

Discovery of two pulsars towards the Galactic Centre

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ABSTRACT

We report the discovery of two highly dispersed pulsars in the direction of the Galactic Centre made during a survey at 3.1 GHz with the Parkes radio telescope. Both PSRs J1745–2912 and J1746–2856 have an angular separation from the Galactic Centre of less than 0.3° and dispersion measures in excess of $1100 \text{ cm}^{-3} \text{ pc}$, placing them in the top 10 pulsars when ranked on this value. The frequency dependence of the scatter-broadening in PSR J1746–2856 is much shallower than expected from simple theory. We believe it likely that the pulsars are located between 150 and 500 pc from the Galactic Centre on the near side, and are part of an excess population of neutron stars associated with the Centre itself. A second survey made at 8.4 GHz did not detect any pulsars. This implies either that there are not many bright, long-period pulsars at the Galactic Centre or that the scattering is more severe at high frequencies than current models would suggest.

Key words: pulsars: general – pulsars: individual: J1745–2912 – pulsars: individual: J1746–2856.

1 INTRODUCTION

Surveys for radio pulsars have been extremely successful over the past decade (Lorimer 2005). All-sky surveys and deep surveys of the Galactic plane have doubled the total number of known radio pulsars to above 1700. At the same time, targeted surveys have discovered very young pulsars in supernova remnants, old millisecond pulsars in globular clusters and a population in the Small and Large Magellanic Clouds. In spite of these successes, no pulsars are known within $\sim 1^\circ$ of the Galactic Centre (GC).

Following the Johnston et al. (1995) targeted search of the GC at 1500 MHz (no detections), the most sensitive search at 1500 MHz is the Parkes multibeam survey which integrated for 35 min over a large fraction of the Galactic plane including the GC. That survey discovered PSR J1747–2802, which has a period of 2.8 s, the smallest angular separation from the GC of all the known pulsars ($\sim 1^\circ$) and a high dispersion measure (DM) of $835 \text{ cm}^{-3} \text{ pc}$ (Morris et al. 2002). At higher frequencies, the most sensitive survey was undertaken with the Effelsberg telescope which surveyed a small region (0.2 or 32 pc radius) around the GC at 4850 MHz (Kramer et al. 2000; Klein 2004). In spite of a sensitivity below $100 \mu\text{Jy}$ and the high observing frequency the survey failed to discover any new pulsars.

Sgr A* is at the heart of our Galaxy and is believed to be a black hole with a mass of $3 \times 10^6 M_\odot$ (Eckart et al. 2002) at a distance of $\sim 8 \text{ kpc}$. A nearby stellar cluster appears to contain early-type stars with masses of $10\text{--}20 M_\odot$. Two of the stars in this cluster are in highly eccentric orbits about the black hole with periods of 15 and 30 yr. It is likely that shorter orbits exist, however confusion in the infrared has so far prevented their detection. The presence of these high-mass stars and young supernova remnants is a good indicator that active radio pulsars are also likely to exist close to the GC. Pfahl & Loeb (2004) estimate that there are 1000 radio pulsars within a few pc of the GC, a small fraction of which are potentially detectable using current instruments provided that scatter broadening does not render them invisible at any sensible observing frequency (see also Cordes & Lazio 1997). However, it is likely that the entire GC volume out to $\sim 200 \text{ pc}$ contains an overabundance of pulsars generally. Estimates show that about 10 per cent of all the high-mass stars (the pulsar progenitors) in the Galaxy are contained within this volume (Figer et al. 2004).

One can therefore expect to detect a population of pulsars which would be extremely useful in probing the GC and its conditions: their number and age distribution would probe the past star formation history (Hartmann 1995); their period derivatives can constrain the gravitational potential in the GC and variations in their dispersion measure can probe the plasma density in the central regions. If pulsars were discovered in the immediate vicinity of the central supermassive black hole, this would open up a whole suite of

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strong-field gravity tests through the measurements of a variety of relativistic effects (Wex & Kopeikin 1999). The high stellar density of the GC makes it, like the globular clusters, a possible site of a millisecond pulsar orbiting a stellar-mass black hole though these will be extremely difficult to detect.

