RAA 2021 Vol. **21** No. **6**, 143(7pp) doi: 10.1088/1674-4527/21/6/143

http://www.raa-journal.org *http://iopscience.iop.org/raa*

Research in Astronomy and Astrophysics

Three pulsars discovered by FAST in the globular cluster NGC 6517 with a pulsar candidate sifting code based on dispersion measure to signal-to-noise ratio plots

Zhichen Pan (潘之辰)[1,2,3⋆], Xiao-Yun Ma (马晓耘)[1], Lei Qian (钱磊)[1,2,3], Lin Wang (王琳)[1,2,3], Zhen Yan (闫振)[4], Jin-Tao Luo (罗近涛)[5], Scott M. Ransom[6], Duncan R. Lorimer[7,8] and Peng Jiang (姜鹏)[1,2,3]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; *panzc@bao.ac.cn*
[2] CAS Key Laboratory of FAST, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China
[3] College of Astronomy and Space Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
[4] Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 20030, China
[5] National Time Service Center, Chinese Academy of Sciences, Xi'an 710600, China
[6] National Radio Astronomy Observatory, Charlottesville, VA 22903, USA
[7] Department of Physics and Astronomy, West Virginia University, Morgantown, WV 26506, USA
[8] Center for Gravitational Waves and Cosmology, West Virginia University, Chestnut Ridge Research Building, Morgantown, WV 26505, USA

Received 2021 March 3; accepted 2021 March 27

Abstract We report the discovery of three new pulsars in the globular cluster (GC) NGC 6517, namely NGC 6517 E, F and G, made with the Five-hundred-meter Aperture Spherical radio Telescope (FAST). The spin periods of NGC 6517 E, F and G are 7.60 ms, 24.89 ms and 51.59 ms, respectively. Their dispersion measures are 183.29, 183.713 and 185.3 pc cm^{-3}, respectively, all slightly larger than those of the previously known pulsars in this cluster. The spin period derivatives are at the level of 1×10^{-18} s s^{-1}, which suggests these are recycled pulsars. In addition to the discovery of these three new pulsars, we updated the timing solutions of the known isolated pulsars, NGC 6517 A, C and D. The solutions are consistent with those from Lynch et al. but with smaller timing residuals. From the timing solution, NGC 6517 A, B (position from Lynch et al.), C, E and F are very close to each other on the sky and only a few arcseconds from the optical core of NGC 6517. With currently published and unpublished discoveries, nine pulsars have been discovered in NGC 651, ranking it 6$^{\rm th}$ for GCs with the most known pulsars. The discoveries take advantage of the high sensitivity of FAST and a new algorithm used to check and filter possible candidate signals.

Key words: Pulsar — Globular Clusters: Individual: NGC 6517 — methods: analytical — surveys — FAST

1 INTRODUCTION

Till the submission of this paper, 230 pulsars had been discovered in 36 globular clusters[1]. A hundred and seventeen of these pulsars, or about 53% of the total, are gathered in the GCs that have nine or more pulsars. There are 39 pulsars in Terzan 5, 27 in 47 Tucanae (hereafter 47 Tuc), 14 in M28, 10 in NGC 6624, 9 in NGC 6752, 9 in NGC 6517 (including the new pulsars in this paper) and 9 in M15. Previous studies on the predictions of the number of pulsars in GCs also show a similar bias that the numbers of GC pulsars can be significantly different from each GC and a much larger number of pulsars should be discovered. These studies usually focused on GCs with more than five pulsars. Bagchi et al. (2011) relied on a Monte Carlo

⋆ Corresponding author

[1] `http://www.naic.edu/$\sim$pfreire/GCpsr.html`, the average number of pulsars in GCs now is larger than one (157 GCs in total, Harris 1996, 2010; or 160 GCs, `https://people.smp.uq.edu.au/HolgerBaumgardt/globular/orbits.html`) (GCs). Since there have been more than 30 GC pulsars discovered by MeerKAT, especially 13 pulsars discovered in NGC 1851 recently, these numbers will change rapidly.

