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Full Text

Preamble

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Pulsar Discovery Prospect of FASTA

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Abstract

The Five-hundred-meter Aperture Spherical radio Telescope (FAST) has discovered more than 650 new pulsars, accounting for 20% of the known Galactic pulsar population. In this paper, we estimate the prospects for a pulsar survey with a planned radio telescope array—the FAST Array (FASTA)—consisting of six "FAST-type" telescopes. Such a sensitive radio telescope array would be a powerful instrument for probing the pulsar population deep within our Galaxy as well as in nearby galaxies. We simulate FASTA pulsar discovery prospects using different Galactic pulsar population models and instrumental parameter combinations. We find that FASTA could detect tens of thousands of canonical pulsars and well over a thousand millisecond pulsars. We also estimate the potential yield if FASTA is used to search for pulsars in the nearby spiral galaxy M31, finding that it would likely discover around a hundred new radio pulsars.

Key words: stars: neutron — stars: pulsars: general — telescopes

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1 Introduction

Pulsars are rapidly rotating neutron stars. To date, astronomers have discovered more than 3300 radio pulsars[1] (Manchester et al. 2005). Studies of pulsars have led to numerous important advances at the frontiers of astrophysics and physics, including theories of gravitation, stellar evolution, the matter distribution in our Galaxy, and the equation of state for ultra-dense matter. The extraordinary impact and prominent scientific applications of pulsar research have made it one of the key science projects for nearly every new generation of advanced radio telescopes.

There are two main types of radio pulsars: canonical pulsars (CPs) and millisecond pulsars (MSPs). CPs are generally thought to be the remaining cores after supernova explosions of progenitor massive stars (10 to 30 M). The radio emission of CPs is powered by the pulsar's rotation energy, so as CPs continue emitting radio signals, they gradually spin down as they age. For example, one of the youngest pulsars, the Crab pulsar, has a spin period of 33 ms, while old CPs can have spin periods as long as tens of seconds (e.g., Tan et al. 2018; Caleb et al. 2022). MSPs (Backer et al. 1982) are old, rapidly rotating neutron stars that have been "spun up" or "recycled" through the accretion of matter from a companion star in a close binary system, with typical spin periods in the range of 1–30 milliseconds.

Pulsar surveys and the resulting discoveries are crucial resources for building our understanding of the Galactic pulsar population. For example, the Parkes Multi-beam Pulsar Survey (PMPS; Manchester et al. 2001) initially discovered 800 pulsars (Manchester et al. 2001; Morris et al. 2002; Kramer et al. 2003; Hobbs et al. 2004; Faulkner et al. 2004) and 1038 after many passes of searches (e.g., Eatough et al. 2013; Knispel et al. 2013; Bates et al. 2013), providing a large sample of pulsar detections with uniform instrument settings. Using this sample, astronomers established basic models of the Galactic pulsar population, including their spatial, period, and luminosity distributions (Lorimer et al. 2006; Faucher-Giguère & Kaspi 2006). Lorimer et al. (2006) suggest there are $(3.0 \pm 0.1) \times 10^4$ canonical pulsars beaming toward Earth with luminosities above 0.1 mJy kpc^2, while Faucher-Giguère & Kaspi (2006) predict there are $(1.2 \pm 0.2) \times 10^5$ detectable canonical pulsars in the Galaxy. However, subsequent pulsar surveys using other instruments such as Arecibo PALFA (Cordes et al. 2006), Green Bank North Celestial Cap pulsar survey (GBNCC; Stovall et al. 2014), and FAST Galactic Plane Pulsar Snapshot survey (GPPS; Han et al. 2021) suggest that the population extrapolated from PMPS might be overestimated, possibly because PMPS concentrates on the Galactic Plane which has a high density of pulsars (Swiggum et al. 2014; McEwen et al. 2020; Han et al. 2021).

In the early 1990s, as one of the early concepts for the Square Kilometre Array (SKA), Chinese radio astronomers proposed building 30 large spherical reflectors in Guizhou, southwest China, each with a diameter of roughly 200–300 m. This design was referred to as the Kilometer-square Area Radio Synthesis Telescope (KARST; Peng & Nan 1998; Nan et al. 2002). Although it was not selected as the final design for the SKA, it led to the birth of the Five-hundred-meter Aperture Spherical Telescope (FAST; Nan 2006; Nan et al. 2011; Li et al. 2018), currently the most sensitive single-dish radio telescope. Since its commissioning, FAST has produced numerous notable scientific outcomes in pulsar studies (e.g., Qian et al. 2020; Cameron et al. 2020; Han et al. 2021, etc.).