We therefore embarked on two surveys of the GC at frequencies of 3.1 and 8.4 GHz, frequencies which bracket that of the Effelsberg 5-GHz survey. The lower frequency reduces the effects of scatter broadening by a factor of ~ 16 compared to surveys at 1.5 GHz, but at the same time the telescope beam size is large enough to survey a significant area of sky in a reasonable amount of time. At the higher frequency, the small beam restricts the sky coverage and the flux densities of pulsars are smaller but the scatter broadening is lower by a factor of more than 1000 compared to 1.4 GHz. Cordes & Lazio (1997) identified frequencies near 8 GHz as the ideal for this type of search.

2 OBSERVATIONS AND DATA REDUCTION

The surveys were carried out using the Parkes radio telescope at centre frequencies of 3.1 and 8.4 GHz. At the lower frequency the total bandwidth was 576 MHz in each of two polarizations which was subdivided into 192 channels each of width 3 MHz. At 8.4 GHz, 288 channels were employed for a total bandwidth of 864 MHz. The outputs from the channels were 1-bit digitized and sampled every 250 μ s and subsequently written to disc for off-line processing. Fig. 1 shows the surveyed areas superposed on a continuum image of the GC region.

Observations at 3.1 GHz were carried out from 2005 July 19 to 22. A total of 32 pointings were made, each with an integration time

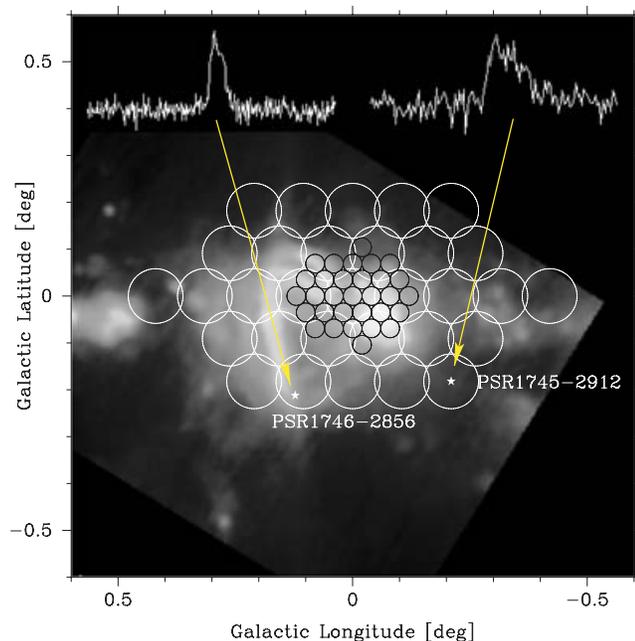


Figure 1. Image of the Galactic Centre region showing the surveyed regions and the profiles of the newly discovered pulsars. The background image shows continuum emission at a frequency of 10.55 GHz from the Effelsberg survey of Seiradakis et al. (1989). The larger circles denote individual survey pointings at 3.1 GHz with the smaller circles representing the pointings for the 8.4-GHz survey. The two stars mark the positions of the discovered pulsars, with their respective pulse profiles shown at the top. Note that both pulsars lie outside the region surveyed both at 8.4 GHz and at 5 GHz with Effelsberg.

of 70 min. At this frequency, the half-power width of the telescope beam is 7 arcmin. The survey therefore covered 0.34 square degrees on the sky or a box approximately 90 pc across at the distance of the GC. On cold sky, the system equivalent flux density was ~ 45 Jy, as measured through observations of the calibrator source Hydra A. However, conditions near the GC contribute substantially to this value. From the maps of Reich et al. (1984), we estimate a contribution of ~ 25 Jy in the outer regions of the survey, ~ 65 Jy in the inner regions and up to ~ 550 Jy at the GC itself. For pulsars with a duty cycle of 10 per cent, the detection threshold (10σ) is then ~ 120 μ Jy (outer regions), ~ 190 μ Jy (inner regions) and ~ 1 mJy at the GC.

Observations at 8.4 GHz were carried out from 2005 September 13 to 16. The survey involved 31 pointings, each observed for 70 min. The half-power width of the telescope beam is 2.4 arcmin and the survey covered 0.04 square degrees on the sky. The system equivalent flux density on cold sky was 48 Jy. Additions to this from emission at the GC were estimated from the maps of Seiradakis et al. (1989) to be ~ 4 Jy in the outer regions of the survey, ~ 10 Jy in the inner regions and ~ 100 Jy at the GC. The 10σ detection threshold is then ~ 70 μ Jy (outer regions), ~ 80 μ Jy (inner regions) and ~ 200 μ Jy at the GC.

