DISCOVERY OF THREE PULSARS FROM A GALACTIC CENTER PULSAR POPULATION

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ABSTRACT

We report the discovery of three pulsars whose large dispersion measures (DMs) and angular proximity to Sgr A* indicate the existence of a Galactic center population of neutron stars. The relatively long periods (0.98–1.48 s) most likely reflect strong selection against short-period pulsars from radio-wave scattering at the observation frequency of 2 GHz used in our survey with the Green Bank Telescope. One object (PSR J1746−2850I) has a characteristic spindown age of only 13 kyr along with a high surface magnetic field $\sim 4 \times 10^{13}$ G. It and a second object found in the same telescope pointing, PSR J1746−2850II (which has the highest known DM among pulsars), may have originated from recent star formation in the Arches or Quintuplet clusters given their angular locations. Along with a third object, PSR J1745−2910, and two similar high-dispersion, long-period pulsars reported by Johnston et al., the five objects found so far are 10–15 arcmin from Sgr A*, consistent with there being a large pulsar population in the Galactic center, most of whose members are undetectable in relatively low-frequency surveys because of pulse broadening from the same scattering volume that angularly broadens Sgr A* and OH/IR masers.

Key words: pulsars: general – pulsars: individual (J1746−2850I, J1746−2850II, J1745−2910)

1. INTRODUCTION

The scientific pay-offs from finding pulsars orbiting near Sgr A* are potentially very high and fall into three main categories. Measurements of relativistic effects through timing of pulsars in tight orbits around Sgr A* would provide methods for better constraining the mass of the central black hole and even estimating its spin (e.g., Laguna & Wolszczan 1997; Wex & Koepckin 1999; Pfahl & Loeb 2004). Timing measurements will also characterize the distribution of dark matter near Sgr A* either in the form of a cluster of black holes and neutron stars (NSs) or in a smoothly distributed volume containing dark-matter particles (Bertone & Merritt 2005; Weinberg et al. 2005). The spatial, age, and period distributions of pulsars near Sgr A* will help describe the stellar population in the region and discriminate between hypotheses attempting to explain the presence of the central cluster of young massive stars: stellar collisions and mergers, migration, and a past episode of intensive star formation. Finally, using pulsars to probe the scattering region around Sgr A* will lead to refinement of electron density models for the inner Galaxy.

There are at least three stellar clusters in the Galactic center region containing massive stars, the progenitors of radio pulsars. Ghez et al. (2003) present evidence that the central cluster around Sgr A* includes early-type stars. Since stars with masses of about 8–20 $M_{\odot}$ are NS progenitors, it is plausible that a considerable NS population exists as well. This leads to the conclusion that a sizable fraction of the NSs would be active radio pulsars. Pfahl & Loeb (2004) estimate that there are $\sim 100$–1000 active pulsars orbiting Sgr A* with periods of less than 100 years. Cordes & Lazio (1997) show that some of these pulsars will be detectable at the distance of the Galactic center, even at the high frequencies needed to mitigate pulse broadening from scattering.

Apart from the central star cluster around Sgr A*, the Arches and Quintuplet clusters are the densest stellar associations within 0.5 of the Galactic center. Both clusters are composed mainly of young massive stars whose supernova explosions will have produced NSs young enough to be active radio pulsars. Stolte et al. (2008) show that the radial distance from the Galactic center to the Arches cluster is 62 ± 23 pc if the cluster is in a circular orbit around Sgr A*, but its distance may be as large as 200 pc.

Of the nearly 2000 pulsars known up to now, only two are within 1° of Sgr A*, PSR J1746−2856 and PSR J1745−2912, which were discovered by Johnston et al. (2006) in a 3.1 GHz survey with the Parkes telescope and have dispersion measures (DMs) of 1168 and 1130 pc cm$^{-3}$, respectively. Johnston et al. (2006) also report the absence of detections by a 8.4 GHz Parkes survey, which indicates there are not many pulsars with flat enough spectra to be detected at high frequencies. The non-detections are also consistent with electron-density models that predict that scattering at frequencies up to $\sim 10$ GHz strongly affects the detectability of pulsars near Sgr A* (Cordes & Lazio 1997).

As part of a larger program to probe the Galactic center pulsar population and ionized gas environment, we have surveyed the inner 0.5 around Sgr A* at 2 GHz with the Green Bank telescope. Pulse broadening due to scattering varies with frequency approximately as $\tau_{\sigma} \propto \nu^{-4}$, so the broadening expected at 2 GHz is $\sim 5$ times larger than at 3.1 GHz. This effect is partially mitigated by the fact that most pulsars have moderate to steep spectra and are more easily detected at lower frequencies when scattering is not a factor.