Today, the plan to build a large spherical reflector array has once again been put on the agenda after FAST's successful delivery and operation. Chinese radio astronomers are considering extending FAST with several similar spherical telescopes to form a telescope array—the FAST Array (FASTA). The initial phase of FASTA will consist of three spherical reflectors, each similar to the existing one (referred to as Phase-I FASTA or FASTA3 hereafter). The second phase will add another three reflectors, bringing the total to six (referred to as Phase-II FASTA or FASTA6 hereafter). FASTA will perform both coherent and incoherent observations of pulsars, providing substantially higher gain than any current system and enabling the discovery of a large number of potentially observable pulsars in the northern sky. In terms of sky coverage, FASTA and SKA will complement each other.

In this work, we estimate the prospects for pulsar discoveries with FASTA in the sky area with Galactic latitude |b| < 10°, considering both FASTA3 and FASTA6, as well as data analysis using incoherent summing or coherent beamforming methods. Such a pulsar survey will help us understand the Galactic pulsar population, especially at the low luminosity end. In Section 2, we describe various pulsar population models and survey parameters used in the simulations. In Section 3, we present population synthesis results and FAST/FASTA detection prospects predicted by different models. In Section 4, we summarize our conclusions and discuss future work.

2.1 The Galactic Pulsar Population Models

There are two general types of models for the Galactic pulsar population: "snapshot" type models and "evolutionary" type models. Within these two types, there are sub-group models that apply different population distribution parameters.

A typical "snapshot" model was built by Lorimer et al. (2006), hereafter L06. They used results from the Parkes Multi-beam Pulsar Survey (PMPS; Manchester et al. 2001) to derive the optimal Galactic pulsar distribution in period (P), luminosity (L), Galactocentric radial distance (R), and Galactic scale-height (z). L06 treated these distributions independently and assumed that all canonical pulsars follow the same fixed distribution regardless of their age. The "snapshot" type model is a simplified approach, since those distributions actually evolve with pulsar age. For example, younger pulsars are on average brighter and spin faster, and they are also located closer to the Galactic plane (associated with their progenitor stars) than older pulsars. Thus, pulsars in different age groups should have different distributions of period, luminosity, and scale height.

The L06 model can be regarded as a "snapshot" of an evolving population. Despite the fact that "snapshot" type models rely on fewer assumptions and have fewer degrees of freedom—making them easier to evaluate—it is still worthwhile to develop models that take evolution into account. Faucher-Giguère & Kaspi (2006), hereafter FK06, presented a typical approach to constructing an "evolutionary" type model. For comparison, FK06 additionally provided an "unevolved" luminosity distribution which is one of the distribution models we applied in this work. Apart from FK06, many efforts have also been made toward optimizing and applying evolutionary models in pulsar population synthesis, e.g., Contopoulos & Spitkovsky (2006); Ridley & Lorimer (2010); Bates et al. (2014); Rajwade et al. (2017); Huang & Wang (2020).

2.1.1 Snapshot Type of Models The "snapshot" type of models typically contains the following input parameters: (1) period distribution; (2) luminosity distribution; (3) radial density R distribution; (4) scale height z. The most widely accepted period distribution for "snapshot" type canonical pulsar population models is the lognormal distribution with a mean of $\log_{10}(\mathrm{P/ms})$ = 2.7 and a standard deviation $\sigma[\log_{10}(\mathrm{P/ms})] = 0.34$, suggested by L06 based on modeling the PMPS result using PSRPOP^2. In this work, we apply this L06 lognormal distribution for our "snapshot" type simulation of the canonical pulsar population.

For the luminosity distribution of CPs, instead of using the simple power law distribution (with a low-frequency cut-off) suggested by L06, we adopt the FK06 luminosity distribution. FK06 suggested a lognormal luminosity distribution to avoid the hard cut-off, with mean and standard deviation of $\log_{10}\mathrm{L}$ = −1.1 and $\sigma[\log_{10}\mathrm{L}] = 0.9$ based on modeling the PMPS result.

