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Full Text

Preamble

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Polarization Profiles of Globular Cluster Pulsars from FAST. I. 25 Profiles from Previously Known Pulsars

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Abstract

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

1. Introduction

Pulsars are among the most highly polarized astrophysical sources in the universe (Lyne & Smith 1968). Their polarization properties and profile shapes are closely tied to radiation mechanisms and magnetic field structures. The rotation vector model (RVM; Radhakrishnan & Cooke 1969) provides a theoretical framework for interpreting polarization position angle (PA) variations across pulse phases, particularly for slow pulsars with spin periods exceeding 30 ms. This model, grounded in the geometry of the pulsar's magnetic field and its orientation relative to the emission beam, offers critical insights into emission mechanisms and magnetic field structure. Expanding upon this, the core and cone model (Lyne & Manchester 1988) explains observed polarization and intensity profiles in terms of core and conal emission components within the pulsar's radio beam. Furthermore, the patchy beam model (Karastergiou & Johnston 2007) explores the relationship between radial emission height and resulting pulse shape, offering insights into the complex structure of pulsar emission regions.

Rotation Measure (RM), derived from polarization measurements, describes the change in polarization angle as radio waves propagate through the interstellar medium, making pulsars valuable tracers for studying Galactic magnetism along the line of sight (Manchester 1974). Current understanding of the Galactic magnetic field structure has been shaped by observations of both slow pulsars and millisecond pulsars (MSPs) distributed along the Galactic plane (GP) and halo. Early work by Manchester (1974) pioneered Galactic magnetic field mapping using RMs from 19 pulsars. Subsequent studies, such as Ng et al. (2020) utilizing RMs from 80 pulsars, demonstrated that line-of-sight magnetic field strengths align with estimated average Galactic magnetic field strength. Most recently, the MeerKAT Thousand-Pulsar-Array (TPA) project has significantly advanced this field, providing RM measurements for 1097 pulsars (Oswald et al. 2025). These studies support the hypothesis that the large-scale Galactic magnetic field exhibits a bisymmetric spiral structure that closely traces the Galactic spiral arms.

These investigations have primarily targeted pulsars within the GP, largely excluding globular cluster (GC) pulsars, which are distributed primarily in the halo of our galaxy. Since the discovery of the first GC pulsar, J1824-2452A, by Lyne et al. (1987), over 340 pulsars have been reported in 45 GCs. A polarization census of GC pulsars offers a powerful probe for investigating the formation and evolution of magnetic field structures within GCs and the magnetic field in the halo surrounding the Galaxy (e.g., Ferrière & Terral 2014).

Polarimetric studies of pulsars in 47 Tucanae (NGC 104) have yielded particularly compelling results. Abbate et al. (2020) demonstrated characteristic bending of the Galactic magnetic field induced by the intracluster medium, and Abbate et al. (2022) subsequently identified clear signatures of small-scale magnetic turbulence within the cluster. Beyond 47 Tucanae, comprehensive polarimetric surveys have extended to additional globular clusters in the southern celestial hemisphere. Notable examples include detailed polarization studies of pulsars in Terzan 5, which reveal that the Galactic magnetic field varies at sub-parsec scales (Martsen et al. 2022). In contrast to GCs in the southern sky, systematic polarimetric studies of northern GC pulsars remain scarce, primarily due to their intrinsically faint emission and limited observational sensitivity. This observational gap underscores the critical need for high-sensitivity polarimetric campaigns, now uniquely enabled by large telescopes like FAST and SKA, to precisely characterize the polarization properties of these elusive pulsar populations.

Furthermore, pulsars residing in GCs often experience unique evolutionary processes due to the highly dynamic and dense environments within GCs, including frequent stellar collisions and gravitational interactions (Rappaport et al. 1989). This raises an important question: do pulsars in GCs exhibit polarization properties similar to those outside GCs? Current understanding remains insufficient to conclusively address this question, highlighting the need for further investigation into the polarization characteristics of GC pulsars.