simulation to model the luminosity distribution of recycled pulsars in GCs. They gave the predictions for 10 GCs under different simulation parameters; Terzan 5, 47 Tuc, M28, M15 and NGC 6440 are the five with the largest number of pulsars. Chennamangalam et al. (2013) utilized Bayesian methods to explore the mean and standard deviation of the luminosity function and total number of pulsars in GCs. While they only applied a simulation to Terzan 5, 47 Tuc and M28, the result affirms that M28 may have a larger number of pulsars than Terzan 5 but is still within the uncertainty range. Turk & Lorimer (2013) followed an empirical Bayesian approach to determine the possible number of pulsars in GCs. The results show that Terzan 5, M15, Terzan 6 and NGC 6441 are the four with the highest number of pulsars. The GC 47 Tuc and M28 only rank $10^{\rm th}$ and $17^{\rm th}$, respectively.

Among all the studies above, the predicted number of pulsars in NGC 6517 varies a lot when compared with GCs that have similar known pulsars. Bagchi et al. (2011) predicted the number of pulsars with different simulation parameters varies between 23±12 and 271±136, being at least two times larger than the predicted numbers among GCs with similar known pulsars, e.g., M3 (with four known pulsars, Hessels et al. 2007 and two unpublished new pulsars from the Five-hundred-meter Aperture Spherical radio Telescope, FAST, Nan et al. 2011 and Jiang et al. 2019) and M5 (with five known pulsars, Anderson et al. 1997, Hessels et al. 2007, and two unpublished new pulsars from FAST). In Turk & Lorimer (2013), NGC 6517 was not included in the twenty GCs with the highest predicted number of pulsars.

All the four previously known pulsars in NGC 6517 were discovered by GBT at a central frequency of 2 GHz with a bandwidth of 800 MHz (Lynch et al. 2011). The pulsars NGC 6517 A, C and D are isolated millisecond pulsars with spin periods shorter than 10 ms. NGC 6517 B has a spin period of 28 ms and lies in a mildly eccentric orbit with an orbital period of ∼60 d, eccentricity of 0.038 and a companion mass of 0.38 $M_{\odot}$.

FAST is performing a GC survey and has produced at least two GC pulsar publications (Pan et al. 2020, Wang et al. 2020). NGC 6517 is one of the promising targets for the FAST GC pulsar survey because it is out of the Arecibo sky and is relatively close to the Earth (10.6 kpc). Drift scan observation of NGC 6517 made in 2017 found no new pulsar detection. Further observations started in June, 2019.

In this paper, we present the FAST discoveries of three new pulsars in NGC 6517. In Section 2, we describe the candidate sifting method. Observation and data reduction are presented in Section 3. Timing results for known and new isolated pulsars in NGC 6517 are provided in Section 4. Sections 5 and 6 are discussion and conclusions, respectively.

2 A SIMPLE PULSAR CANDIDATE SIFTING PIPELINE

Typical pulsar searches could miss weak millisecond pulsar signals with high dispersion measure (DM, e.g., ≥ 100 pc cm^{-3}). The reasons can be explained as follows.

1. The signal-to-noise ratio (SNR) of short period pulsars is affected greatly by DM errors caused by the difference between the pulsar signal's DM and the DM values in the pulsar search DM trial plan. As a result, a faint short periodic signal with high DM may only be in a small number of DM trials.

2. With a given channel bandwidth, the high DM values also broaden pulse widths and weaken the pulse signals, especially for millisecond pulsars.

3. During the candidate sifting, if a candidate with similar period appears only few times, e.g., three times, it may be treated as a faint signal and thus ignored, no matter if this is caused by the DM errors, huge DM steps or the wider pulse that is broadened by the high DM values.

As an example, Einstein@Home reprocessing of the Parkes Multibeam Pulsar Survey data has 24 new pulsars discovered (Knispel et al. 2013). Among these pulsars, there is a high DM pulsar, PSR J1748-3009, with a spin period of 9.7 ms and a DM of 420 pc cm^{-3}. Redetecting this pulsar may not be easy with current pulsar search code, e.g., a typical pulsar search procedure based on PulsaR Exploration and Search TOolkit (PRESTO: Ransom 2001; Ransom et al. 2002, 2003). Depending on user's settings, its signal is so weak that it may only be detected once or twice according to the dedispersion plan obtained with $DDplan.py$ in PRESTO, and thus gets missed by the sifting code, $ACCELsift.py$.