For the beaming fraction of CPs in "snapshot" type models, Emmering & Chevalier (1989) provided a simple approach: f(α,) = 2 _{ }^{ } 2π sin d = cos − cos , where α is the inclination angle, is the beam radius, = max(0, α −) and = min(π/2, α +). One empirical way to estimate the beam radius , provided by Gould (1994), is to treat as a function of the pulsar rotation period: (P) = 5.4°$(\mathrm{P/s})^{-1\ 2}$, while α is a uniformly chosen random value between (0°, 90°). We will further discuss the effects of different beaming fraction models in Section 2.2 where we describe the role of calibration surveys for our simulation.

For the radial density distribution of CPs, L06 suggested a gamma distribution (applying the NE2001 electron density model): f(R) = A(R/R) exp[−C(R − R)/R], where A = 41, B = 1.9, and C = 5.0. This relation implies that the pulsar density is zero at R = 0, which is inconsistent with our understanding of galaxy structure. To avoid this discrepancy and obtain nonzero density at R = 0, Yusifov & Kucuk (2004), hereafter YK04, included an additional parameter R_1 and used a shifted Gamma function, replacing R and R by X = R + R_1 and X = R + R_1. With this model, YK04 obtained the best-fit result with parameters A = 37.6, B = 1.64, C = 4.01, and R_1 = 0.55 kpc. In this work, we compare FAST and FASTA simulated pulsar survey detection prospects using both L06 and YK04 radial distributions.

For the scale height (z) distribution of CPs, L06 found an optimal scale height of 180 pc using the NE2001 electron density model. This number is significantly lower than the expected value of 300–350 pc from independent studies of the local CP population (e.g., Mdzinarishvili & Melikidze 2004). When applying the "smooth" electron density distribution model (Lyne et al. 1985), the optimal scale height of 330 pc is consistent with the observed local CP population (Lorimer et al. 2006), which is the value we use in this work.

To describe the Galactic MSP population with "snapshot" type models, the approaches are similar to the aforementioned CP cases, though the modeled parameters for MSPs are limited by the relatively small sample size of currently known MSPs. For the period distribution of MSPs, Lorimer et al. (2015), hereafter L15, suggested a lognormal distribution with mean $\log_{10}(\mathrm{P/ms})$ = 0.65

and standard deviation $\sigma[\log_{10}(\mathrm{P/ms})] = 0.25$. For the luminosity distribution of MSPs, following Smits et al. (2009), we adopt the same luminosity distribution as canonical pulsars. The beaming fraction of MSPs we use is f(α,) = cos − cos , where = max(0, α −) and = min(π/2, α +). As suggested by Kramer et al. (1998), the beam radius is a constant value for MSPs. Here we apply = 31°, which corresponds to (P) = 5.4°(P/s)$^{-1\ 2}$ at P = 30 ms. We use 500 pc as the scale height for the Galactic MSP population as suggested by Smits et al. (2009). For the R distribution, we apply both the L06 and YK04 radial distributions.

The input model parameters we applied to model the Galactic CP and MSP populations using the "snapshot" type models are summarized in Table 1 .

2.1.2 Evolutionary Type of Models The "evolutionary" type of models also use parameters to describe the Galactic pulsar population: (1) period distribution; (2) luminosity distribution; (3) radial density R distribution; (4) scale height z. The main difference between evolutionary and "snapshot" type models is that for evolutionary models, these pulsar parameters are all described as functions of pulsar age. In this work, we apply 1 Gyr for the maximum age of the canonical pulsar population and 5 Gyr for the maximum age of the MSP population, based on the current distribution of observational pulsar characteristic age (Rajwade et al. 2017).

The period distribution for evolutionary type models is described by: (1) the initial (birth) spin period distribution; (2) the pulsar spin-down model; (3) the pulsar age. FK06 developed a typical "evolutionary" model and found the optimal initial period distribution for canonical pulsars follows a normal distribution with mean P_0 = 300 ms. The observed pulsar rotation period at present can be evaluated using the initial period and the age of the pulsar. The spin-down model depends on the braking index n and the magnetic field strength B. In this work, we adopt the FK06 spin-down model and initial period distribution for canonical pulsars, noting that other "evolutionary" type models may employ different spin-down models and initial period distributions (e.g., Contopoulos & Spitkovsky 2006).

