Galactic Center Pulsars with the ngVLA

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Pulsars in the Galactic Center (GC) are important probes of General Relativity, star formation, stellar dynamics, stellar evolution, and the interstellar medium. Despite years of searching, only a handful of pulsars in the central 0.5° are known. The high-frequency sensitivity of ngVLA will open a new window for discovery and characterization of pulsars in the GC. A pulsar in orbit around the GC black hole, Sgr A*, will provide an unprecedented probe of black hole physics and General Relativity.

1. Scientific Goals

Currently, only six pulsars in the central 30’ of the Galaxy have been detected. The most spectacular of these, J1745−2900, is a transient magnetar located only 0.1 pc in projection from Sgr A*. This small number stands in sharp contrast to predictions for the number of pulsars based on the rapid star formation rate and high density of young massive stars that can serve as pulsar progenitors. Numerous searches at a wide range of wavelengths have been carried out.

Until recently, the standard explanation for the absence of pulsars was the presence of hyperstrong interstellar scattering that smeared pulses over a timescale of > 10² s at low frequencies. Higher frequency searches reduced scattering effects but suffered
from lower sensitivity due to the typical steep spectrum of pulsars. The discovery of J1745−2900 in 2013, however, suggested that scattering effects from the hyperstrong screen cannot fully account for the absence of detected pulsars, leading to the “missing pulsar” problem. Possible solutions to the absence of observed pulsars include more complex scattering models, stellar population synthesis arguments, and mechanisms for the suppression of the pulsar emission mechanism.

The population of millisecond pulsars (MSPs), which are the most prized targets for dynamical studies, has not been probed at all by existing observations. Even with the much reduced scattering strength inferred by J1745−2900, nearly all MSPs would remain undetected by existing surveys through a combination of time smearing and low flux density. ngVLA Galactic Center (GC) pulsar surveys will probe both the slow pulsar and MSP populations.

The ngVLA will make dramatic changes to our understanding of the GC pulsar population and potentially lead to the discovery of a pulsar in a short-period bound orbit to Sgr A*. This will come primarily through the factor of 10 improvement in sensitivity at high frequencies that the ngVLA promises.

Specific science goals are

- Searching for and Timing a Pulsar Bound to Sgr A*: It has been demonstrated that pulsars orbiting Sgr A* will be superb probes for studying the properties of the central supermassive black hole. It is sufficient to find and time a normal, slowly rotating pulsar in a reasonable orbit, in order to measure the mass of Sgr A* with a precision of $1M_\odot$, to test the cosmic censorship conjecture to a precision of about 0.1% and to test the no-hair theorem to a precision of 1%. These tests are possible even with a rather modest timing precision of 100 µs due to the large mass of Sgr A* and the measurement of relativistic and classical spin-orbit coupling, including the detection of frame-dragging.

- Searching for and Characterizing the GC Pulsar Population: Finding GC pulsars will not only lead to unique studies of the General Relativistic description of black holes, but we also gain invaluable information about the GC region itself: the characteristic age distribution of the discovered pulsars will give insight into the star formation history; MSPs can be used as accelerometers to probe the local gravitational potential; the measured dispersion and scattering measures (and their variability) would allow us to probe the distribution, clumpiness and other properties of the central interstellar medium; this includes measurements of the central magnetic field using Faraday rotation. Proper motions of young pulsars can be used to point back to regions of recent star formation and/or supernova remnants. Broadly, we define the GC pulsar population to be that which falls within the Central Molecular Zone (diameter ~ 250 pc).

- Characterizing the Scattering Environment: Interstellar scattering prevents detection of pulsars at low frequencies. This scattering appears to be strongly variable as a function of position towards the GC. Observations of low frequency masers, extragalactic background sources, as well as known pulsars can characterize the scattering screen and provide insights into the window function for pulsar detection.

