

Three Pulsars Discovered in Globular Cluster M15 (NGC 7078) with FAST

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Abstract

We present the discovery of three pulsars in Globular Cluster M15 (NGC 7078) by the Five-hundred-meter Aperture Spherical radio Telescope (FAST). In the three pulsars, PSR~J2129+1210J (M15J) is a millisecond pulsar with a spinning period of 11.84 ms and a dispersion measure of 66.68 pc cm⁻³. Both PSR~J2129+1210K and L (M15K and L) are long period pulsars with spinning periods of 1928 ms and 3961 ms, respectively, while M15L is the GC pulsar with the longest spinning period till now. The discoveries of M15K and L support the theory that core-collapsed Globular Clusters may contain partially recycled long period pulsars [citep{verbunt-2014-slowpulsar}](#). With the same dataset, the timing solutions of M15A to H were updated, and the timing parameter P1 of M15F is different from the previous results, which is approximately 0.027% times 10⁻¹⁸ s⁻¹ from our work and 0.032% times 10⁻¹⁸ s⁻¹ from Anderson's [citep{anderson-1993}](#). As predicted by Rodolfi et al. [citep{ridolfi-2017}](#), the luminosity of M15C kept decreasing and the latest detection in our dataset is on December 20th, 2022. We also detected M15I for one more time. The different barycentric spin periods indicate that this pulsar should locate in a binary system, manifesting itself as the exceptional one in such a core-collapsing GC.

Full Text

Preamble

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Three Pulsars Discovered in Globular Cluster M15 (NGC 7078) with FAST

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Abstract

We present the discovery of three pulsars in the globular cluster M15 (NGC 7078) using the Five-hundred-meter Aperture Spherical radio Telescope (FAST). Among these, PSR J2129+1210J (M15J) is a millisecond pulsar with a spin period of 11.84 ms and a dispersion measure of 66.68 pc cm⁻³. Both PSR J2129+1210K and L (M15K and M15L) are long-period pulsars with spin periods of 1928 ms and 3961 ms, respectively, with M15L being the longest-spinning-period pulsar known in any globular cluster to date. The discoveries of M15K and M15L support the theory that core-collapsed globular clusters may contain partially recycled long-period pulsars (Verbunt & Freire 2014). Using the same dataset, we have updated the timing solutions for M15A through H. Notably, the timing parameter P_1 for M15F differs from previous results: our work yields approximately $0.027 \times 10^{-18} \text{ s s}^{-1}$, compared to $0.032 \times 10^{-18} \text{ s s}^{-1}$ from Anderson (1993). As predicted by Ridolfi et al. (2017), the luminosity of M15C has continued decreasing, with our most recent detection occurring on December 20, 2022. We also detected M15I one additional time. The different barycentric spin periods indicate that this pulsar is located in a binary system, making it exceptional in such a core-collapsed environment.

Keywords: Radio pulsars (1353) — Globular star clusters (656) — Radio astronomy (1338)

1. Introduction

Pulsars, rapidly rotating neutron stars, are typically discovered using single-dish radio telescopes. Since the discovery of the first globular cluster (GC) pulsar (PSR B1821-24A; Lyne et al. 1987), GCs have proven to be fertile grounds for millisecond binary pulsars. Approximately 160 GCs exist in the Milky Way (Forbes et al. 2018), and pulsar surveys in these clusters have been conducted for decades. As of the submission of this letter, a total of 305 pulsars have been identified in 40 GCs¹.

M15 (NGC 7078) is a core-collapsed GC (Harris 1996) that stands out as one of the oldest (12.0 Gyr) and most metal-poor Galactic GCs ($[Fe/H] = -2.255$), featuring a significantly dense core (Sosin & King 1997; Koleva et al. 2008). Multi-decade observations have yielded profound results, including studies of M15A (Wolszczan et al. 1989) and the double neutron star system M15C (Anderson et al. 1990; Deich & Kulkarni 1996). M15 hosts nine known pulsars, eight of which were discovered in the 1980s and 1990s using the Arecibo telescope. M15I was found by the Five-hundred-meter Aperture Spherical Radio Telescope (FAST; Nan et al. 2011) globular cluster pulsar survey².