The luminosity distribution is also age-dependent. Since the radiated energy of pulsars is thought to originate from the loss of rotational energy, the luminosity distribution can be modeled as a function of period (P, in units of s) and period derivative (P, in units of 10^{-15} s s^{-1}). It is commonly assumed to be a power-law: L = γP P , where the values of a, b, and γ may vary among different models (e.g., Lyne et al. 1975; Vivekanand & Narayan 1981; Faucher-Giguère & Kaspi 2006; Rajwade et al. 2017). The original "evolutionary" model, FK06, found optimal values of a = −1.5, b = 0.5, and γ = 0.18 based on the PMPS pulsar sample, which we follow in this work.

As a comparison, we also test the luminosity distribution derived from the fan-beam model (Wang et al. 2014; Huang & Wang 2020). The luminosity function of the fan-beam model depends not only on P and P but also on emission geometry in the term $L = (W/P)^{-4}P\quad{}^{2\ -6}$, where W /P is the duty cycle and is the radial distance between the magnetic pole and the emission direction accounting for the pulse peak in units of degrees. Following Huang & Wang (2020), we adopt $= 10^{2\cdot75}$, W /P = 5%, and q = 1.25 in our simulation. Unlike the conal beam case, in the fan-beam model the impact angle between the line of sight (LOS) and the magnetic axis may extend to 90°, meaning our LOS would sweep across at least one emission beam from either pole, so the beaming fraction is always 1. The default evolutionary model applied an empirical beaming fraction given by Tauris & Manchester (1998): $f(P) = 0.09(\log P - 1)^2 + 0.03$, which is a function of pulsar period.

The current position of each simulated pulsar in our Galaxy is determined by its initial birth position (following the z and R birth distribution) and its birth velocity. According to FK06, the initial birth z distribution follows an exponential function with a relatively small scale height of 50 pc, consistent with the distribution of supernovae where massive stars end their lives. For the R distribution, FK06 applied the YK04 radial distribution as the birth radial distribution. In this work, we have tried both the L06 and YK04 radial distributions as the birth radial distribution. For the pulsar birth velocity distribution, we assume a Gaussian distribution centered on 0 km/s with a width of 265 km/s for the birth velocity in each of the x, y, and z directions, following Rajwade et al. (2017). The pulsar position then evolves from its initial position according to its velocity and age, using the model of the Galaxy's gravitational potential (Carlberg & Innanen 1987; Kuijken & Gilmore 1989).

For evolutionary MSP population models, we adopt the L15 distribution for their initial birth period, which is a lognormal distribution with average $\ln(P/\mathrm{ms}) = 1.5$ and standard deviation $\sigma[\ln(P/\mathrm{ms})] = 0.58$. We have tried two types of luminosity distribution: (1) the FK06 fixed lognormal distribution with $\log_{10}L = -1.1$, $\sigma[\log_{10}L] = 0.9$; (2) the FK06 evolved power-law distribution model, $L = \gamma P\ P$, where $a = -1.4$, $b = 0.5$, and $\gamma = 0.009$ (Rajwade et al. 2017). The initial birth z distribution we adopt is the same as the evolutionary model for canonical pulsars: an exponential function with a scale height of 50 pc (FK06). For the R distribution, similar to our CP simulation, we have tested both the L06 and YK04 radial distributions as the birth radial distribution. For the pulsar birth velocity distribution, following Rajwade et al. (2017), we assume a Gaussian distribution centered on 0 km/s with a width of 80 km/s for the birth velocity in each of the x, y, and z directions.

The input model parameters we applied to model the Galactic CP and MSP populations using the evolutionary type models are summarized in Table 2 .

2.2 FAST and FASTA Pulsar Survey Simulations

In this work, we used PsrPopPy to perform the simulation. The simulation process of PsrPopPy contains two main steps: (1) generate synthetic pulsar populations of the Milky Way Galaxy; (2) perform simulated surveys on the synthetic pulsar population using corresponding survey parameters.