The proximity of the Galactic Center and the power of the ngVLA combine to provide an unprecedented and unique opportunity to study the environment of a galactic nucleus through pulsars.
### 2. Pulsar Searching in the GC

Numerous searches for GC pulsars have been carried out over a wide range of frequencies. Prior to 2013, these searches had led to the detection of only five pulsars in the central 0.5° (e.g., Kramer et al. 2000; Johnston et al. 2006; Deneva et al. 2009; Macquart et al. 2010; Siemion et al. 2013; Eatough et al. 2013b). Theoretical expectations based on the high star formation rate and the density of high mass stars in the central molecular zone suggest that there should be hundreds or thousands of detectable pulsars within this region (Pfahl & Loeb 2004). In particular, the immediate environment of the Sgr A* contains a $10^5$ M☉ cluster of massive stars with ages ~ 4 Myr–8 Myr bound to the black hole, which are possible progenitors to neutron stars and pulsars (Blum et al. 2003; Pfuhl et al. 2011).

The strong interstellar scattering towards the GC may account for the absence of detected pulsars, especially at low radio frequencies. Turbulent electrons along the line of sight will produce angular broadening of sources in the image domain and temporal broadening of sources in the time domain. The temporal scattering scales for a thin scattering screen is related to the angular broadening by the following equation:

$$\tau_s = 6.3 \text{ s} \times \left( \frac{D}{8.5 \text{kpc}} \right) \left( \frac{\theta_s}{1.3 \text{ arcsec}} \right)^2 \left( \frac{D}{\Delta} - 1 \right) \nu^{-4},$$

(1)

where $D = 8.3 \pm 0.3$ kpc (Genzel et al. 2010) is the distance to the GC, $\Delta$ is the distance from the GC to the scattering medium, and $\nu$ is the observing frequency in GHz.
The observed angular diameter $\theta_s$ is extrapolated to a frequency of 1 GHz using a scaling of $\nu^{-2}$. For Kolmogorov turbulence with an inner scale $r_{in} > b_{\text{max}}$, we expect $\theta_s \propto \nu^{-2}$ and $\tau_s \propto \nu^{-4}$. Several pieces of evidence demonstrate that scattering may be important in the GC. Sgr A* itself is observed to show substantial angular broadening, as are OH masers and some extragalactic background sources. These pieces of evidence have been used to argue for a hyperstrong scattering screen that is located within the central few hundred parsecs of the GC (Lazio & Cordes 1998b). If the source to screen distance is small, an observed angular broadening implies a large temporal broadening. In the case of the hyperstrong model, $\tau_s \gtrsim 10^3$ s at 1 GHz, sufficient to make even slow pulsars undetectable up to $\sim 10$ GHz.

The discovery and characterization of the GC magnetar J1745–2900 has indicated that the hyperstrong scattering model cannot hold for all of the GC (Eatough et al. 2013a; Spitler et al. 2014; Bower et al. 2014). The GC magnetar, with $P = 3.76$ s is detected to frequencies as low as $\sim 1$ GHz, with a characteristic $\tau_s = 1.3$ s at 1 GHz. The GC magnetar also shows angular broadening identical to that of Sgr A*. Together, these results imply a source to screen distance of order 6 kpc, well outside of the GC, and the ability to readily detect pulsars in the GC at frequencies of a few GHz. It remains unclear whether the magnetar-like scattering screen describes all of the GC region or may be patchy. Characterization of the other GC pulsars show distances to the scattering screen $\lesssim 2$ kpc (Dexter et al. 2017). Other environmental effects may also alter the neutron star population in the GC (Dexter & O’Leary 2014).

In the case of both hyperstrong and magnetar-like scattering, there is still a substantial benefit in reduction of scattering that is achieved by going to higher frequencies. This benefit has to be offset against the steep spectral index of both slow pulsars and MSPs and decreasing sensitivity of many search telescopes with increasing frequency. The average slow pulsar has a spectral index of $\alpha \approx -1.4$ (Bates et al. 2013) although some objects including magnetars have flat spectra to very high frequencies (Torne et al. 2017).

Figure 1 shows the distribution of known field pulsars along with sensitivity curves for the VLA and the ngVLA at a range of frequencies and for hyperstrong and magnetar-like scattering. These curves reveal that for magnetar-like scattering the ngVLA will have sensitivity to discover the majority of field pulsars at the GC and a significant fraction of MSPs. In the more challenging case of hyperstrong scattering, the high frequency ngVLA is essential for obtaining sensitivity to slow pulsars.

