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ABSTRACT

The recent discovery of a magnetar in the Galactic centre region has allowed Spitler et al. to characterize the interstellar scattering in that direction. They find that the temporal broadening of the pulse profile of the magnetar is substantially less than that predicted by models of the electron density of that region. This raises the question of what the plausible limits for the number of potentially observable pulsars – i.e., the number of pulsars beaming towards the Earth – in the Galactic centre are. In this paper, using reasonable assumptions – namely, (i) the luminosity function of pulsars in the Galactic centre region is the same as that in the field, (ii) the region has had a constant pulsar formation rate, (iii) the spin and luminosity evolution of magnetars and pulsars are similar, and (iv) the scattering in the direction of the Galactic centre magnetar is representative of the entire inner parsec – we show that the potentially observable population of pulsars in the inner parsec has a conservative upper limit of ~ 200, and that it is premature to conclude that the number of pulsars in this region is small. We also show that the observational results so far are consistent with this number and make predictions for future radio pulsar surveys of the Galactic centre.

Key words: Galaxy: centre — stars: neutron — pulsars: general — methods: statistical

1 INTRODUCTION

Discovering radio pulsars in the Galactic centre (GC) has been a long-sought goal, due to the promise it bears in probing the gravitational field of the massive black hole in the region (e.g., Pfahl & Loeb 2004; Liu et al. 2012), and in deciphering the nature of the interstellar medium in its vicinity. Despite several radio surveys (e.g., Kramer et al. 2000; Johnston et al. 2006; Deneva et al. 2009; Deneva 2010; Macquart et al. 2010; Bates et al. 2011; Eatough et al. 2013a; Siemion et al. 2013), no pulsars were found. So far, the only pulsar in the inner parsec of the GC was found to be a ~ 3.76 s magnetar, which was discovered following an X-ray flaring episode in April 2013 (Kennea et al. 2013), and a subsequent periodicity search (Mori et al. 2013). This was later confirmed in the radio as PSR J1745−2900 (Eatough et al. 2013b; Buttu et al. 2013). Kennea et al. (2013), Mori et al. (2013) and Rea et al. (2013) analysed the X-ray absorption of this source, and found that it is consistent with being at a similar distance as Sgr A*. Rea et al. (2013) localised the magnetar to an angular distance of $\sim 2.4''$ from Sgr A*. At the GC distance of 8.25 kpc (Genzel et al. 2010), this corresponds to a minimum distance of ~ 0.1 pc. Interstellar scattering was thought to be a major problem in detecting pulsars in the GC, as models of electron density dictate a scattering timescale of at least 6.3 $\nu_{\rm GHz}^{-4}$ s, but potentially up to 200 times larger (Cordes & Lazio 1997), indicating that observations at higher frequencies are more favourable, with Macquart et al. (2010) suggesting optimal frequencies in the 10–16 GHz range for searches of non-millisecond pulsars. However, recent pulse broadening measurements (Spitler et al. 2013) and angular broadening measurements (Bower et al. 2013) of the GC pulsar have demonstrated that scattering may not be as severe a limitation.

The GC magnetar has the largest dispersion measure ever measured for a pulsar, 1778 ± 3 cm^{-3} pc, and the largest rotation measure ever measured for any object other than Sgr A* itself, -66960 ± 50 rad m^{-2} (Eatough et al. 2013c; Shannon & Johnston 2013). Eatough et al. (2013c) have shown that the large Faraday rotation can be explained by a large magnetic field associated with the plasma within 10 pc of the GC black hole, suggesting a highly complicated and magnetized interstellar medium in the GC region, well suited for scattering electromagnetic radiation. Spitler et al. (2013) measure a pulse broadening timescale of 1.3 ± 0.2 s for J1745−2900 at 1 GHz, which, albeit large, is much less than predicted values. The lack of detections of previous surveys implies either that previous surveys have not been sensitive

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enough, or that the GC tends to produce magnetars. Given that observations of the GC have hitherto detected one magnetar and no normal pulsar[1], in this paper, we attempt to constrain the number of potentially observable pulsars (including magnetars) in the region using recent studies of the pulsar luminosity function and spectral indices. We employ two complementary methods[2] – firstly, a Bayesian parameter estimation approach, and secondly, a Monte Carlo (MC) approach to constrain the pulsar population in the GC.