Data reduction was carried out using the SIGPROC¹ software package. An initial pass through the data involved resampling to 1 ms and applying 415 (at 3.1 GHz) or 62 (at 8.4 GHz) trial dispersion delays to the data for a range of dispersion measures (DMs) up to 10 000 cm^{-3} pc. A 2^{22} -point fast Fourier transform was then carried out on the dedispersed time-series and the resultant power spectrum searched for significant spikes. Harmonic summing in four stages up to a factor of 16 was carried out and the most significant signals written to disc. These were then time-folded to produce a candidate pulse profiles for subsequent visual inspection.

A search for isolated dispersed bursts of emission with signal-to-noise ratios above a 5σ threshold was also performed (McLaughlin et al. 2006). Time-series were smoothed with boxcars of various widths to increase our sensitivity to broadened pulses. No sources of bursts were found, though the high frequency of these surveys and hence the relatively low dispersion delay, makes distinguishing radio frequency interference from signals of astrophysical origin difficult.

3 TWO NEW PULSARS

Two periodicities, near 945 and 187 ms, were stand-out candidates from the data reduction of the 3.1-GHz data, with signal-to-noise ratios of 41.5 and 9.4. Confirmation of the first pulsar, PSR J1746–2856, came from analysis of archival data from the Parkes multi-beam survey at 1.4 GHz. The 945-ms pulsar is highly scattered at that frequency but is clearly detected with a signal-to-noise ratio of 16. A re-detection at 3.1 GHz was made at Parkes on 2005 August 26. The second pulsar, PSR J1745–2912, was not seen in the archival 1.4-GHz data but was confirmed at Parkes at 3.1 GHz on 2005 August 27. Successful detection of both pulsars at 5 GHz was also made using the Effelsberg telescope in early 2005 September, and more accurate positions were obtained by performing a grid search around the discovery locations. The location and pulse profiles for both pulsars are shown in Fig. 1.

The pulsars have very large DMs; only 14 pulsars were previously known with DMs in excess of 1000 cm^{-3} pc and of these only

¹ <http://sigproc.sourceforge.net>

Table 1. Parameters for PSRs J1745–2912 and J1746–2856.

	J1745–2912	J1746–2856
RA (J2000)	17 ^h 45 ^m 50(10)	17 ^h 46 ^m 49 ^s .5(5)
Dec. (J2000)	–29°12′(2)	–28°56′31″.0(2)
Gal. longitude (°)	359.79	0.12
Gal. latitude (°)	–0.18	–0.21
P (ms)	187.3794(2)	945.224316(3)
\dot{P} ($\times 10^{-15}$)		12.5(3)
DM (cm^{-3} pc)	1130(20)	1168(7)
Epoch	53609.30	53704.50932
S _{3.1} (mJy)	0.12	0.76
Age (Myr)		1.2
B ($\times 10^{12}$ G)		3.5

PSR B1758–23 is within 15 degrees of the GC. Scattering times were estimated using a technique described in Löhmer et al. (2001). We assumed that there is no significant scattering at 4.8 GHz and used the pulse profiles obtained at Effelsberg as an estimate of the true pulse profile. We then convolved this profile with a truncated exponential with one free parameter (the scattering time) and compared it to the observations at lower frequencies using least-squares fitting. For PSR J1745–2912 we obtain a scattering time of 25 ± 3 ms at 3.1 GHz and for PSR J1746–2856 the scattering time is 15 ± 2 ms at 3.1 GHz and 170 ± 15 ms at 1.4 GHz. This implies the power-law index of the scattering as a function of frequency is -3.0 ± 0.3 , significantly smaller in magnitude than the expected value of -4.4 , but in line with the results obtained for other high-DM pulsars (Löhmer et al. 2001). Extrapolating to 1 GHz with a -3 index, gives values of 750 and 450 ms, respectively.

Following the confirmation of the pulsars, subsequent timing observations of PSR J1746–2856 were carried out using the Lovell telescope at the Jodrell Bank Observatory at a frequency of 1.4 GHz with additional data at 3.1 GHz from the Parkes telescope. A total of 49 observations since mid-2005 have allowed us to determine a timing solution for this pulsar. As yet, a timing solution has not been obtained for PSR J1745–2912 due mainly to its lack of detectability at 1.4 GHz. Parameters for both pulsars are listed in Table 1.