When PsrPopPy generates synthetic pulsar populations, the overall idea of how it controls the total number is reversed from how we intuitively think about this question. It does not first assume a total Galactic neutron star population with a beaming fraction to get the population of pulsars beaming toward us, and then estimate how many pulsars we can detect. Instead, it uses the real numbers of discoveries from existing pulsar surveys and the corresponding survey parameters to calibrate the total number of the synthesized pulsar population. The calibration surveys need to have good completeness. A commonly used calibration pulsar survey is PMPS, which discovered over a thousand pulsars in a uniform setup. For example, Rajwade et al. (2017) applied the same detection threshold and observing ranges of PMPS to their synthesized pulsar population with a pulsar detection sample size of 1065. In this case, PsrPopPy keeps generating new simulated pulsars until the generated population contains exactly 1065 pulsars detectable by the same setup as PMPS. All pulsars generated in this process, if they are beaming toward us, are stored as the whole synthetic pulsar population for further analysis, regardless of whether they are detectable by PMPS. Simulated pulsars which are not beaming toward us are all discarded. In this way, the total population mostly depends on the calibration surveys, while the beaming fraction is not a key dominant factor that directly affects the simulated detection number of pulsars. It affects the simulation result in a relatively secondary way due to its relation with other characteristics of pulsars, namely the pulsar rotation period P, since longer period pulsars have smaller beaming fractions, effectively shifting the period distribution toward shorter P.

PsrPopPy can adopt multiple calibration surveys together when generating synthetic pulsar populations. Here, following Huang & Wang (2020), we adopt a combination of PMPS together with two Swinburne pulsar surveys (SWIL, Edwards et al. 2001; and SWHL, Jacoby et al. 2007) as calibration surveys, providing a sample of 1214 canonical pulsars (Huang & Wang 2020) and 48 MSPs (Lorimer et al. 2015).

In the second step of the simulation, after generating a realization of the Galactic pulsar population (for canonical pulsars or MSPs, respectively), we simulate pulsar surveys using FAST and FASTA instrument parameters. The FAST survey parameters (including gain, system temperature, bandwidth, center frequency, time and frequency resolution, etc.) are set according to FAST performance and survey description papers (e.g., Li et al. 2018; Jiang et al. 2019, 2020; Han et al. 2021). For FASTA surveys, we apply the same survey parameters as the FAST Galactic plane survey (Han et al. 2021). In the ideal coherent beamforming process, an array consisting of N antennas would have sensitivity N times better ($G = N \times G$). In practice, we consider a phasing efficiency parameter of 0.94 (Chen et al. 2021) when estimating the gain value ($G = 0.94 \times N \times G$). The gain value for FAST is 16 K/Jy, thus the estimated gain for FASTA3 and FASTA6 are 45 K/Jy and 90 K/Jy, respectively.

For incoherent sum cases, the gain of an array consisting of N antennas would be $G = \sqrt{N} \times G$. Therefore, the incoherent gain for FASTA3 and FASTA6 are 28 K/Jy and 40 K/Jy. We note that the sensitivity of FAST drops drastically when the zenith angle (ZA) is greater than 26.4°. According to Jiang et al. (2019), the gain of FAST is 16 K/Jy when $ZA < 26.4°$, while it decreases as a linear function of ZA and becomes 11 K/Jy when $ZA = 40°$. We have taken this effect into account in our simulation for both FAST and FASTA.

All survey parameters we adopted for FAST and FASTA are summarized in Table 3 . We use FASTA3 and FASTA6 to represent the coherent beam-forming cases, while for incoherent summing cases we use FASTA3-i and FASTA6-i, respectively.

3.1 Detection Prospects of Galactic CPs/MSPs with FASTA

With each set of synthetic pulsar population model parameters summarized in Table 1 and Table 2, we simulate 20 realizations of pulsar populations. For each realization, we perform 20 survey simulations for each set of survey parameters listed in Table 3. Therefore, for each parameter combination, we run 400 simulations in total to obtain the detection prospects for either canonical pulsars or MSPs. The results are summarized in Table 4 and Table 5 .

For canonical pulsars that FAST can detect, the predicted numbers from different models range from 4200 to 8460, while for the most sensitive FASTA6 coherent beamform mode, the predicted detectable CPs range from 8380 to 17330. These predictions all include currently known pulsars. Therefore, when considering the number of new CP discoveries, we need to subtract 1000 known Galactic-plane CPs in the sky field of the FAST/FASTA survey. For MSPs, FAST detection prospects from different models range from 520 to 1480, and the number of FASTA6-detectable MSPs ranges from 1140 to 4680. Similar to the CP case, these predictions include known MSPs, and when considering new MSP discoveries, 100 known MSPs in the survey field need to be subtracted.