One solution for this is to use smaller DM steps during the dedispersion. With a smaller DM step, the faint pulsar signal may show up more times and thus can be designated as a candidate. While the small DM step also causes more computing time during dedispersion, it is necessary to estimate if twice the time cost for possible ∼10% or even lower additional pulsar discoveries is worthwhile. Since the new pulsar signal actually exists in the original search results but is missed during the sifting, a modified sifting code may have a chance to pick up the pulsar signals. Thus, we designed a graphic-based sifting code to show how the SNR values change with the different DM values.

We divide all the candidates from the pulsar search routine (e.g., $accelsearch$ in PRESTO) for one observation into groups by their periods. Assuming the SNR of a signal with dispersion will reach the maximum when the DM value is close to the real one, the SNR to DM value plot for candidates in each group can be examined to see the dispersion features. Based on PRESTO, we used the so called "Sigma" as the SNR for the following analysis. The pulsar-like signal should exhibit an SNR peak in a non-zero DM value. Due to this, we named the code JinglePulsar[2], as the DM to SNR curve resembles the shape of a bell and the first successful test of the code was around Christmas. In tests, we realized that the periods of candidates in one group may also be sightly different. In order to see the difference clearly, we inspected one more plot showing the period distribution of candidates in each group. During the candidate grouping, we normally use 4 or 5 digit precision. The candidates from one observation normally were put into hundreds of groups, resulting in hundreds to thousands of plots that need to be checked. With other filtering conditions, such as the lower limit for how many times the candidate appears (we use 3) and the lower limit for highest SNR values of candidates in a group (normally 6 to 8), the number of groups can be only 1% of the number of candidates. The candidate in each group with highest SNR value will be checked again by folding the observation data with the DM value and period of the candidate. Current candidate ranking codes based on machine learning can be utilized to check the folding results. Alternatively, for a targeted search, such as GC pulsar search, all the plots can be checked by humans.

We tested these candidate sifting improvements using the same Parkes observations of 47 Tuc as described in Pan et al. (2016). We dedispersed all the data with a DM range of 23.5 to 25.5 pc cm^{-3} and only searched for isolated pulsars, aiming to find all known isolated pulsars and possible unknown faint pulsars. There are 313 757 raw candidates from the PRESTO search routine $accelsearch$. These candidates were separated into 2195 groups by their spin period. After checking the DM to SNR plots by humans, we only selected 48 signals. These 48 candidates were then confirmed to be 16 known pulsars and related harmonics. In this test, we successfully detected all the 10 isolated pulsars, including 47 Tuc aa and ab which were discovered by a segmented search in which all the observation data were added incoherently (47 Tuc aa), or, utilizing PRESTO (47 Tuc ab), respectively. We also looked up all the known pulsars that were missed during our test on the data. While none of them were found, this confirmed that we detected all the known pulsars from the 313 757 raw candidates. Figure 1 displays the SNR to DM plots and spin period distribution plots of 47 Tuc aa and ab from our test. We also redetected six binaries among all the 15 known binary pulsars. The reason is that they are bright enough to be detected as isolated pulsars when the acceleration of their orbital movements is close to zero in several minutes during observations. Unfortunately, no new pulsars were discovered.

[2] https://www.github.com/jinglepulsar

3 OBSERVATION AND DATA REDUCTION

In the FAST sky, we aim to select GCs with high DM values and known pulsars. The known pulsars in it can be applied for the sifting tests even though there were no new pulsars discovered, and with the known pulsars, the DM range can be largely decreased, thereby saving dedispersion time. NGC 6517, NGC 6749 and NGC 6760 are the three GCs chosen in the FAST sky, they have known pulsars and pulsars in them have relatively high DM values. Hosting four previously known pulsars, NGC 6517 is the first GC selected for a high DM millisecond pulsar search.