The organization of this paper is as follows. In §2.1, we describe our Bayesian technique and apply it to a few past surveys of the GC to obtain upper limits on the the number of GC pulsars. In §2.2, we describe our MC approach and use it to constrain the number of GC pulsars. In §3, we discuss our results and implications for future surveys.

2 CONSTRAINING THE GC PULSAR CONTENT

2.1 Bayesian Approach

To quantify the likely size of the pulsar population in the GC region, we treat the GC as a population of pulsars at a common distance from the Earth, $D_{\rm GC}$, and consider a survey of this region at some frequency ν as having some finite probability of detecting a pulsar with flux density S and a radio spectral index α. Here, as usual, we adopt a power-law relationship for the radio spectra (see, e.g., Lorimer et al. 1995) so that $S \propto \nu^{\alpha}$. For a survey with some limiting sensitivity $S_{\rm min}$ at frequency ν, the corresponding limiting pulsar pseudo-luminosity scaled to 1.4 GHz

$$L_{\rm min} = S_{\rm min} \left(\frac{1.4\ {\rm GHz}}{\nu} \right)^{\alpha} D_{\rm GC}^2. \tag{1}$$

This limiting luminosity can be used to compute the detection probability, i.e., the probability of observing a pulsar above this limit, based on a choice of the pulsar luminosity function. Faucher-Giguère & Kaspi (2006) have shown that the luminosity distribution of normal pulsars in the Galactic field is log-normal in form. For the log-normal luminosity function, the detection probability

$$\theta = \frac{1}{2}\, {\rm erfc} \left[\frac{\log L_{\rm min} - \mu}{\sqrt{2}\sigma} \right], \tag{2}$$

where μ and σ are the mean and standard deviation of the log-normal.

Using Bayes' theorem, we can utilize the above detection probability to estimate the number of pulsars in the GC. The joint posterior probability density for the number of non-recycled pulsars in the GC and the spectral index, given n observed non-recycled pulsars,

$$p(N, \alpha | n) \propto p(n | N, \alpha)\ p(N)\ p(\alpha), \tag{3}$$

where $p(n|N, \alpha)$ is the likelihood function, and $p(N)$ and $p(\alpha)$ are the prior probability density functions of N and α, respectively. To account for the fact that we have observed one magnetar in the GC and zero normal pulsars, the observed number of non-recycled pulsars is written as $n = n_{\rm np} + n_{\rm mag}$, where $n_{\rm np} = 0$ is the observed number of normal pulsars and $n_{\rm mag} = 1$ is the observed number of magnetars. The aforementioned Bayesian relation can then be rewritten, and the the likelihood function expanded, as

$$p(N, \alpha | n_{\rm np}, n_{\rm mag}) \propto p(n_{\rm np} | N, \alpha)\ p(n_{\rm mag} | N, \alpha)\ p(N)\ p(\alpha). \tag{4}$$

Here we make the reasonable assumption of statistical independence for $n_{\rm np}$ and $n_{\rm mag}$ given N and α, as the formation scenarios for normal pulsars and magnetars are likely different.

The parameter that we are trying to constrain, namely, the total number of non-recycled pulsars N, can be written in terms of the magnetar fraction f – the ratio of magnetars to normal pulsars – as

$$N = N_{\rm np} + N_{\rm mag} = N(1-f) + Nf. \tag{5}$$

The value of f is highly uncertain. In the Galactic field, 25 magnetars are known[3], at least four of which emit in the radio, and of which only one was found in a radio survey (Levin et al. 2010). There are about 2000 non-recycled pulsars in the field[4] (Manchester et al. 2005), giving $f \approx 0.01$. Considering only radio-emitting magnetars, f becomes 0.002, and considering only radio-loud magnetars detected in surveys, the magnetar fraction reduces to 0.0005. Due to the intermittency in the radio emission of magnetars, together with the selection effects that plague radio surveys, the exact value of the magnetar fraction is unknown. So we decided to parametrize f in our analysis, giving

$$\begin{aligned} p(N, f, \alpha | n_{\rm np}, n_{\rm mag}) \propto\ & p(n_{\rm np} | N, f, \alpha)\ p(n_{\rm mag} | N, f, \alpha) \\ & \times p(N)\ p(f)\ p(\alpha). \end{aligned} \tag{6}$$