M15A is a bright, isolated pulsar with a notable flux density of approximately 0.2 ± 0.05 mJy at 1415 MHz, discovered in 1989 (Wolszczan et al. 1989). M15B was reported one year later with a period of approximately 56.13 ms and a luminosity roughly twice as faint as M15A, though still considered a bright isolated pulsar (Anderson et al. 1990). M15C resides in a highly eccentric binary system with an orbital period of 8 hours and eccentricity of 0.68 (Anderson et al. 1990). Its companion is also a neutron star, making it similar to the well-known PSR 1913+16 system (Taylor & Weisberg 1982) and a promising target for general relativity tests (Anderson et al. 1990). Previous studies have reported on the brightness and polarimetric properties of M15C, noting a consistent decrease in flux and significant changes in its (polarized) pulse profile (Kirsten et al. 2014; Ridolfi et al. 2017), suggesting that M15C is undergoing precession. Continuous observation of M15C therefore remains imperative for understanding the effects of precession on pulsar characteristics, the structure of M15C's emission beam, and for potentially detecting signals from its companion.

After 2016, no follow-up observations of M15 were reported. The latest timing solutions for M15A, B, and C dated to 2006, while those for the other pulsars remained unchanged since the 1990s (Anderson 1993; Jacoby et al. 2006). There is a nearly thirty-year gap between the discovery of M15H and M15I. M15I was discovered in 2021 (Pan et al. 2021) and had only been detected in one observation, still considered a new pulsar due to its limited appearances. According to simulations, M15 is possibly one of the GCs with the highest expected number of pulsars (Bagchi et al. 2011; Turk & Lorimer 2013). Consequently, conducting a pulsar search within M15 is absolutely essential, and M15 has been one of the highest-priority targets since the beginning of the FAST GC pulsar survey. In this letter, we report the discoveries of three pulsars in M15, the re-detections

of M15C and I, and updated timing solutions for M15A through H.

The structure of this letter is as follows: Section 2 presents the observations and data reduction, Section 3 shows the updated timing solutions, Section 4 provides discussion, and Section 5 summarizes our conclusions.

2. Observation and Data Reduction

Observations of M15 with FAST began in October 2018 using the L-band 19-beam receiver, which covers a frequency range of 1 to 1.5 GHz with 4096 channels, corresponding to a channel width of 0.122 MHz. All observational data were recorded as psrfits files in pulsar search mode, and only data from the central beam were used in this study. The receiver's beam size is 3 arcminutes, while M15's core radius and half-light radius are 0.14 and 1.00 arcminutes, respectively (Harris 1996). Thus, the central beam provides sufficient coverage of the area where pulsar signals are expected.

Aiming to discover new pulsars, we performed a total of 18 observations from 2018 to 2023. Most observations were conducted in Tracking mode, with only one observation in Snapshot mode to cover the entire GC area.

We employed the pulsar search code PRESTO (Ransom 2011) for data analysis. Data were dedispersed using *prepsubband* in PRESTO. The dispersion measure (DM) range of known pulsars in M15 is 65.5 to 67.7 pc cm⁻³; accordingly, we dedispersed the data within a DM range of 63 to 69 pc cm⁻³ using a DM step of 0.05 pc cm⁻³. Subsequently, we applied *realfft* to transform the dedispersed time series to the frequency domain and then applied *accelsearch* for periodic signal detection. Because the binary pulsar M15C was one of our primary targets, the acceleration search parameter *zmax* was set to 100 and the number of harmonics to sum was 32. The search results were sifted using *ACCEL_{sift}.py*, and data were folded with *prepfold* from PRESTO according to the DM values and periods of candidates. To save time, we used RPPPS⁴ to run these PRESTO routines in parallel.

In a previous study, Verbunt et al. explained the possibility of slow pulsars existing in core-collapsed GCs (Verbunt & Freire 2014). As an example, a slow pulsar with a 2.4 s period was found in the core-collapsed GC NGC 6624 (Abbate et al. 2022). As M15 is also a core-collapsed GC, it may similarly contain long-period pulsars. It is worth noting that M15A is an isolated pulsar with a period longer than 100 ms (110.6 ms; Wolszczan et al. 1989), indicating that applying the Fast Fold Algorithm (FFA) to M15 data may be suitable for finding new long-period pulsars.

We used the FFA code Riptide-FFA⁵ for data processing. For FFA search settings, we followed the examples provided on the Riptide-FFA website⁶, using three period search ranges: a short period range of 0.2 s to 1 s, a medium range of 1 s to 5 s, and a long range from 5 s to 180 s.

All search results from both PRESTO and Riptide-FFA are presented in Table 1.

Symbols indicate detections found in search results, while \square symbols mark those not detected in search results but identifiable by folding with timing solutions. For the new pulsars, M15J was detected in 11 out of 18 observations. M15K and L are bright enough to be detected in observations longer than 1 hour, though their detections depend on radio frequency interference (RFI) masking conditions. Therefore, we do not include detailed detection information for these new pulsars here.

3. Results

A total of 18 observations were carried out from October 2018 (MJD 58404) to February 2023 (MJD 59995), spanning 1591 days. Due to variations in observation scheduling, individual observations lasted from half an hour to five hours.

