 2016, MNRAS, 459L, 26P
Pan, Z., Ma, X., Qian, L., et al. 2021, arXiv:2103.14927
Pan, Z., Ransom, S. M., Lorimer, D. R., et al. 2020, ApJ, 892L, 6P
Prager, B. J., Ransom, S. M., Freire, P. C. C., et al. 2017, ApJ, 845, 148
Ransom, S. M. 2001, PhD thesis, Harvard Univ., http://www.cv.nrao.edu/~sransom/ransom_thesis_2001.pdf
Ransom, S. M., Cordes, J. M., & Eikenberry, S. S. 2003, ApJ, 589, 911
Ransom, S. M., Eikenberry, S. S., & Middleditch, J. 2002, AJ, 124, 1788
Ransom, S. M., Hessels, J. W. T., Stairs, I. H., et al. 2005, Sci, 307, 892
Ridolfi, A., Freire, P. C. C., Gupta, Y., & Ransom, S. M. 2019, MNRAS, 490, 3860
Ridolfi, A., Gautam, T., Freire, P. C. C., et al. 2021, MNRAS, 504, 1407
Robinson, C., Lyne, A. G., Manchester, R. N., et al. 1995, MNRAS, 274, 547
Thorsett, S. E., Arzoumanian, Z., Camilo, F., & Lyne, A. G. 1999, ApJ, 523, 763
Verbunt, F., & Freire, P. C. C. 2014, A&A, 561, 11V
Wang, L., Peng, B., Stappers, B. W., et al. 2020, ApJ, 892, 43W
Yan, Z., Pan, Z., Ransom, S. M., et al. 2021, ApJ, submitted
Yao, J. M., Manchester, R. N., & Wang, N. 2017, ApJ, 835, 29
Yu, Q.-Y., Pan, Z.-C., Qian, L., et al. 2020, RAA, 20, 091