Figure 1 [Figure 1: see original paper] shows the Galactic distribution of the simulated pulsar population and predicted survey detection in polar coordinates. We choose the predicted results from the current FAST and the most sensitive FASTA6 coherent beamform mode to illustrate. The synthetic pulsar population in this example plot is generated based on snapshot mode with YK04 radial density distribution.

3.2 Detection Prospects of Radio Pulsars in M31 with FASTA

To date, astronomers have not discovered radio pulsars in the nearby galaxy M31. FASTA will have great potential to make the breakthrough discovery of the first pulsar in M31. According to Savino et al. (2022), the distance to M31 is 776 ± 22 kpc. Considering an integration time of 2 hours per pointing (corresponding to a total survey time of 37 hours with 10-min overhead, covering M31 in 17 pointings) and a bandwidth of 400 MHz with dual-polarization observation, FAST will be able to detect pulsars with L-band luminosity greater than 670 mJy kpc^2 at the distance of M31. For FASTA3-i, FASTA6-i, FASTA3, and FASTA6, the corresponding luminosity limits at L-band would be 380, 270, 240, and 120 mJy kpc^2, respectively. We can then estimate the detection prospects for radio pulsars in M31 based on how many pulsars in M31 have luminosities above the detection limit of each configuration, assuming M31 has a similar pulsar population to our Galaxy.

We considered three types of population models: (1) the snapshot model with FK06 lognormal luminosity distribution; (2) the evolutionary model with FK06 luminosity distribution; (3) the evolutionary model with fan-beam luminosity distribution. These models are the same as those used in previous sections for estimating detection prospects of Galactic canonical pulsars, but we did not distinguish between L06 and YK04 radial distributions for M31 pulsar detection prospect estimation.

For the snapshot model with FK06 lognormal luminosity distribution, the corresponding pulsar detection numbers for FAST, FASTA3-i, FASTA6-i, FASTA3, and FASTA6 are 1, 3, 7, 9, and 28, respectively. For the evolutionary model with FK06 luminosity distribution, the corresponding numbers are 12, 29, 47, 60, and 164. For the evolutionary model with fan-beam luminosity distribution, the corresponding numbers are 34, 55, 77, 92, and 188. Although the detection prospects predicted by these three models differ significantly, they all show the same trend as instrument sensitivity increases, especially for FASTA6, indicating a good chance to detect a significant number of radio pulsars in M31.

3.3 Survey Time Estimation

The total observable sky for FAST with Galactic latitude |b| < 10° is 4035 deg^2. If FASTA uses a Phased Array Feed (PAF) with FWHM of 30 , the survey will require 20550 pointings in total. With a planned integration time of 5 minutes, the entire survey will need 1713 observing hours. Including 10 minutes overhead for each pointing, the survey will take 5138 hours total.

Since overhead takes a significant amount of time for each pointing, it is natural to ask whether increasing the observing integration time per pointing would improve the return-cost-rate of the survey in terms of pulsar detection number versus total survey time. To explore this, we run simulations with observing integration times of 10, 15, and 20 minutes along with different combinations of pulsar population model and survey configuration (i.e., different gain) listed in Section 3.1. According to the radiometer equation, telescope sensitivity is proportional to instrument gain and the square-root of integration time. To make comparisons more concise, we convert different integration times to a gain-increment equivalent to 5-min integration time: $G\ q\quad = G \times \surd(t\quad /5\,\mathrm{min})$. The corresponding equivalent gain values are listed in the top panel of Table 6 . We then simulate CP detection numbers as a function of different gain values (ranging from 0.5 to 160) for different population models with 5-min integration time. The results are shown in Figure 2 [Figure 2: see original paper].

Using the snapshot model with L06 radial distribution (blue line in Figure 2) as an example, we list the simulated pulsar detection numbers with different observing integration times and survey configurations in the middle panel of Table 6 . We also convert these numbers to percentages relative to the FAST 5-min integration result (bottom panel of Table 6) to provide a more straightforward view of the detection number increment. Comparing the survey time increment percentage and detection number increment percentage, we find that 5-min integration time remains the most efficient survey setting.

4 Discussion and Conclusion

In this work, we estimated pulsar detection prospects for simulated FAST and FASTA pulsar surveys with Galactic latitude $|b| < 10°$ using various pulsar population models. We tested models from both snapshot and evolutionary types with different combinations of distribution parameters. Our results indicate that FASTA could detect around ten thousand canonical pulsars and well over a thousand millisecond pulsars. Additionally, we estimated the yield of searching for pulsars in the nearby spiral galaxy M31 using FASTA and found it has the potential to discover around a hundred new radio pulsars. We also found that the most efficient observational settings for a Galactic-plane pulsar survey in terms of observing time versus discovery number is to apply 5-min integration time.