We compute the two likelihood functions using the binomial probability distribution, following Boyles et al. (2011). In the case of normal pulsars, we have

$$p(n_{\rm np} | N, f, \alpha) = (1-\theta)^{N(1-f)}, \tag{7}$$

and for magnetars,

$$p(n_{\rm mag} | N, f, \alpha) = N f \gamma (1-\gamma)^{Nf-1}, \tag{8}$$

where γ is the magnetar detection probability. Magnetars are characterized by a flat spectral index, i.e., their luminosities appear to be independent of the observing frequency. Under this assumption we derive the magnetar detection probability from the normal pulsar detection probability as

$$\gamma = \theta(\alpha = 0) = \frac{1}{2}\, {\rm erfc} \left[\frac{\log\, (S_{\rm min} D_{\rm GC}^2) - \mu}{\sqrt{2}\sigma} \right], \tag{9}$$

and $p(n_{\rm mag}|N, f, \alpha)$ becomes $p(n_{\rm mag}|N, f)$.

To avoid any bias in our analysis, we adopt non-informative priors for N and f (i.e., uniform probability within given ranges stated below). For α, we use the results of Bates et al. (2013) and take

$$p(\alpha) \propto e^{-\frac{(\alpha - \bar{\alpha})^2}{2\sigma_{\alpha}^2}}, \tag{10}$$

[1] In this paper, we use the term 'normal pulsar' to mean a non-recycled pulsar that is not a magnetar.

[2] The software package that we developed to perform the analysis described in this paper is available freely for download from `http://psrpop.phys.wvu.edu/gcpulsars`.

[3] `http://www.physics.mcgill.ca/~pulsar/magnetar/main.html`

[4] `http://www.atnf.csiro.au/people/pulsar/psrcat/`

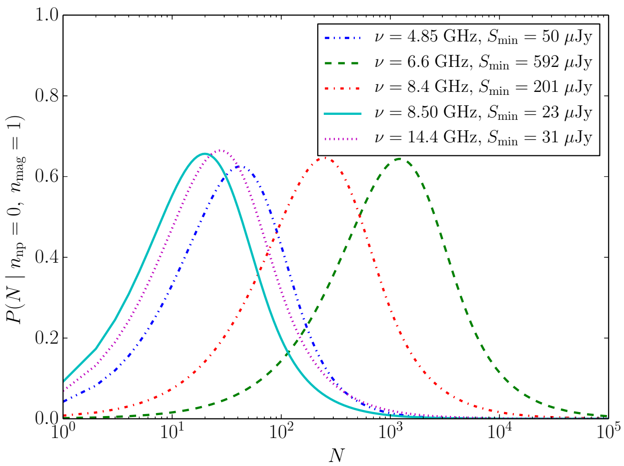

Figure 1. Posterior probability density functions of N for each of the surveys listed in Table 1.

Table 1. Results of our analysis for a few GC surveys. $\langle N \rangle$ is the expected value of N while $N_{\max}$ is the 99% upper limit on N.

ν (GHz)	$S_{\min}$ (μJy)	$\langle N \rangle$	$N_{\max}$	Survey reference
4.85	50	800	12000	Deneva (2010)
6.6	592	16000	92000	Bates et al. (2011)
8.4	201	9000	86000	Johnston et al. (2006)
8.50	23	1200	21000	Deneva (2010)
14.4	31	3000	47000	Macquart et al. (2010)

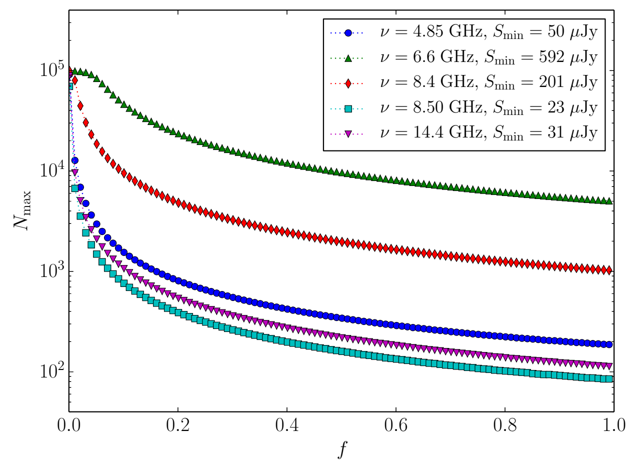

Figure 2. The 99% upper limit on N, $N_{\max}$, as a function of magnetar fraction, f, for each of the surveys listed in Table 1.