2. SURVEY PARAMETERS AND DATA PROCESSING

The survey was carried out in 2007 September with the Green Bank telescope, using a center frequency of 1.95 GHz and the SPIGOT backend with a bandwidth of 800 MHz. The lower 200 MHz of the receiver band was excluded from the analysis due to the presence of severe radio frequency interference. The effective analyzed bandwidth was 600 MHz divided into 768 channels. Data were taken with a sampling time of 82 $\mu$s in two polarizations, which were summed before further processing. The grid of survey pointings around Sgr A* is shown in Figure 1.
overlaid on a 330 MHz image of the Galactic center region. We observed 37 grid pointings for 1 hr each, but data from eight pointings were not usable due to technical issues and these pointings are omitted from the figure.

Data processing was performed at the Cornell Center for Advanced Computing (CAC) using the Cornell pulsar search code\(^3\) and the Presto package.\(^4\) The full-resolution data were searched with 1245 evenly spaced trial DM values in the range 10–2000 pc cm\(^{-3}\), and 155 evenly spaced values in the range 2000–2500 pc cm\(^{-3}\). Data were also searched over 1000 values from 100 to 2100 pc cm\(^{-3}\) with a time resolution of 0.65 ms and 300 values from 2100 to 3000 pc cm\(^{-3}\) with 1.3 ms resolution. A Fast Fourier Transform was performed on the resulting time series and the power spectrum was searched for periodic signals by summing up to 16 harmonics and applying a harmonic sum threshold of 6\(\sigma\).

Time series were also searched for individual dispersed pulses using two algorithms, one that applies simple templates (Cordes & McLaughlin 2003) and another that searches for clusters of related points using a friends-of-friends group-finding algorithm (see Figure 1 in Huchra & Geller 1982; see Deneva et al. 2009 for detailed description of application to single pulse searching). The matched filtering approach smooths each time series with rectangle functions of widths 2\(\nu\) samples, where \(n = 0–7\), and searches for events above a 5\(\sigma\) threshold. It is most sensitive to pulses whose widths are close to one of the boxcar filter widths, for a maximum width of 10 ms. The cluster algorithm identifies individual samples above a 3\(\sigma\) threshold and then combines contiguous points into events to which the larger 5\(\sigma\) threshold is applied.

\(^3\) http://arecibo.tc.cornell.edu/PALFA/
\(^4\) http://www.cv.nrao.edu/~sransom/presto

### Table 1

| Parameter | \(J1746–2850I\) | \(J1746–2850II\) | \(J1745–2910\) |
|-----------|-----------------|-----------------|-----------------|
| RA (J2000) | 17\(^h\)46\(^m\)06\(^s\)6(2) | 17\(^h\)46\(^m\)03\(^s\)7(1) | 17\(^h\)45\(^m\)16\(^s\)34(3) |
| Decl. (J2000) | –28°50'42"(5) | –28°49'19"(21) | –29°10'(3) |
| \(P\) (s) | 1.0771014910(4) | 1.478480373(2) | 0.982 |
| \(P\)' (s/s) | 1.34311(2) \times 10^{-12} | 1.276(6) \times 10^{-14} | 0.982 |
| \(DM\) (pc cm\(^{-3}\)) | 962.7(7) | 1456.3 | 1088 |
| Age (Myr) | 0.013 | 0.013 | 2 |
| B (G) | 3.8 \times 10^{13} | 2.8 \times 10^{12} | 2 |
| \(E\) (erg s\(^{-1}\)) | 4.24 \times 10^{34} | 1.47 \times 10^{32} | 2 |
| \(w\) (50\%, ms)\(^b\) | 50 | 50 | 2 |
| \(w\) (50\%, ms)\(^a\) | 30 | 31 | 2 |
| \(w_{1,95}\) (50\%, ms) | 45 | 130 | 2 |
| \(w_{1,5}\) (50\%, ms) | 100 | 145 | 2 |
| \(S_{0}\) (mJy) | 0.4 | 0.4 | 2 |
| \(S_{14}\) (mJy) | 0.5 | 0.1 | 2 |
| \(S_{1,95}\) (mJy) | 0.6 | 0.2 | 2 |
| \(S_{1,5}\) (mJy) | 0.8 | 0.4 | 2 |
| Spectral index \(\alpha\) | –0.3 | –0.3 | 2 |
| \((S_{\nu} \propto \nu^{\alpha})\) | –1.1 | –1.1 | 2 |

Notes.
1. Assuming a 1.4 \(M_{\odot}\) NS with a 10 km radius and moment of inertia \(I = 10^{45}\) g cm\(^{-3}\).
2. Subscripts refer to observing frequencies in GHz.