The advent of the Five-hundred-meter Aperture Spherical radio Telescope (FAST; Nan et al. 2011) has significantly improved the sensitivity of pulsar observations, enabling more precise polarization measurements. Studies of single-pulse polarization of PSR B1929+10 have facilitated analysis of periodic modulation (Kou et al. 2021), demonstrating FAST's exceptional sensitivity. Additional studies have included polarization measurements for the Chinese pulsar timing array (Xu et al. 2025) and a survey of 682 pulsars (Wang et al. 2023). FAST has also advanced studies of GC pulsars—among 93 pulsars discovered in 17 GCs within the FAST sky, more than two-thirds were discovered by FAST. Timing solutions have been obtained for over 70 pulsars, including recent reports in NGC 6517 (Yin et al. 2024) and M3 (Li et al. 2024). However, only 11 polarization profiles of these 93 pulsars have been measured to date (e.g., Pan et al. 2023; Wang et al. 2023).

Here, we present polarization profile measurements of 25 pulsars in GCs, including 15 measured for the first time, as our initial results from ongoing timing and monitoring of GC pulsars with FAST. All 25 pulsars were discovered before FAST. Our work provides valuable samples for studying pulsar magnetic field structures, emission mechanisms, and magnetic field properties of GCs. Observations and data acquisition are described in Section 2, data reduction in Section 3, results and discussion in Section 4, and conclusions in Section 5.

2. Observations and Data Acquisition

In the FAST sky, 27 GC pulsars were discovered before FAST construction was completed. These pulsars have undergone long-term timing measurements, and 90% exhibit signal-to-noise ratios (S/N) greater than 10 with our data sets, enabling us to obtain their polarization profiles and precise measurements.

As our first phase of work, we processed data for 25 pulsars from eight GCs: M53 (M53A), M3 (M3A, B, and D), M5 (M5A–E), NGC 6517 (NGC 6517A–D), NGC 6539 (NGC 6739A), NGC 6760 (NGC 6760A and B), M71 (M71A), and M15 (M15A–H). Two candidate sources, M3C and NGC 6749B, were excluded as they were only detected in single epochs and could not be confirmed as genuine pulsars through follow-up observations (e.g., Li et al. 2024).

The data were observed using FAST's 19-beam receiver, covering a frequency range of 1–1.5 GHz. Signals were channelized and digitized using a Reconfigurable Open Architecture Computing Hardware (ROACH) unit developed by the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) group. The data were subsequently packetized and stored in search mode PSRFITS format including four polarizations (AA, BB, AB, BA). The channel bandwidth and sampling time were 122 kHz and 49.152 s, respectively. Detailed information about the FAST receiver system, including system temperature and sky coverage, can be found in Jiang et al. (2020). At the beginning of each observation, a 1-minute noise diode signal was injected with a period of 0.2 s. The integration time for each observation was determined by the declination of the GCs. We observed each GC for as long as possible to achieve higher S/N. Source and observation details are provided in .

3. Data Reduction

3.1. Polarization Calibration

Signals from both the noise diode and pulsars were folded into sub-integrations using the software package DSPSR (van Straten & Bailes 2011), with sub-integration lengths of 60 s. The number of phase bins for the search pulse is 128. For most of these 25 pulsars, the ephemerides obtained from either PSRCAT (Manchester et al. 2005) or publications were accurate enough for our FAST data. However, NGC 6760A exhibited a shift in its spin period, so we used the PDMP routine from PSRCHIVE to search for the spin period.

Since the effective bandwidth of the 19-beam receiver is approximately 1.05–1.45 GHz, we removed the bands of 1.00–1.05 and 1.45–1.50 GHz using the PAZI routine of PSRCHIVE (Hotan et al. 2004). Additionally, according to known radio frequency interferences (RFIs) at the FAST site (Zhang et al. 2020), the band of 1260–1285 MHz was removed. We also manually removed obvious RFIs in time and frequency domains. To improve S/N in each frequency band, we scrunched the folded data into 256 sub-bands.

We subsequently conducted standard polarization calibration to account for contributions from the telescope and observing system, typically characterized by the Mueller matrix, **M**, as described in Lorimer & Kramer (2005). The matrix components characterize specific instrumental and observational effects: **M**_{PA} accounts for the parallactic angle effect, with FAST's feed fixed relative to the polarization plane; **M**_{CC} represents cross-coupling from the two orthogonal probes of the receiver (with minimal leakage of 0.04% for the 19-beam receiver, making the single-axis model accurate to within this level; Ching et al. 2022); and **M**_{AMP} accounts for gain and phase variations introduced by differences in amplifier chains. Polarization calibration was performed via the PAC routine in PSRCHIVE.