where $\bar{\alpha} = -1.41$ is the mean spectral index and $\sigma_\alpha = 0.96$ is the standard deviation. The final Bayesian relation can then be written as

$$p(N, f, \alpha | n_{\rm np}, n_{\rm mag}) \propto \ (1-\theta)^{N(1-f)} \ Nf\gamma(1-\gamma)^{Nf-1} \times \ p(N) \ p(f) \ e^{-\frac{(\alpha-\bar{\alpha})^2}{2\sigma_\alpha^2}}. \tag{11}$$

This is then integrated over f and α to obtain the marginalized posterior of N, $p(N|n_{\rm np}, n_{\rm mag})$.

We applied our technique to the surveys of the GC analyzed by Wharton et al. (2012), namely those discussed in Johnston et al. (2006), Deneva (2010), Macquart et al. (2010) and Bates et al. (2011). In applying our analysis to these past surveys, we made the reasonable assumption that, had the magnetar become active earlier, all these surveys would have detected it. We computed the survey sensitivity limits based on information provided in those papers, and additionally performed a normalization to ensure that the minimum flux density values are average values over the part of the beam that cover the inner 1 pc of the GC, modelling each beam as a gaussian. We used the broad ranges of [1, 10^5] for N and [0.001, 0.999] for f. We found that for the more sensitive surveys (Deneva 2010; Macquart et al. 2010), the mean of the posterior on N is in the range 800–3000 and the 99 per cent upper limit is in the range 12000–47000. Our results are tabulated in Table 1. Figure 1 shows the posterior probability density functions of N derived from each of the surveys listed in Table 1.

As mentioned previously, the magnetar fraction in the Galactic field is uncertain, and that in the GC is unknown. To study how the 99% upper limit on N would vary with magnetar fraction, instead of using a wide prior on f, we chose delta functions in the range (0.0, 1.0), and for each of those magnetar fractions, we computed the upper limit. Figure 2 shows the results of this analysis. For a small magnetar fraction, the upper limits would be close to the values reported in Table 1. If, on the other hand, formation of radio-loud magnetars are somehow favoured in the GC region, the fact that we have detected one magnetar implies that we can expect a smaller population size.

2.2 Monte Carlo Approach

The Bayesian technique described above is relatively agnostic about the period and luminosity evolution of normal pulsars. To make use of the results known from studies of normal pulsars in the Galaxy (see, e.g., Faucher-Giguère & Kaspi 2006), we perform an MC simulation of the GC pulsar population and apply it to the Deneva (2010) survey. In this method, we follow Faucher-Giguère & Kaspi (2006) to simulate a population of $N_{\rm sim}$ pulsars, evolved over time starting from the distributions of birth spin period, surface magnetic field at birth and age. Picking $N_{\rm sim}$ from the range [5×10^3, 8×10^4], we compute the number of pulsars that have not crossed the death line, i.e., the number of radio-loud pulsars, denoted by $N_{\rm GC}$. We then apply radiation beaming correction and compute the number of potentially observable pulsars. Given that Spitler et al. (2013) measure the scattering timescale at 1 GHz as ~ 1.3 s, we scale it to the observation frequency with a power-law spectral index $\alpha_\tau = -3.8$ to compute the scatter-broadened pulse widths for each pulsar. We then compute the luminosities L at 1.4 GHz, followed by computations of the signal-to-noise ratio (S/N). We then apply the S/N threshold of the survey to get the detectable number of pulsars, denoted by $n_{\rm obs}$.