We estimated the pulsar detection prospects using both incoherent sum and coherent beam-forming data analysis methods for FASTA. The baseline design of FASTA has not been determined yet, but as a first-order approximation we can consider the maximum baseline of FASTA to be 300 km. Since this baseline is 1000 times longer than the effective diameter of FAST (300 m), we would need to form 10^6 coherent beams to cover the area of one current FAST beam. Therefore, to cover the sky area of the proposed survey, the number of beams needed is on the order of 10^{12}. This would inevitably result in a significant increase in data processing demand, which seems infeasible with current computational instruments and techniques. Nevertheless, we can remain hopeful that this requirement can be met in a few decades since Moore's Law suggests computational capability increases by one order of magnitude every 5–7 years, and there may be other potential technical revolutions in the future. Initially, a pulsar survey with incoherently summed data would be more realistic, and we could first apply coherent beam-forming data for specific sky areas such as M31 or selected globular clusters.

With the high sensitivity of FASTA, it is likely that more pulsars (especially long-period pulsars, intermittent pulsars, and RRATs) could be detected when adopting additional single-pulse searches. According to existing pulsar surveys with large spherical radio telescopes, Deneva et al. (2009) found that single-pulse searches led to 13% extra pulsar discoveries from the Arecibo PALFA survey, Han et al. (2021) found a 14% extra yield from the FAST GPPS survey, while the CRAFTS survey of FAST, as a drift-scan survey with each point source drifting across the 3 beam in 12 s, benefits more from single-pulse searches and has discovered 31% additional pulsars using this method. These findings indicate that there may be an extra 10–20% of detectable pulsars not accounted for in our analysis.

Our limited understanding of the low end of the pulsar radio luminosity function leads to a large range for predicted pulsar yields. The current parameters are mostly derived from the Parkes Multibeam survey pulsar sample (e.g., Yusifov & Kucuk 2004; Lorimer et al. 2006; Faucher-Giguère & Kaspi 2006; Lorimer et al. 2015), and building pulsar population models typically involves calibrating distribution parameters with the PMPS sample (e.g., Rajwade et al. 2017; Huang & Wang 2020). It is therefore not surprising that pulsar detection numbers predicted by different models and distribution parameters converge nicely on PMPS surveys but result in very different outcomes when applying different observing settings like FAST or FASTA, which have significantly higher gain. Thus, the results of how many new weak pulsars can be discovered in FAST and FASTA surveys will provide very useful constraints on pulsar luminosity distribution.

Han et al. (2021) suggested that FAST pulsar surveys will probably finish with fewer new pulsar discoveries than predicted, indicating that current models extrapolated from PMPS might overestimate the undetected Galactic pulsar population. This also means that known pulsars discovered in the PMPS survey constitute a larger proportion of the overall pulsar population than previously expected. If that is the case, possible explanations include: (a) there are fewer pulsars at the low end of the luminosity function than thought; (b) pulsar distances estimated using their DM and the Galactic electron density model are uncertain; (c) scattering smear from the interstellar medium makes it difficult to detect far-away pulsars.

In conclusion, our estimation of the pulsar detection prospects for FASTA based on a variety of models generally converges to a consistent picture. Due to limited knowledge of the real Galactic pulsar population, it is hard to pinpoint the exact number of pulsar detections for the FASTA pulsar survey with a narrow range of uncertainty. We look forward to the outcomes of currently ongoing FAST pulsar surveys and future FASTA pulsar surveys with good completeness, as they will provide significantly better constraints on the Galactic pulsar population and its distribution parameters.

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Footnotes

[1] ATNF Pulsar Database v1.68; www.atnf.csiro.au/research/pulsar/psrcat

[2] A FORTRAN package to carry out Monte Carlo simulation of the Galactic pulsar population developed by Lorimer et al. (2006) http://psrpop.sourceforge.net/

[3] https://github.com/samb8s/PsrPopPy (Bates et al. 2014)

[4] https://github.com/devanshkv/PsrPopPy2

[5] https://www.astropy.org (Astropy Collaboration et al. 2013, 2018)