### 3. SURVEY RESULTS

Table 1 summarizes the properties of the three discovered pulsars. PSR \(J1746–2850I\) and PSR \(J1746–2850II\) were discovered in the same survey pointing and were confirmed with the Green Bank Telescope in 2008 June; subsequent monthly timing observations at 2 GHz are ongoing. We observed both pulsars at 1.5 and 4.8 GHz with the dual goals of estimating their spectral indices and improving their position measurements. We also observed PSR \(J1946–2850I\) at 9 GHz in order to confirm that its relatively flat spectrum extends to higher frequencies. PSR \(J1745–2910\) was discovered in 2009 February and will be timed starting in 2009 June. Profiles of the three pulsars are shown in Figure 2.

We estimated the period-averaged flux density for each pulsar by scaling from signal-to-noise ratio of the folded pulse profile \((S/N)_{\text{prof}}\) using the calculated radiometer noise level for the sum of two polarization channels,

\[
S = \frac{(S/N)_{\text{prof}} T_{\text{sys}}}{\sqrt{N_{\text{pol}} \Delta\nu T_{\text{obs}}/n_{\text{bin}}}},
\]

and we have used \(T_{\text{sys}}\) of 32 K, 27 K, 19 K, and 27 K at 1.4, 2, 4.8, and 9 GHz, including sky background contributions in the Galactic center direction of 12 K at 1.4 GHz scaled as \(\nu^{-2.5}\) (Reich & Reich 1988). The gains \(G\) are 2.0 K Jy\(^{-1}\), 1.9 K Jy\(^{-1}\), 2.0 K Jy\(^{-1}\), and 1.8 K Jy\(^{-1}\), respectively at the four frequencies. The number of bins in the pulse profile \(n_{\text{bin}} = 128\). The total bandwidth \(\Delta\nu = 600\) MHz at 1.4 and 2 GHz, and 800 MHz at 4.8 and 9 GHz.

No isolated dispersed pulses were detected above a 5\(\sigma\) threshold in any of the 2 GHz survey pointings. For a 100 ms pulse width (comparable to the observed pulse widths from Table 1), we derive an upper limit on the flux density of single pulses

\[
S_{\text{max}} = \frac{m T_{\text{sys}}}{G \sqrt{N_{\text{pol}} \Delta\nu W}} \approx 6.5 \text{ mJy}
\]
A timing solution for J1746–2850I was obtained from observations with the GBT made at 24 epochs between 2008 June and 2009 August and fitted for period $P$, period derivative $\dot{P}$, DM, and sky coordinates. The long period and large period derivative indicate that this is a young object with a characteristic age $\tau_c = P/2\dot{P} = 13$ kyr and large surface magnetic field, $3.8 \times 10^{13}$ G. Assuming a power-law spectrum $S_\nu \propto \nu^\alpha$, we found that J1746–2850I has a relatively flat spectrum, with $\alpha = -0.3$. The mean spectral index for normal pulsars is $-1.5$ and fewer than 10% have $\alpha > -0.5$ (Lorimer et al. 1995). Of the two currently known radio-emitting magnetars, XTE1810–197 has $\alpha = -0.5$ in the frequency range 0.7–42 GHz (Camilo et al. 2006), and 1E1547.0–5408 exhibits a flat or rising spectrum over 1.4–6.6 GHz (Camilo et al. 2007). The flat spectrum of PSR J1746–2850I in addition to its spin parameters suggest that this object belongs to a class of young NSs bridging the gap between magnetars and canonical radio pulsars.

3.2. PSR J1746–2850II

J1746–2850II was timed simultaneously with J1746–2850I because the two pulsars are contained within the same beam of the GBT at 1.4 and 2 GHz. It has the highest DM of any pulsar known to date, indicating that of the five pulsars currently known within 1° of Sgr A*, J1746–2850II is likely closest to Sgr A* in radial distance. It is an old pulsar, with a characteristic age $\tau_c = 2$ Myr. While most of the timing observations were made at 2 GHz, the receiver was unavailable in 2008 July and August so observations were made at 1.5 GHz. J1746–2850II is significantly scattered at this frequency (Figure 2). While it was detected during a 2.25 hr observation in 2008 June, it was too weak to detect in our routine 1 hr observations at 1.5 GHz. Consequently, its timing solution has a larger position uncertainty than that of J1746–2850I.