4 EXPECTED DM AND SCATTERING AT THE GALACTIC CENTRE

Sgr A* itself is known to be extremely scatter broadened and this is also true of maser and extragalactic sources at small angular separations from the GC. Although the exact nature and location of the screen which causes the scattering is not known, there are good reasons to believe that it is very close to the GC. Cordes & Lazio (1997) and Lazio & Cordes (1998) have shown that any pulsars located beyond the GC scattering screen should be extremely scatter broadened, rendering them undetectable in conventional pulse searches at frequencies below a few GHz. They estimate that the scattering screen lies at a distance of ~ 130 pc from the GC, encloses the GC and is likely to be patchy. The estimates of the scattering times and DMs of pulsars at the GC are ~ 400 s (at 1 GHz) and $\sim 2000 \text{ cm}^{-3}$ pc.

The two pulsars are both at an angular separation of 0.3 from the GC, corresponding to ~ 40 pc lateral displacement. If they had a similar radial displacement from the GC, they would be well inside

the putative scattering screen. Their measured scatter broadening values of ~ 500 ms would therefore be about two orders of magnitude lower than expected. This discrepancy is made even worse if the pulsars are located behind the GC. Furthermore, the measured DMs are a factor of 2 less than expected for the GC. We can also examine the scatter broadening of OH maser spots in the GC. The two OH masers nearest PSR J1745–2912 are OH359.762+0.120 and OH359.880–0.087 with angular sizes of 1700 and 2800 mas (scaled to 1 GHz) respectively (van Langevelde et al. 1992; Frail et al. 1994). We can convert our measured time-scatter broadening values of ~ 750 ms at 1 GHz to an angular broadening and obtain a value of 700 mas assuming a distance of 8.5 kpc and a scattering screen located close to the pulsar. Again this likely indicates the pulsars are in front of the GC.

Both the Taylor & Cordes (1993) and Cordes & Lazio (2002) models of the electron density consist of an outer, thick disc component, an inner, annular component, and spiral arms. Although the models differ significantly in some parts of the Galaxy, they give very similar results in the inner ~ 1 kpc, largely due to the lack of constraints there. If the pulsars are indeed in front of the scattering screen but within the inner few hundred pc, the expected DM would then be only $\sim 650 \text{ cm}^{-3}$ pc in both of the models listed above. Scattering is expected to be ~ 50 ms (at 1 GHz). The measured values of the DM and the scattering time are significantly higher than the models would suggest, perhaps indicating that a filled centre model, rather than an annular one, may be more appropriate.

In any case, it seems most likely that the pulsars would have to be located in front of the scattering screen and at least 150 pc from the GC. This still leaves the question as to their place of birth; in the sections below we consider possible origins for the birth location of these pulsars.

5 LOCATION AND ORIGIN OF THE NEWLY DISCOVERED PULSARS

5.1 Field pulsars: formation at $D > 1$ kpc from the GC

There is a possibility that these pulsars are merely field pulsars on the near side of the GC but not associated with any (excess) neutron star population there. However, the 3.1-GHz survey would not expect to find any pulsars from the normal field population for two reasons. First, the survey area is tiny; the Parkes multibeam survey detected pulsars at a rate of ~ 1 per square degree in the inner Galaxy whereas our survey covered only 0.34 square degrees with a roughly similar effective sensitivity (taking into account the survey parameters, the background temperature and the spectral index of pulsars). Secondly, there is good evidence that the number of field pulsars per unit area actually *decreases* close to the GC (Johnston 1994; Yusifov & Küçük 2004; Lorimer 2004), making detections even more unlikely in this volume.