We started the NGC 6517 tracking observation on 2019 June 25, as one of the targets for the FAST GC pulsar survey, which is part of the FAST Search of Pulsars in Special Population (SP^2, Pan et al. 2020) survey. The FAST 19-beam receiver spans a bandwidth of 1.05 to 1.45 GHz with 4096 channels (channel width 0.122 MHz) The beam size is ∼3 arcmin and the system temperature is ∼24 K (Jiang et al. 2020). We sampled the data from two polarizations with 8-bit precision every 49.152 µs. The first observation was done on 2019 June 25$^{\rm th}$, lasting for half an hour.

The DM from Earth to NGC 6517 is ∼174 to 183 pc cm^{-3}, determined by its known pulsars. We dedispersed the data within a DM range of 168.7 to 185.9 pc cm^{-3}. With a desired time resolution of 0.2 µs, the DM step calculated by $DDplan.py$ in PRESTO is 0.1 pc cm^{-3}. In order to search for binary pulsars, the acceleration search was applied by setting the zmax values to be 300. The search results were sifted by JinglePulsar, which resulted in redetecting all known pulsars and three new signals (featured in Fig. 2) which were then confirmed to be new pulsars. The single pulse search was also implemented but no obvious signal was detected. We also searched the data from the timing observation with the same settings, with two more extremely faint isolated pulsars, namely NGC 6517 H and I, discovered. These two discoveries will be mentioned in another paper (Pan et al. in prep).

FAST can also record baseband data for the 500 MHz bandwidth. The data are 8-bit sampled for the two polarizations. Using 190 pc cm^{-3} as the DM value, we applied coherent dedispersion to create a half-hour observation from the baseband data which we searched as well. The search detected pulsars A to G. The SNR from the baseband data is a bit increased, however, we detected no new pulsars.

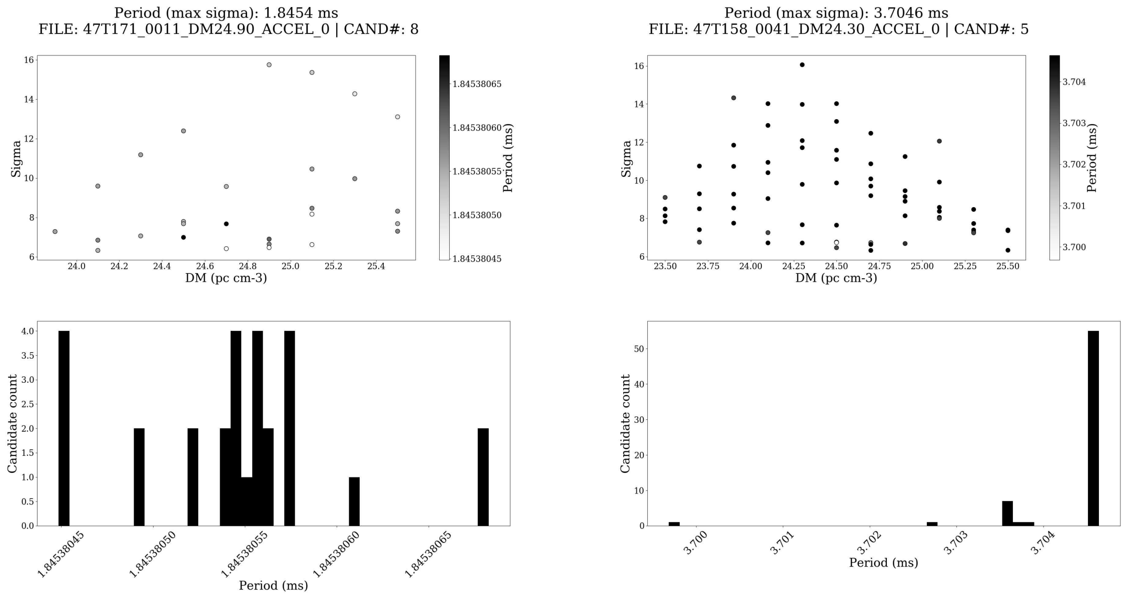

Fig. 1 The redetections of 47 Tuc aa (*left*) and ab (*right*). The upper panels display the relationship between the SNR and DM, and the lower panels depict the period distributions of the candidate periods.