The pulse profile of J1746–2850II at 4.8 GHz is symmetric and Gaussian-like without a discernible scattering tail (Figure 2). We simulate the effect of scattering broadening by convolving a Gaussian matching the 4.8 GHz profile with an exponential depending on the scattering time, $\tau_{sc}$. We compare the results to the 1.5 and 2 GHz profiles using least-squares fitting and obtain $\tau_{sc} \approx 140$ ms at 2 GHz and 266 ms at 1.5 GHz.

3.3. PSR J1745–2910

PSR J1745–2910 has a period of 0.982 s and DM of 1088 pc cm$^{-3}$. Its nominal position is 12° from Sgr A* and ~8° from J1745–2912. Due to the large uncertainties in the positions of both pulsars, they may be between 3°–14° apart. Using Equation (1), we estimate the flux density of J1745–2910 to be $\sim 0.2$ mJy at 2 GHz.

3.4. PSR J1746–2856 and PSR J1745–2912

The two pulsars discovered at 3.1 GHz by Johnston et al. (2006) are in our 2 GHz search area (Figure 1). PSR J1746–2856 was blindly detected at up to ~6° from its position. PSR J1745–2912 was not detected either blindly or by folding data from search pointings near its position with its period of 187 ms. The reported scattering time for this pulsar is $25 \pm 3$ ms at 3.1 GHz. If we assume a Kolmogorov scattering spectrum with a dependence of the scattering time on frequency of $\tau_{sc} \propto \nu^{-4.0}$, the scattering time for PSR J1745–2912 at 2 GHz is 144 ms. This is close to its period and therefore we attribute the non-detection to scattering broadening.

4. THE GALACTIC CENTER ENVIRONMENT

Scattering from the dense region near Sgr A* has been modeled as both a thin screen and as an extended scattering volume. Lazio & Cordes (1998) estimate that the scattering screen around the Galactic center is $132^{+300}_{-50}$ pc from Sgr A*. The NE2001 model (Cordes & Lazio 2003) uses an ellipsoidal scattering volume with a scale height of 26 pc and characteristic radius of 145 pc. For Sgr A* to Sgr A, we have assumed DM = 1600 pc cm$^{-3}$ with a corresponding pulse-broadening time $\sim 400$ s or $\sim 2000$ s at 1 GHz for the screen or extended models, respectively. Pulsars on the near side of Sgr A* will have smaller values of DM and much smaller pulse broadening times.

All five pulsars within 1° of Sgr A* have high DMs that are too large to be accounted for by the Galactic disk components of the NE2001 electron density model. If the pulsars are part of a disk population in the foreground of Sgr A*, the large DMs might be due to an unmodeled excess of intervening ionized gas associated with foreground H ii regions. However, the two Johnston et al. (2006) pulsars are far in angular separation from one another and from the three pulsars we have found, making unlikely the possibility of a single H ii region contributing to their large DMs. Similarly unlikely is the coincidence of five out of five pulsars being affected by separate H ii regions.

In the absence of any unmodeled H ii regions, the NE2001 model places all five pulsars within $\sim 100$ pc of Sgr A* using the DM values (Figure 3). However, the predicted pulse broadening times for the pulsars are several orders of magnitude larger than the measured value for J1746–2850II and the upper bounds on the other objects. This signifies that the near-side boundary and/or density of the idealized Galactic-center component of the model are incorrect or that the scattering volume is patchy, as suggested by Lazio et al. (1999). In either case, like any distance calculated using DM, the distances of the five pulsars from Sgr A* are highly model dependent and cannot be refined.
to better than $\pm 100$ pc. However, unless there is an electron density component in the foreground disk (or spiral arm) of the Galaxy, the large DMs imply that the pulsars are no more than about 200 pc from Sgr A*. Galactic center pulsars will be key for improving the Galactic center component of the next electron density model, NE2008 (J. M. Cordes et al. 2009, in preparation).