RM values were calculated for all observations using the RMFIT routine in PSRCHIVE. This method involves iteratively determining the differential position angle (ΔPA) of linear polarization by splitting the data bandwidth into two half-bands, with the relationship ΔPA = $\lambda^2 \times$ RM. We calculated ionospheric contributions to RM using IONFR, a code that estimates ionospheric Faraday depth by incorporating publicly available global total electron content (TEC) maps and the most recent geomagnetic field model (Sotomayor-Beltran et al. 2013). Both RM values before and after ionospheric correction are provided in .

3.2. Acquisition of Polarization Parameters

To optimize S/N for each pulsar, we used the PAM routine within PSRCHIVE to integrate data in both time and frequency domains, generating high-quality mean pulse profiles. Polarization parameters were derived following the procedure detailed in Wang et al. (2023). From each averaged profile, we applied the PDV routine in PSRCHIVE to obtain Stokes parameters I, Q, U, and V. The on-pulse region was defined as the range where intensities exceed three times the standard deviation of baseline noise (3σ). Linear (L_{on}) and circular (V_{on}) polarization for on-pulse bins were calculated following standard procedures.

The measured linear polarization, L, is defined as $L^2 = Q^2 + U^2$. Uncertainties σQ, σU, and σV *correspond to RMS values of Q, U, and V in the off-pulse region, respectively. Polarization ratios—comprising linear polarization ratio, circular polarization ratio, and absolute circular polarization ratio—were computed as* *ΣL*{on}/ΣI, ΣV*{on}/ΣI, and Σ/V*{on}|/ΣI. Uncertainties were calculated following equations detailed in Wang et al. (2023), where N_{on} represents the number of bins within the on-pulse region.

We also applied the PDV routine to measure pulse widths at 50% and 10% of peak intensity (W50 and W10). Following Kijak & Gil (1997), uncertainties in pulse widths are given by 2t_b/H, where t_b represents the time resolution of phase bins and H is a scaling factor (H = 0.5 for W50, H = 0.1 for W10). Position angles (PAs) were calculated via PA = ½ arctan(U/Q). PA uncertainties (σ_{PA}) were determined through standard error propagation, retaining only PAs with confidence levels greater than 3σ. All polarization parameters, uncertainties, and pulse widths are summarized in .

4. Results and Discussion

4.1. Pulse Width

We compared pulse width distributions (W10 and W50) for our 25 GC pulsars with those of MSPs in the GP from Wang et al. (2023). As shown in [Figure 1: see original paper], both populations exhibit similar distributions for W10 and W50. Additionally, we examined relationships between W10/W50 and pulsar spin periods for GC pulsars and GP MSPs. Power-law fits yielded indices of −0.268 for W10 and −0.330 for W50. For comparison, Karastergiou et al. (2024)

reported a power-law index of −0.308 for the W10–period relationship based on a sample including both MSPs and slow pulsars observed with MeerKAT. Our results are consistent with their findings.

4.2. Profiles and Polarization

Polarization profiles for the 25 GC pulsars are presented in [Figure 2: see original paper], with corresponding parameters summarized in , including fractions of linear polarization, circular polarization, absolute circular polarization, W10, W50, and RM values. Ten of these were previously measured by Wang et al. (2023), and our results are consistent with theirs.

Notably, M15C is the only pulsar in our sample residing in a double neutron star system. It exhibits a relatively long spin period (30.5 ms) and is characterized by a single, narrow pulse in its mean profile. The polarization profile from our 7200 s observation on 2022 April 28 shows S/N = 4, significantly lower than the 2019 profile (7320 s observation) reported by Wu et al. (2024). This disparity suggests significant variability, consistent with predictions that M15C's luminosity has been decreasing due to orbital variation (Ridolfi et al. 2017).

M5A, NGC 6539A, and M15E exhibit orthogonal jumps at phase 0.5. M5A shows two linear polarization pulses within a single total intensity pulse. M5E displays a complex profile, with linear polarization ratio in the third component reaching nearly 100%. Despite modest total intensity S/N = 10.6, M15H exhibits 37% absolute circular polarization—the highest in our sample. M53A and NGC 6760A also show high circular polarization ratios of −21% and 19%, respectively. Among our 25 GC pulsars, M5C, M5D, and M5E are the only three exhibiting inter-pulse emission, commonly attributed to radiation from the pulsar's opposite magnetic pole.

Given that M5C is an eclipsing black widow system, we measured polarization profiles across different orbital phases using 5-minute integrations. However, we observed no significant polarization variations, in contrast to the behavior reported for black widow PSR J1720–0533 (Wang et al. 2021).