4 TIMING

So far, a total of 20 observations has been carried out during 447 d between June 2019 (MJD 58659) and September 2020 (MJD 59105). Depending on the different observation arrangements, observations lasted for less than 0.5 hr to more than 2 hr. In the data taken on 2019 June 25$^{\rm th}$, we searched for the best DM values for which the SNR values of pulsars are highest. The DM values are 182.614, 182.457, 174.487, 183.29, 183.713 and 185.3 pc cm^{-3} for pulsars NGC 6517 A, and C to G, respectively. In each observation, all the pulsars were detected except for pulsar G due to its low flux density. The templates used for time of arrival (TOA) generation were made from the longest observation which was acquired on 2020 January 23rd. Due to the observation arrangement, the gap between observations can be more than 1 month. Thus, the method utilized for determining rotation counts (Freire & Ridolfi 2018) was used for timing all the six isolated pulsars. After determining an initial timing solution, we folded all the observations again with their ephemerides and obtained the improved solutions. Table 1 shows the timing solutions for the three new pulsars.

As the previously known isolated pulsars NGC 6517 A to D were also detected, we timed them with the same FAST data. The timing solution for three isolated pulsars, NGC 6517 A, C and D, are displayed on Table 2. Comparing with the timing solutions in Lynch et al. (2011), they are consistent. Due to the high sensitivity of FAST, the timing residuals (4.77 µs for A, 7.26 µs for C and 2.86 µs for D) are lower than those in Lynch et al. (2011). For the binary pulsar NGC 6517 B, the gaps in our FAST observations make it difficult for us to obtain the timing solution. We will keep monitoring it and update the timing solution for NGC 6517 B in a future paper.

5 DISCUSSION

The three new pulsars are extremely faint and we believe this is the reason why they have not been discovered by previous studies. NGC 6517 E and F can be detected by ~0.5-hour FAST observation in L-band, while their fluxes seem to be affected a little by scintillation. Pulsar G is the faintest among them, and was only detected 16 times among the 20 observations. Their DM values are all higher than previously known pulsars, indicating that they may be farther away. Their pulse frequency derivatives are small, signifying that they are all recycled pulsars rather than young pulsars, no matter if they are millisecond pulsars or relatively long period pulsars.

Figure 3 shows the positions of all the seven pulsars in NGC 6517 (B from Lynch et al. 2011). Pulsars A, B, C, E and F are very close to each other on the sky and near the GC optical center (J2000, 18:01:50.52 –08:57:31.6, Lynch et al. 2011), especially pulsars A, E and F which are only separated by a few arcseconds. This case happens rarely in other GCs, with the only two other known examples being two pairs of GC pulsars, 47 Tuc F to S, and G to I.

With nine pulsars, NGC 6517 now is the 6$^{\rm th}$ (the same as NGC 6752 and M15) for GCs in terms of numbers of pulsars discovered, suggesting that previous GC pulsar