We have performed a simulation of the normal Galactic population of pulsars using the z -height and radial distributions of Johnston (1994) and the space velocity distribution of Lyne & Lorimer (1994) with a random orientation of the birth kick. We allow a random (flat) distribution of ages up to a maximum of 10^7 yr and let the pulsars evolve in the Galactic potential. In this simulation we find only 0.1 per cent of the pulsars are located in the region covered by the 3.1-GHz survey. In contrast, if we simulate a population of GC neutron stars with a Gaussian radial distribution with $\sigma = 70$ pc, we find that some 10 per cent of the sample remains inside the region of the 3.1-GHz survey and only ~ 1 per cent inside the 8.4-GHz survey

region. There are estimates that about 10 per cent of all high-mass star formation takes place in the inner few hundred pc of the Galaxy. If this is the case then, in the region covered by the 3.1-GHz survey, one would expect to have 10 times more pulsars with origins from the GC population compared to those pulsars which have migrated inwards from the outer Galaxy.

The similarities in the parameters of these two pulsars are striking. Their DMs and scattering times are similar, and they have a similar angular separation from the GC. This seems unlikely to be random chance. Taking all this information together, it therefore seems highly probable that both the newly discovered pulsars are part of an ‘extra’ population directly and closely linked to conditions at the GC.

5.2 Formation within 500 pc of the GC

The pulsars could have been born in the stellar cluster which surrounds Sgr A* and occupies about only 0.02 pc (Pfahl & Loeb 2004). In this case, their orbital speed around the GC would be $\sim 1000 \text{ km s}^{-1}$ and the birth kick would be unlikely to perturb them significantly from their orbit. This possibility therefore seems unlikely.

The pulsars could originate from a progenitor population within ~ 1 pc of the GC. At this distance, the gravitational effect of the black hole is small and the birth process could kick the pulsars out to their current position. A pulsar with a velocity of 100 km s^{-1} travels 100 pc in 1 Myr, the characteristic age of PSR J1746–2856, and no especially large kick velocity needs to be invoked. In this picture, the pulsars’ proper motion would be in a direction away from the GC.

The pulsars could also originate from a distance of ~ 200 pc from the GC inside of which there is known to be significant high-mass star formation (Figer et al. 2004). The velocity of the pulsars would be moderate so as to ensure their retention in the GC region. Long-term timing of the two pulsars may help to distinguish between these two cases.

6 NO DETECTIONS AT 8.4 GHz

What are the implications of failing to detect any pulsars at 8.4 GHz? Recall that the area surveyed is only a ± 15 -pc box around the GC. At the GC distance, the survey region is inside the scattering screen proposed by Lazio & Cordes (1998) and any putative pulsars will therefore suffer from broadening. However, assuming the screen is 130 pc from the GC, the scattering time at 8.4 GHz is then expected to be only ~ 80 ms.

Ignoring this effect for now, the sensitivity of the survey is such that a pulsar with a luminosity (at 8.4 GHz) greater than 7 mJy kpc^2 would have been detected. Extrapolating down to 1.4 GHz, assuming a spectral index of -1.6 , gives a luminosity limit of 125 mJy kpc^2 . Of the 1160 known pulsars with a flux density measurement at 1.4 GHz, 133 of them (11 per cent) have luminosities in excess of this. Given that there are 3×10^4 (Lorimer et al. 2006) active pulsars beaming in our direction and that the known population is not complete even at this luminosity level, at least 0.4 per cent of all pulsars should have luminosities in excess of this value. Therefore, either fewer than 250 pulsars beaming in our direction are in the inner GC region which, given our simple simulation outlined above, would imply a total of less than 2500 pulsars beaming in our direction from that region. However, there remains the possibility that we are not luminosity-limited but rather scatter-broadening limited even at this

high frequency. Note that in the inner 1 pc, the luminosity limit is a factor of 3 higher because of the high background temperatures there (see Section 2). This increases the upper limit to the number of detectable pulsars by a similar amount. This is then broadly in line with modelling of the GC population of neutron stars (Cordes & Lazio 1997; Pfahl & Loeb 2004).

7 SUMMARY

We have discovered two pulsars within 0.3 of the GC during a targeted survey at 3.1 GHz. Both pulsars have very high DMs and scatter broadening times. It seems unlikely that the survey has penetrated through the scattering screen which surrounds the GC at a distance of ~ 150 pc. However, the pulsars are likely to have originated in an excess population associated with the GC and be located within a few hundred pc of it. Both the DM and scattering are then higher than expected in the current electron density models, perhaps favouring a filled centre model rather than the existing annular one. No detections were made at 8.4 GHz, with the implication being that either there are less than a few thousand pulsars beaming in our direction in the inner pc of the Galaxy or that the scattering is more severe than previously thought.

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