From the Riptide-FFA results, a harmonically related signal with a signal-to-noise ratio (SNR) of 9.2 was detected in data recorded on December 14, 2019. This signal had a period of 110.83 ms, an optimal DM of 66.40 pc cm⁻³, and a pulse profile with 10 peaks. Subsequent investigations confirmed that this signal was the tenth harmonic of a new pulsar, leading to the discovery of M15J. Such signals were successfully detected in multiple observations, and with additional recent FAST data, we obtained a phase-connected timing solution (see Table 2). M15J is an isolated pulsar with a spin period of 11.84 ms and a DM of 66.68 pc cm⁻³.

From the observation on December 21, 2020, Riptide-FFA detected two long-period pulsars, M15K and M15L. These signals have periods of approximately 1920 ms and 3961 ms, respectively, with DM values of 65.00 pc cm⁻³ providing the best SNR. Due to RFIs, their SNR is very limited. Consequently, we obtained timing solutions only with JUMPs (see Figure 3), fitting only the spin periods (Table 2). To achieve more detections, weak RFIs must be masked and removed from the data.

3.2. Known Pulsars

M15C appeared three times in the search results. To maximize signal recovery, we also used the ephemeris from the ATNF Pulsar Catalogue⁷ (Manchester et al. 2005). While this ephemeris is no longer sufficiently accurate for our FAST data, we could still identify M15C signals in folding results and successfully obtain its timing solution. The fitted orbital period, projected semi-major axis, epoch of periastron, eccentricity, and longitude of periastron are 0.3352820162(3), 2.51842(1), 50000.064743(8), 0.681404(9), and 345.312(2), respectively, consistent with previous results (e.g., Anderson 1993).

We detected all other pulsars in M15, with detection rates shown in Table 1. We obtained fully phase-connected timing solutions for M15A, B, D, E, F, and H (see Table 2; ephemerides from the ATNF Pulsar Catalogue were also used for timing M15G and H). For M15G, we could not remove all JUMPs because

it is too faint, with only six detections. The timing solutions for M15A, B, D, E, and H are basically consistent with previous studies, while M15F exhibits an offset in P_1 , which will be discussed in a subsequent section.

The most recently discovered pulsar, M15I, was detected once more on December 20, 2022 (MJD 59933). Compared to its discovery and confirmation observation on September 22, 2020, the M15I signal on December 20, 2022, matched well in both spin period and pulse profile shape (see Fig. 1). From the September 22, 2020 observation, its barycentric period and acceleration inferred from the period derivative are 5.1221966(4) ms and $-0.011(11) \text{ m s}^{-2}$, respectively, while from the December 20, 2022 observation they are 5.1221974(2) ms and $0.0071(36) \text{ m s}^{-2}$, respectively. These variations suggest that M15I is in a binary system. Based on the efficiency of acceleration search (Ransom 2001), if M15I is a binary, the orbital period should be longer than 50 hours.

4. Discussion

In Figure 2, we present the timing positions and Chandra X-ray source positions in M15 as observational coordinates. The position of M15G is taken from Anderson (1993). Among these pulsars, none has an X-ray counterpart. Figure 3 shows the timing residuals for all pulsars in M15. Due to data quality limitations, not all observational data were utilized. The pulse profiles of M15I, K, and L are from only one observation because of their limited detections and significant interference.

4.1. Detection Rates

The fluxes of M15A, B, D, and E appear to remain stable. These four pulsars are bright enough to be detected even in half-hour observations, and their timing solutions are consistent with previous studies (Anderson 1993). The timing results for M15C will be discussed in the next subsection. Our timing solution for M15F differs from Anderson's: the P_1 from our timing is approximately $0.027 \times 10^{-18} \text{ s s}^{-1}$, compared to $0.032 \times 10^{-18} \text{ s s}^{-1}$ from Anderson (1993). M15G, which was redetected only once in FAST data on January 2, 2022 (Pan et al. 2021), now has six detections total. More observations are needed to obtain its position and spin frequency derivative. M15H was searched for 7 times among the 18 observations (39% detection rate), but when folded with the timing solution, its signal appears in every observation, suggesting that both flux variation and scintillation affect its detection. M15I was detected one additional time, as mentioned above.

M15J is an isolated millisecond pulsar (MSP) detected 11 times (61% detection rate). For M15K and L, due to RFIs, both can be seen in every observation, but only very limited observations (8 times for M15K, 4 times for M15L) can be used to extract TOAs. Thus, we fitted only the spin frequencies, F_0 .