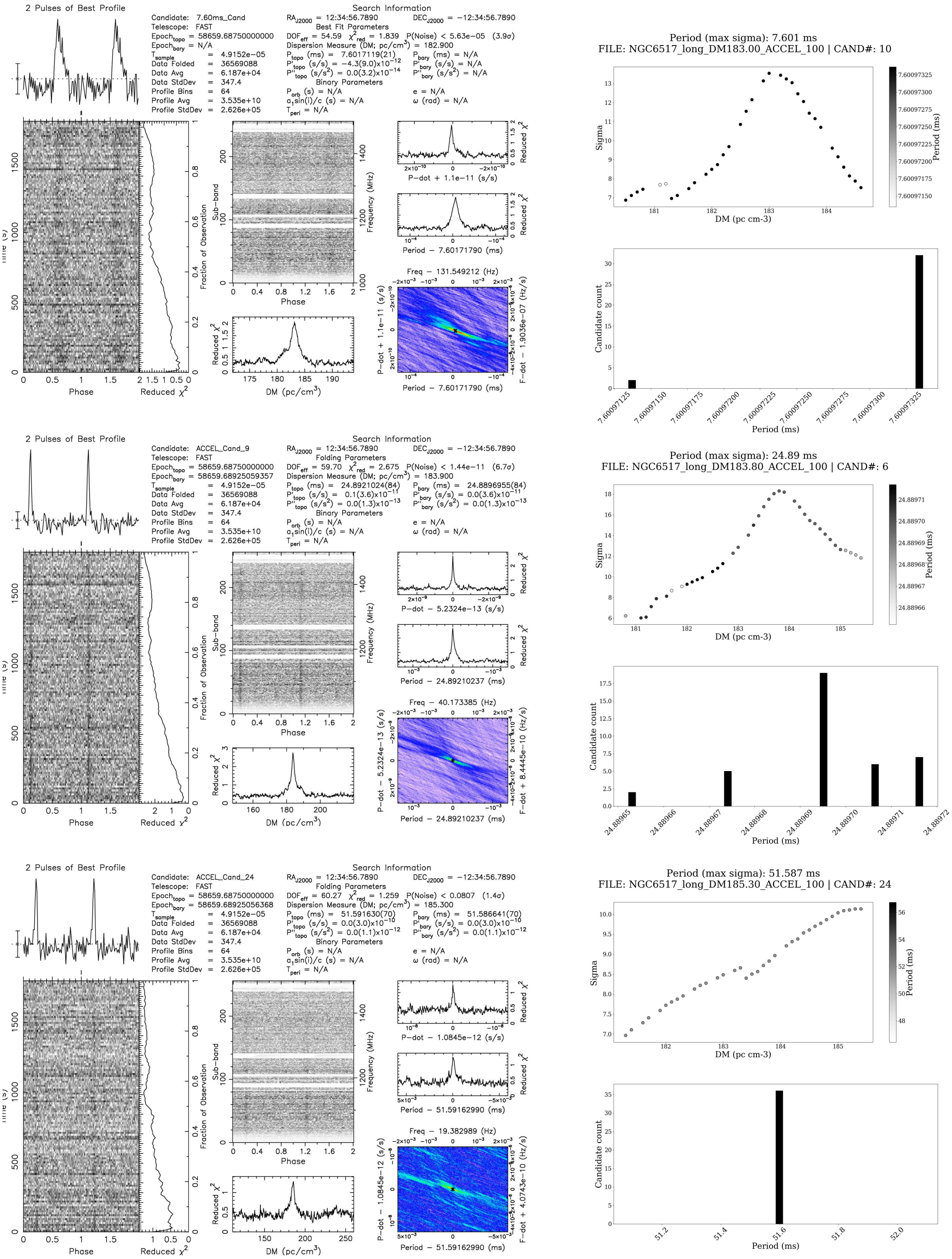

Fig. 2 The discovery plots of NGC 6517 E, F and G (from top to bottom), respectively. Left panels are the PRESTO folding results of these pulsars and right panels are the DM to SNR plots from our code. For pulsar G, because its DM value is close to the upper limit for the search DM range, there is not a peak.

detection predictions may still have errors. Our current pulsar surveys also found more pulsars in GCs which are either predicted to have more pulsars or have fewer pulsars. On the other hand, there is no doubt that the three new pulsars were discovered due to better sensitivity. While we are still looking for new pulsars in other GCs with FAST,

Table 1 Timing Solutions for New Pulsars NGC 6517 E, F and G

	NGC 6517 E J1801-0857E	NGC 6517 F J1801-0857F	NGC 6517 G J1801-1857G
Number of TOAs	20	20	20
RMS Timing Residual (μs)	16.87	6.96	143.3
Measured quantities			
Right Ascension, RA (hh:mm:ss, J2000)	18:01:50.6232(3)	18:01:50.7409(3)	18:01:50.099(2)
Declination, DEC (dd:mm:ss, J2000)	–08:57:31.29(2)	–08:57:31.27(2)	–08:57:27.9(1)
Pulse Frequency (Hz)................	131.55003245964(8)	40.17357389106(2)	19.383088017(8)
Pulse Frequency Derivative (s^{-2})	$1.794(2)\times10^{-14}$	$4.312(7)\times10^{-15}$	$-3(2)\times10^{-17}$
Set Quantities			
Reference Epoch (MJD)	58871	58871	58871
DM (cm^{-3} pc)	183.29	183.71	185.30
Timing Model Assumptions			
Solar System Ephemeris Model	DE200	DE200	DE200