For each value of $N_{\rm sim}$, 10^4 MC realizations were generated to ensure stability in the mean of $n_{\rm obs}$. Figure 3 shows a plot of observed number of pulsars along with both 68.3 and 99.7 per cent confidence limits versus the mean value of the

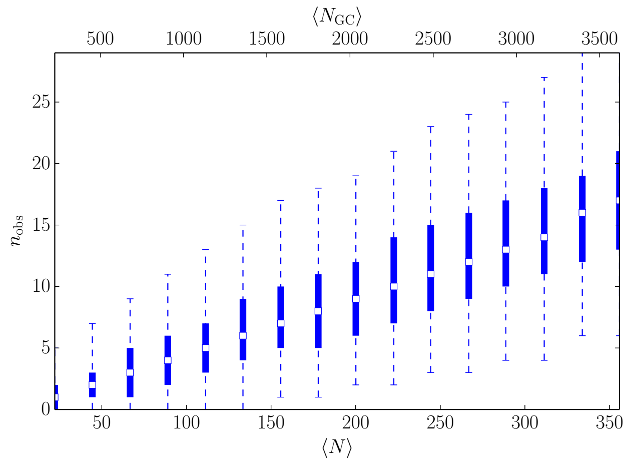

Figure 3. The number of observed pulsars, $n_{\rm obs}$ versus the mean of the number of potentially observable pulsars, $\langle N\rangle$ and the mean of the total number of radio-emitting pulsars in the GC, $\langle N_{\rm GC}\rangle$. Each point represents 10^4 MC realizations. The white markers indicate the mean of $n_{\rm obs}$ and the thick error bars represent the corresponding 68.3 per cent confidence intervals. The dashed error bars are 99.7 per cent confidence limits.

number of potentially observable pulsars in the GC, $\langle N\rangle$, and the mean value of the total number of radio-emitting pulsars in the region, $\langle N_{\rm GC}\rangle$. As can be seen, the lower limits of the 99.7 per cent confidence intervals become inconsistent with an actual detection of zero normal pulsars for $\langle N\rangle$ around 150. Any number $\langle N\rangle \gtrsim 150$ would mean that more pulsars should have been observed. The fact that none have been detected gives an upper bound to the number of potentially observable pulsars in the GC. The assumptions that go into this simulation are that the luminosity function of GC pulsars is the same as that of field pulsars, and that the age distribution of pulsars in the GC follow the uniform distribution for field pulsars (i.e., a constant formation rate). Although a burst of supernovae has been proposed to have occurred in the GC ~ 10 Myr ago (Sofue 1994), near-infrared observations have revealed some evidence that the star formation rate in the region has been roughly constant over the past ~ 10 Gyr (Figer et al. 2004). If these assumptions, including those about the birth spin period and magnetic field distributions are applicable to magnetars as well, the upper limit on the potentially observable population size (of both normal pulsars and magnetars) increases to approximately 200.

3 DISCUSSION

The analyses we have performed in this paper differ from that of Wharton et al. (2012) mainly in that we use a more realistic luminosity function. Whereas Wharton et al. (2012) used a power-law luminosity function, it is more appropriate to use the log-normal as found by Faucher-Giguère & Kaspi (2006). We also take into account the recent discovery of one magnetar in the GC, and, in the case of the Bayesian analysis, the fraction of magnetar to normal pulsars in the field. An important assumption we make here is that scattering in the inner parsec is uniform and is consistent with that of the line of sight to the GC magnetar. This appears to be a reasonable assumption, given that Bower et al. (2013) have shown that the angular sizes of the magnetar and Sgr A* are consistent with both sources being behind the same scattering screen. The results of our Bayesian analysis suggest that the population of potentially observable pulsars in the inner parsec of the GC could be as large as several thousand, whereas our MC analysis yields an upper limit of ~ 200. The reason the Bayesian analysis yields a broader constraint is because it makes fewer assumptions than the MC method. While the former only assumes a form for the luminosity distribution, the latter makes assumptions about the spin-down behaviour and formation rate of pulsars in the GC. We note that, for a typical radio pulsar beaming fraction of ~ 10 per cent (Tauris & Manchester 1998), the total number of radio-emitting pulsars in the region, for either method, would be an order of magnitude larger. As per the MC method, the value of $\langle n_{\rm obs}\rangle$ corresponding to an actual detection of one pulsar is ~ 7. This is consistent with the results of Dexter & O'Leary (2013) who use an estimate of the number of massive stars in the GC, a model of natal kick velocity, and the observed interstellar scattering to get $\langle n_{\rm obs}\rangle \approx 10$. Our conservative upper limit of ~ 200 suggests that there may not be any detectable pulsar close enough to Sgr A* to probe the gravitational field of the GC black hole. However, Kocsis et al. (2012) have suggested that pulsars in the inner parsec that are not close enough to Sgr A* can still be useful in detecting intermediate and stellar mass black holes in orbit around the GC black hole.