3. Constraints on Black Hole Parameters

In order to estimate the impact of ngVLA on timing of a pulsar around Sgr A* and testing the no-hair theorem, we have extended the work by Wex & Kopeikin (1999) and Liu et al. (2012). We have set up a numerical integration scheme for orbits around Sgr A*, using MCMC parameter estimation code; we extract the parameter uncertainties and covariances. Figure 2 shows estimates of the uncertainty in black hole mass, spin, and quadrupole moment for a set of pulsar orbits timed with the VLA and the ngVLA. Results for a more complete set of orbits will be presented in a future publication (Shao et al., in prep.). Effectively, the precision on these parameters in this regime scales directly with increased collecting area.

The parameter constraints are governed primarily by the rms time of arrival (TOA) residuals, $\sigma_{\text{TOA}}$. For given intrinsic pulsar emission properties and scattering proper-
Figure 2. Constraints on black hole parameters from timing observations of a pulsar in a bound orbit for the VLA (solid lines) and for the ngVLA (dashed lines). Constraints are given for black hole mass ($M_\bullet$), spin ($\chi_\bullet$), and quadrupole ($q_\bullet$). These constraints were calculated for a $P = 0.5$ s pulsar with orbital eccentricity $e = 0.8$ and timing residuals of $\sigma_{\text{TOA}} = 1$ ms and 0.1 ms for the VLA and ngVLA, respectively. Simulations include weekly observations over a 5 yr interval.

Another limitation of current GC pulsar searches is the insensitivity to a large fraction of binary pulsars. The minimum detectable pulsar pseudo-luminosity ($L = S d^2$) for a pulsar survey scales roughly as

$$L_{\text{min}} \propto d^{-2} G^{-1} T_{\text{obs}}^{-1/2}$$

where $d$ is distance, $G$ is the telescope gain, and $T_{\text{obs}}$ is the observing time. Because the GC is so far away, GC searches have typically observed for as long as possible ($\approx 6$ hr at the VLA). While this increases the sensitivity to faint isolated pulsars, it can also reduce the effectiveness of typical binary pulsar search methods. For example, the acceleration...
Figure 3. TOA residuals for a $P = 0.5$ s pulsar with a 10 ms pulsar width, using an integration time of 4 hr and a bandwidth of 1 GHz. The residuals are shown for hyperstrong scattering with $\tau = 2300$ s at 1 GHz (left) and for a level of scattering comparable to the magnetar J1745–2900, with $\tau = 1.3$ s at 1 GHz (right).

search technique is only effective for orbital periods with $P_{\text{orb}} \gtrsim 10T_{\text{obs}}$ (Johnston & Kulkarni 1991; Ransom et al. 2003). A VLA GC pulsar search that observes for 6 hr would be most sensitive to binary pulsars with orbits longer than about 60 hr, which includes only about 50% of known pulsar binaries (and only 30% of binaries in globular clusters).

The increased sensitivity of the ngVLA means that flux density limits achieved by the VLA can be reached in much shorter observing times, thus allowing for the possibility of detecting much shorter period binary pulsars. For $(G_{\text{ng}}/G_{\text{VLA}}) = 5$, the ngVLA could reach the same flux density limit as a 6 hr VLA observation in only $T_{\text{ng}} = T_{\text{VLA}}/\sqrt{5} \approx 15$ min. In this shorter observing span, an acceleration search could be used to find pulsars with orbits as short as 2.5 hr, which would include about 95% of all known pulsar binaries.

Long baseline astrometry of the pulsar relative to Sgr A* can also contribute to parameter constraints for long-period systems. For the case of 100 $\mu$as astrometric error (Bower et al. 2015), we can measure the orientation of the pulsar orbit in the sky, i.e., the longitude of the ascending node with sufficient precision to improve General Relativistic constraints.

4. Other Probes of Black Hole Physics and the Uniqueness of ngVLA

There are a number of experiments currently seeking to characterize Sgr A*, the properties of the SMBH, and General Relativity. These include the Event Horizon Telescope (EHT) and its millimeter wavelength imaging of Sgr A* and large optical telescope campaigns to measure stellar orbits near Sgr A*. ngVLA timing of a pulsar in a bound orbit compares favorably against these techniques and provides important complementary information (Psaltis et al. 2016).

EHT constraints will primarily arise from modeling the static and time-domain images of the immediate region surrounding Sgr A* out to a radius of $\sim 10R_S$ (Broderick et al. 2014). General Relativity and BH properties introduce image distortions that
can be translated into parameter constraints. These measurements, however, must be interpreted in light of the complex astrophysics of accretion, jet launching, and particle acceleration in the vicinity of the BH. Simulations have shown that EHT results will be able to measure the BH mass, spin, and quadrupole moment.