4.3. Statistical Analysis

Pulsars M53A, M3A, M3B, M3D, and NGC 6760B exhibit significant S-shaped PA distributions that can be well-modeled using the RVM. In contrast, over 50% of slow pulsars display S-shaped PA variations consistent with RVM (Johnston et al. 2023). A similar proportion was reported by Karastergiou et al. (2024) for MSPs in the GP based on MeerKAT observations. This discrepancy may underscore potential differences in PA distributions between pulsars in GCs and those in the GP, though we emphasize that these differences could be due to our small GC pulsar sample; more sensitive observations of a larger GC pulsar sample are needed.

The average linear, circular, and absolute circular polarization ratios for our 25

GC pulsars are 20%, −1%, and 11%, respectively. Oswald et al. (2023) reported average fractions of 28%, 5%, and 32% for linear, circular, and absolute circular polarization, respectively, based on 271 primarily slow pulsars in the GP observed with Parkes at ~1400 MHz. Our circular and absolute circular polarization fractions are significantly lower, possibly reflecting intrinsic differences between pulsars in GCs and the GP, though we again emphasize that our small sample size may contribute to these differences.

[Figure 3: see original paper] shows histograms and cumulative distributions of polarization ratios for slow pulsars, GC isolated pulsars, and GC binary pulsars. Although GC pulsar evolutionary processes are influenced by internal GC dynamics, differing from MSP evolution in the Galactic disk, their polarization ratio distributions appear consistent. The distribution for GC isolated pulsars appears slightly different, but we attribute this primarily to our limited sample size (25 pulsars). Future observations of more GC pulsars will test this hypothesis.

RM values and ionospheric-corrected RM values are listed in . Pulsars within the same GC show similar RMs. For example, RMs for M15 pulsars range from −70(2) to −76(1) rad m^{-3}. Pulsars in GCs such as M53 and M3 show low absolute RM values (1–16 rad m^{-3}). M71A exhibits the largest absolute RM value at 481 rad m^{-3}. The distribution of GCs in Galactic coordinates is shown in [Figure 4: see original paper], with RM values color-coded. GCs farther from the GP (M53 and M3) show lower RMs, whereas those closer to the GP (M71 and NGC 6517) show relatively larger RMs, consistent with the Galactic RM distribution reported by Hutschenreuter et al. (2022). Future work will involve measurements of more GC pulsars.

5. Conclusions

We measured polarization profiles for 25 pulsars in GCs with FAST, with 15 profiles measured for the first time. The diverse polarization profiles reveal complex structures and emission patterns. Power-law indices for W10 and W50 versus period for MSPs in GCs and the GP are −0.268 and −0.330, respectively, consistent with normal pulsars. Only 20% of our sample (M3A, M3B, M3D, M53A, and NGC 6760A) exhibit characteristic S-shaped PA curves, significantly fewer than in the normal pulsar population (Johnston et al. 2023).

Linear, circular, and absolute circular polarization ratios were measured for each pulsar. M53A shows the highest linear polarization ratio (56%), while M15H shows the highest absolute circular polarization ratio (37%). Average circular (−1%) and absolute circular (11%) polarization fractions for these GC pulsars are lower than for normal pulsars measured with Parkes (5% and 32%; Oswald et al. 2023). However, the polarization ratio distributions are consistent with those of normal pulsars from Wang et al. (2023), indicating that the high stellar density environment in GCs may not drastically affect MSP beam evolution.

Ionospheric-corrected RM values were measured for each GC pulsar. Pulsars within the same GC exhibit similar RMs. GCs closer to the GP tend to have larger RMs (e.g., M71 and NGC 6517), consistent with previous studies (Hutschenreuter et al. 2022).

Our study presents polarization profiles for 25 pulsars, representing 26% of all 97 known GC pulsars in the FAST sky. Additional ongoing work includes studies of M2 (B. Li et al. 2025, in preparation), M13 (L. Wang et al. 2025, in preparation), M14 (K. Liu et al. 2025, in preparation), and NGC 6749 (P. C. C. Freire et al. 2025, in preparation). More GC pulsars still require public timing solutions (e.g., M92B), or have DMs too high for L-band FAST observations (e.g., some pulsars in Glimpse C01). Polarization studies of these pulsars will be reported in our next paper.

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Note: Figure translations are in progress. See original paper for figures.