4.2. The Double Neutron Star M15C

M15C is a well-studied pulsar-neutron star system. The mass of its companion and orbital parameters have all been precisely determined in previous studies (Anderson 1993; Deich & Kulkarni 1996; Jacoby et al. 2006). Compared with results from 2014, M15C displayed much higher linear polarization in 2016 (Ridolfi et al. 2017). It has been predicted that M15C's signal will become fainter and finally disappear between 2041 and 2053. In our dataset, the most recent detection of M15C was on December 20, 2022, in a three-hour observation. The SNR of the M15C signal remained low (about 6.9), indicating that it is almost outside our line of sight. No signals from M15C have been detected since that observation (e.g., in a 3-hour observation on January 20, 2023).

For polarization analysis, data should be recorded in four polarizations with the noise diode on at the beginning. We have only three such observations. Fortunately, in data obtained on December 14, 2019, M15C was strong enough. Consistent with previous studies, M15C continues to exhibit high linear polarization (see Figure 4).

4.3. Slow Pulsars M15K and M15L

In previous surveys, only two pulsars in GCs have been identified with periods exceeding one second: B1718-19 (1004 ms, in NGC 6342; Wijers & Paczynski 1993) and J1823-3022 (2497 ms, possibly in NGC 6624; Abbate et al. 2022). B1718-19A is in a binary system with a low-mass non-degenerate companion, associated with the core-collapsed GC NGC 6342. Due to a DM difference (9.3 pc cm^{-3} from the average DM for known pulsars) and an offset of 3 arcminutes from the GC center, J1823-3022 may not be associated with the core-collapsed GC NGC 6624.

The spin periods of M15K and L are 1.9 s and 3.9 s, respectively, ranking them 3rd and 1st among all GC pulsars. Currently, properties such as their positions and period derivatives remain unknown. The beam size of FAST's 19-beam receiver is 3 arcminutes. Although the precise positions of these two pulsars remain unknown, their detection in the central beam indicates they are not far from M15's core. The absence of this crucial information currently hinders our ability to determine whether they are young or recycled pulsars and whether they are truly associated with M15. Their detections and TOAs are severely affected by significant RFIs. Eliminating these RFIs to enhance signal quality and obtaining their timing solutions are primary objectives for future work.

A plausible conjecture for the presence of these two pulsars is that they may be partially recycled: due to large recoils resulting from binary interactions during disruption, recycled pulsars in binary systems were ejected from the center and have had insufficient time to sink back to the central region.

4.4. Confirmation of M15I

M15I is a millisecond pulsar that had been detected and confirmed in only a single observation. Normally, a pulsar is not considered confirmed until detected in another independent observation. During the observation on September 22, 2020, the FAST telescope experienced a mechanical issue that caused it to point away from M15 for approximately 7000 seconds. The M15I signal was detected in this observation and disappeared during that 7000-second segment, agreeing with the interpretation that the signal was from the sky and entered the receiver in the direction of M15. When the pointing changed, the signal disappeared accordingly. Thus, M15I was detected and confirmed in one observation. A similar method has been suggested for detecting and confirming highly nulling pulsars, called spatial modulation search (Qian & Pan 2021). However, as the first example, M15I needs one more detection to prove that the pulsar indeed exists and that the method works.

With *accelsearch* from PRESTO, M15I was detected again with a *zmax* value of 100 on data dedispersed with a DM value of 67.6 pc cm^{-3} . With a very small but detectable acceleration, it is an exceptional pulsar in such a core-collapsed GC. The reason for its flux variation is unknown, and more observations should be performed to obtain its timing solution.

5. Conclusion

In this paper, we present our studies of pulsars in the core-collapsed GC M15. Our conclusions are as follows:

1. Observations of M15 have been conducted with FAST since 2018, resulting in re-detection of all nine previously known pulsars and discovery of M15J, K, and L.
2. Updated timing solutions for M15A, B, D, E, and H are consistent with previous results (Anderson 1993), while the timing results for M15F show a smaller P_1 .
3. M15C, the double neutron star binary system, was detectable by FAST until December 20, 2022. Its flux has continued decreasing, likely due to precession. Consistent with 2016 results, its pulse profile remains highly linearly polarized in the December 14, 2019 observation. As it disappears from FAST data, it may become possible to receive signals from the companion.
4. M15I was detected one more time on December 14, 2022, and should be a binary in a wide orbit.
5. The newly discovered pulsar M15J is an isolated pulsar with a spin period of 11.84 ms and a DM value of 66.68 pc cm^{-3} .
6. As two long-period pulsars, M15K and L have spin periods of 1.98 s and 3.61 s. M15L is now the longest-spinning-period pulsar known in any

GC. Due to RFIs, obtaining their phase-connected timing solutions is challenging. Their spin frequency derivatives could be key to determining whether they are recycled.

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