How many pulsars can we expect to see in future surveys of the GC? To answer this question, we started with the most constraining posterior on N obtained using the Bayesian method, based on the Deneva (2010) survey. We performed MC simulations similar to those described in §2.2, with the following differences: (i) Instead of picking a set of equi-spaced values, we picked N randomly from the Bayesian posterior; (ii) We did not apply any beaming correction, as the Bayesian posterior gives the number of potentially observable pulsars. The rest of the simulation proceeds as described before, yielding an observed number of pulsars $n_{\rm obs}$. We performed these MC simulations for a few hypothetical surveys using the Green Bank Telescope (GBT), for each of its receivers from L-band to K-band. The backend used was assumed to be able to sample the maximum instantaneous bandwidths supplied by the receivers. For the GBT K-band Focal Plane Array receiver, we assumed that it was configured to use the VEGAS[5] backend such that the instantaneous bandwidth sampled is 8750 MHz. The sensitivity of each survey was calculated based on a minimum signal-to-noise ratio of 8, a duty cycle of 10 per cent and an observation time of 7 hours, which is approximately the duration for which the GC is visible from Green Bank. The receiver temperature, receiver gain, number of polarizations and bandwidth used in our sensitivity calculations were taken from the GBT Proposer's Guide[6]. The GC background temperatures were calculated from peak flux densities and spectral indices reported in Law et al. (2008). For each survey, we repeated the simulation 10^4 times to ensure that the mean

[5] `http://www.gb.nrao.edu/vegas`

[6] `https://science.nrao.edu/facilities/gbt/proposing/GBTpg.pdf`

Table 2. Predictions for surveys, both past and future, based on our most constraining posterior on N. Here, $n_{\rm obs}$ is the mean value of the number of detectable pulsars, given along with 68.3 per cent confidence limits. Values have been rounded to the nearest integer, and the lower limits have been truncated at 0.

Survey	ν (GHz)	$S_{\rm min}$ (μJy)	$T_{\rm GC}$ (K)	$n_{\rm obs}$
Past surveys				
PMPS	1.374	3519	690	0 ± 0
Deneva (2010)	4.85	50	285	1^{+0}_{-1}
Bates et al. (2011)	6.6	592	90	0 ± 0
Johnston et al. (2006)	8.4	201	90	0 ± 0
Deneva (2010)	8.50	23	116	3^{+0}_{-3}
Macquart et al. (2010)	14.4	31	103	2^{+0}_{-2}
Future GBT surveys				
L-Band	1.45	105	435	0 ± 0
S-Band	2.165	75	373	1^{+0}_{-1}
C-Band	5.0	41	285	2^{+0}_{-2}
X-Band	9.2	17	116	3^{+0}_{-3}
Ku-Band	13.7	14	103	4^{+0}_{-4}
K-Band	22.375	10	83	6^{+0}_{-6}

value stabilizes, and computed the mean and standard deviation for the number of detections. Our results are tabulated in Table 2. Encouragingly, our results suggest that there are some prospects for a detection with surveys of this sensitivity in the near future. We caution, however, that in spite of the large number of pulsars we estimate to be present in the GC, and the fact that these surveys have high sensitivity, we may yet detect no pulsar.

As a self-consistency test, to verify that the Bayesian technique we developed in §2.1 and used to predict $n_{\rm obs}$ as described above actually works, we applied the above MC simulations to all the past surveys listed in Table 1, again using our most constraining posterior on N. We also applied it to the most sensitive survey of the GC at 1.4 GHz, the Parkes Multi-beam Pulsar Survey (PMPS; Manchester et al. 2001; Morris et al. 2002). The results of these MC simulations are tabulated in Table 2. For all past surveys, we obtained 1-sigma limits of the number of detected pulsars that are consistent with zero.

Our MC technique described in §2.2 yields a conservative upper limit of ~ 200 potentially observable pulsars, whereas our Bayesian technique yields broader constraints that are an order of magnitude larger. Further deep surveys of the GC in the radio, and monitoring for X-ray outbursts from potential magnetars in the region will help conclusively establish the size of the GC pulsar population.

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