4.1. The Arches and Quintuplet Clusters

Could J1746−2850I have been born in either the Arches or Quintuplet cluster? Both clusters contain numerous massive stars, which are NS progenitors. Kim et al. (2006) find the present day mass function of the Arches cluster to extend to at least $40 M_\odot$, while Figuer et al. (2002) find the Arches cluster to contain stars exceeding $100 M_\odot$ with the age of the cluster estimated to be $2 \pm 1$ Myr, old enough for NSs to have formed. Current estimates for the maximum progenitor mass that will produce a NS are $20 M_\odot$ for solitary progenitors and as high as $50–80 M_\odot$ for binary progenitors due to mass loss in Roche lobe overflow (Belczynsky & Taam 2008). The Quintuplet cluster has an estimated age of $\sim 4$ Myr (Figer et al. 1999) but contains the Pistol Star, whose mass of $150 M_\odot$ points to an age no larger than 2 Myr. These estimates indicate that the Quintuplet cluster is also old enough to have already formed NSs.

The current position estimate for J1746−2850I places it within 2′ of the Quintuplet cluster (Figure 1). If the cluster and the pulsar are roughly 8.5 kpc from Earth, this angle corresponds to a distance of 5 pc. A transverse velocity of 375 km s$^{-1}$ would have allowed the pulsar to reach its present location from the Quintuplet cluster within 13 kyr. Our double discovery in a single pointing suggests that the Arches and Quintuplet region may have a relative excess of pulsars.

4.2. Galactic Center Pulsar Population

We show here that the pulsar detections within 15 arcmin of Sgr A* imply the existence of a Galactic center subpopulation of pulsars and that this population may be quite sizable. First, given the small solid-angle coverage of our survey, $\Delta \Omega \approx 10^{-4.2}$ sr, we do not expect to find any pulsars from the Galactic disk population. Integrating either a simple disk model with a uniform density or using the spatial distribution reported by Lorimer et al. (2006), we find that only 1 to 2 disk pulsars beamed toward us are expected in the volume between Earth and Sgr A*. When we include the survey sensitivity, which depends on the pulsar period, and the luminosity and period distributions, the expected number of detected pulsars $\ll 1$.

To assess the rough parameters of a Galactic center pulsar population, we employed a simple modeling approach. We used an ellipsoidal distribution with characteristic radius in the plane of the Galaxy $R_{GC}$ that contains $N_{GC}$ pulsars. The scale height of the population was fixed at $H_{GC} = 0.026$ kpc, equal to that of the scattering region in the NE2001 model. Through Monte Carlo, we generated pulsars consistent with this spatial distribution and drawn from populations with the period and luminosity distributions of Lorimer et al. (2006). Detection criteria were applied using the GBT observation parameters reported earlier and the Parkes survey parameters reported by Johnston et al. (2006), and taking into account the effects of pulse broadening from both residual dispersion smearing and scattering on the harmonic sum. As a test statistic we used the likelihood function $L = \prod_i P(l_i, b_i, \langle N_i \rangle, k_i)$. A term in the product corresponds to the Poisson probability of detecting on average $\langle N \rangle$ pulsars of the simulated population in the $i$th survey beam, where there are $k$ actual detections, $P(\langle N \rangle, k) = \langle N \rangle^k e^{-\langle N \rangle}/k!$. The population was generated 1000 times for each $N_{GC}, R_{GC}$ pair. Figure 4 shows contours of $L$, which indicate that $N_{GC} \gtrsim 2000$ and $R_{GC} \gtrsim 0.3$ kpc are lower bounds on parameter values.

Extending our grid up to $N_{GC} = 10^4$ and $R_{GC} = 5$ kpc, we found no upper bounds on the parameters. We expect such bounds from a more comprehensive analysis that includes other survey results over a larger region, which we defer to another paper.
5. CONCLUSIONS

We have discovered three pulsars within 12′ of Sgr A*. The low (≪ 1) number of detectable disk pulsars in our survey volume and the high DMs of the new pulsars indicate that they are within the dense scattering region surrounding Sgr A* and part of a NS population associated with the Galactic center. Based on a Monte Carlo simulation of this population which incorporates our survey results as well as those of Johnston et al. (2006), we conclude that there are \( N_{GC} \gtrsim 2000 \) active pulsars associated with the Galactic center. Based on the average lifetime of canonical pulsars, \( \sim 10 \) Myr, we obtain a rough estimate of the radio pulsar birth rate in the Galactic center of \( \gtrsim 2 \times 10^{-4} \) yr\(^{-1} \). Considering that this is a lower limit, and that not all supernovae produce radio pulsars, this result is consistent with the rate of Galactic center supernovae (\( \sim 10^{-3} \) yr\(^{-1} \)) based on a survey of compact radio sources (Lazio & Cordes 2008) and observations of soft X-ray emitting plasma (Muno et al. 2004).

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