Table 2 Timing Solutions for Perviously Known Pulsars NGC 6517 A, C and D

	NGC 6517 A J1801-0857A	NGC 6517 C J1801-0857C	NGC 6517 D J1801-1857D
Number of TOAs	20	20	20
RMS Timing Residual (μs)	4.77	7.26	2.86
Measured Quantities			
Right Ascension, RA (hh:mm:ss, J2000)	18:01:50.6097(1)	18:01:50.73731(7)	18:01:55.3632(2)
Declination, DEC (dd:mm:ss, J2000)	–08:57:31.853(6)	–08:57:32.699(3)	–08:57:24.284(9)
Pulse Frequency (Hz)................	139.360884729(3)	267.47267494(3)	236.600598138(8)
Pulse Frequency Derivative (s^{-2})	$9.9124(8)\times10^{-15}$	$4.573(9)\times10^{-15}$	$-4.3(2)\times10^{-16}$
Set Quantities			
Reference Epoch (MJD)	54400	54400	54400
DM (cm^{-3} pc)	182.614	182.457	174.487
Timing Model Assumptions			
Solar System Ephemeris Model	DE200	DE200	DE200

Parkes with an ultra-wideband low frequency receiver, MeerKAT and other large telescopes, the relatively high pulsar number of NGC 6517 may be the result of the FAST GC pulsar search priority, in that we searched it earlier. It is highly likely to find more faint pulsars in other GCs and thus increase the average number of GC pulsars overall.

As seen in Figure 2, for all the three new pulsars, even for pulsar G which is quite faint, the SNR to DM curves have clear peaks. The data points in the curves could be reduced to be half (DM step is 0.2 pc cm^{-3}) or even one fourth (DM step is 0.4 pc cm^{-3}), and we could still find these pulsars. With larger DM steps, the computing time for pulsar search will also be saved. However, the DM to SNR curve becomes narrower when the pulsar spin period is shorter. The three new pulsars have relatively longer periods so that we can detect them with relatively larger DM step.

The DM values for pulsars A, B and C in NGC 6517 are slightly different from those reported by Lynch et al. (2011). These may arise from either errors utilizing different bands or are caused by the DM variations. We will continue monitoring this GC and report this in another paper. While the pulsars NGC 6517 H and I have DM values between NGC 6517 D's and others, the timing should be done to obtain their positions for further analysis.

With current discoveries, NGC 6517 hosts nine pulsars. Among them, NGC 6517 B is the only binary and is in a ∼60 d orbit. NGC 6624 (eight isolated, one binary), NGC 6752 (eight isolated, one binary), M15 (seven isolated, one binary, one unknown), Terzan 1 (8 isolated) and NGC 6522 (four isolated) have similar highly isolated pulsar ratios. NGC 6517 also contains three long spin period pulsars which have spin period longer than 20 ms. Besides NGC 6517 (three among nine), Terzan 5 (three among 39), NGC 6624 (three among 10), M71 (three among four, discovered by FAST, unpublished) and M15 (four among nine) have three or more pulsars with spin period 20 ms or longer. Verbunt & Freire (2014) introduced the encounter rate for a single binary, γ. Based on this, they suggested that for core collapse GCs, binary pulsar systems have a much higher probability of being destroyed at any stage of the evolution and thus these clusters mostly house isolated and/or partially recycled pulsars. Thus, the pulsars from NGC 6517, M15 and NGC

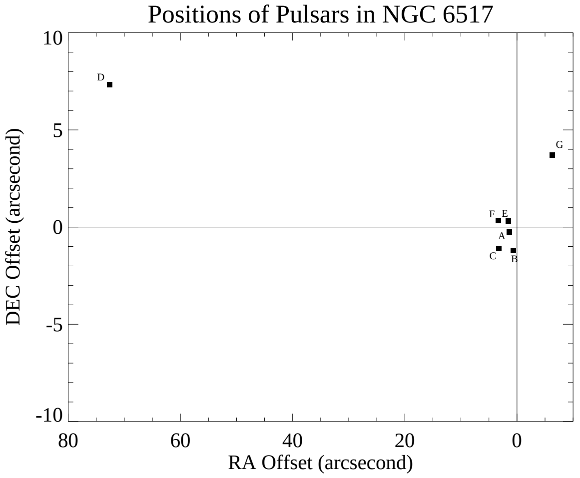

Fig. 3 The positions of NGC 6517 A to G. The X and Y axes are RA and DEC offsets from the NGC 6517 optical center (J2000, 18:01:50.52 –08:57:31.6, Lynch et al. 2011) respectively. The error bars for positions are much smaller than the size of squares which represent the pulsars. The beam size of FAST is ∼3 arcmin, which covers a much larger region than this plot.