Stellar astrometry with existing and future large optical telescopes has the potential to measure orbital precession. Current constraints on the black hole mass from stellar orbits have an accuracy of order 10% (e.g., Genzel et al. 2010) and future measurements with existing facilities are projected to improve on these results substantially (Waisberg et al. 2018). The closest star, S2, has a period of 15 yr and is currently going through periastron passage. Improved instruments may discover fainter stars in shorter orbits leading to greater precision. Sub-milliarcsecond astrometry provides a length-scale precision that is orders of magnitude less precise than millisecond-accuracy pulsar timing, leading to complementary but correspondingly less accurate BH and General Relativity parameter constraints.

5. The Accretion Flow, ISM, and Stars

Pulsed emission provides a powerful probe of the plasma and magnetic field along the line of sight through a variety of measurements. The dispersion measure (DM) gives the total electron column density. The rotation measure (RM) gives the integrated line of sight magnetic field and electron density. The scattering measure (SM) characterizes turbulent plasma, which is typically localized to individual regions along the line of sight.

A short period pulsar will orbit inside of the Bondi radius (~ $10^5 R_S$; $P \sim 10^3$ yr) of Sgr A*. Polarimetry of Sgr A* and the magnetar J1745−2900 has shown that a substantial fraction of the observed Sgr A* RM originates from the accretion flow on scales between 10 $R_S$ and $10^5 R_S$, providing strong constraints on the accretion rate and the nature of the radiatively inefficient accretion flow (Bower et al. 2003; Marrone et al. 2007). A pulsar in an eccentric orbit would provide a measure of the radial profile of the accretion flow, inaccessible to any other technique.

On larger angular scales, a collection of GC pulsars would provide multiple probes of the interstellar medium (ISM) in the GC region (Schnitzeler et al. 2016). With a sufficient density of pulsars, the ngVLA can map out magnetized and ionized structures throughout the central molecular zone. Astrometry of these pulsars can provide origins of individual pulsars in known SNR or young stellar clusters.

ngVLA pulsar studies will complement ngVLA and SKA studies of the GC ISM through other means. The scattering medium has been studied in the past through imaging of stellar masers and extragalactic background sources (van Langevelde & Diamond 1991; van Langevelde et al. 1992; Frail et al. 1994; Lazio & Cordes 1998a). Sensitivity and angular resolution constraints have limited observations, however, to a small number of sight lines. The ngVLA will provide the sensitivity and resolution to measure the angular sizes of a wide range of maser species and a large number of background sources and map out the spatial variations of the scattering towards the inner degree of the GC. This will provide important insight into both the source of scattering and characterization of the scattering that can lead to optimization of pulsar searches.
6. Implications for Array Design

A number of elements of the array design are constrained by our scientific goals.

- Correlator and beamformer requirements: Searches for pulsars will make use of beamforming capabilities as well as high-time resolution imaging with the correlator. Different regimes of the search space will be optimized through tradeoffs in field of view and bandwidth. Timing observations will rely primarily on wideband receivers and beamformer backends.

- Effect of the various receiver options on GC searches: Pulsar searching requires high instantaneous sensitivity that cannot always be traded off against greater integration time. High frequency (~ 30 GHz) sensitivity is likely to be required to avoid the effects of scattering for detection of MSPs.

- Effect of array configuration on GC searches: Searching and imaging primarily require a compact configuration. Timing observations can be obtained with beamforming of extended configurations but these will introduce challenges in calibration and availability due to weather. Characterization of the scattering environment and pulsar astrometry will require > 1000 km baselines to resolve compact sources and achieve sub-milliarcsecond positional accuracy.

7. Summary

The order of magnitude increase in high frequency sensitivity that the ngVLA provides will be essential for the discovery and characterization of pulsars in the Galactic Center, the nearest and best studied galactic nucleus. Characterization of the population within the Central Molecular Zone will give new insights into the ISM and stellar populations of one of the most dynamic regions in the Galaxy. Discovery of a pulsar in orbit around Sgr A* will provide an unprecedented opportunity for fundamental physics in the environment of a black hole.

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