6624 are consistent with the expectation for these core-collapsed GCs.

6 CONCLUSIONS

The conclusions are as follows:

1. We discovered three new pulsars in NGC 6517. With current discoveries, NGC 6517 now has nine pulsars in it, ranking $6^{\rm th}$ (the same as NGC 6752 and M15) among GCs in terms of numbers of pulsars.

2. Based on FAST data, we obtained or updated the timing solutions for the six isolated pulsars in NGC 6517. All these isolated pulsars have small period derivatives, indicating that they are recycled pulsars.

3. The new candidate sifting code, JinglePulsar, was tested on 47 Tuc data and then applied for NGC 6517 pulsar search, resulting in the discoveries. With these tests, we suggest that with an optimized sifting method, the DM step in pulsar search for relatively long period (e.g., 10 ms or longer) pulsars can be at least twice as long as what is used now, largely saving computing time.

4. From our timing solution, pulsars A, B, C, E and F are close to each other and near the GC center.

5. The current GC pulsar searches are performed by large telescopes (arrays) like FAST, Parkes UWB and MeerKAT. It is worthwhile re-investigating the simulations on GC pulsar number prediction.

Acknowledgements This work is supported by the Basic Science Center Project of the National Natural Science Foundation of China (NSFC, Grant Nos. 11703047, 11773041 and U2031119). This work made use of data from the Five-hundred-meter Aperture Spherical radio Telescope (FAST). FAST is a Chinese national mega-science facility, built and operated by the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). We appreciate all the people from the FAST group for their support and assistance during the observations. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. ZP is supported by the CAS "Light of West China" Program. LQ is supported by the Youth Innovation Promotion Association of CAS (id. 2018075). SMR is a CIFAR Fellow and is supported by the NSF Physics Frontiers Center award 1430284.

References

Anderson, S. B., Wolszczan, A., Kulkarni, S. R., & Prince, T. A. 1997, ApJ, 482, 870

Bagchi, M., Lorimer, D. R., & Chennamangalam, J. 2011, MNRAS, 418, 477

Chennamangalam, J., Lorimer, D. R., Mandel, I., & Bagchi, M. 2013, MNRAS, 431, 874

Freire, P. C. C., & Ridolfi, A. 2018, MNRAS, 476, 4794

Harris, W. E. 1996, AJ, 112, 1487

Harris, W. E. 1996, eprint(arXiv:1012.3224)

Hessels, J. W. T., Ransom, S. M., Stairs, I. H., Kaspi, V. M., & Freire, P. C. C. 2007, ApJ, 670, 363

Jiang, P., Yue, Y., Gan, H., et al. 2019, Science China Physics, Mechanics, and Astronomy, 62, 959502

Jiang, P., Tang, N.-Y., Hou, L.-G., et al. 2020, RAA (Research in Astronomy and Astrophysics), 20, 064

Knispel, B., Eatough, R. P., Kim, H., et al. 2013, ApJ, 774, 93

Lynch, R. S., Ransom, S. M., Freire, P. C. C., & Stairs, I. H. 2011, ApJ, 734, 89

Nan, R., Li, D., Jin, C., et al. 2011, International Journal of Modern Physics D, 20, 989

Pan, Z., Hobbs, G., Li, D., et al. 2016, MNRAS, 459, L26

Pan, Z., Ransom, S. M., Lorimer, D. R., et al. 2020, ApJL, 892, L6

Ransom, S. M. 2001, PhD thesis, New Search Techniques for Binary Pulsars

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

Turk, P. J., & Lorimer, D. R. 2013, MNRAS, 436, 3720

Verbunt, F., & Freire, P. C. C. 2014, A&A, 561, A11

Wang, L., Peng, B., Stappers, B. W., et al. 2020, ApJ, 892, 43