Astro2020 Science White Paper

Fundamental Physics with Galactic Center Pulsars

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract: Pulsars in the Galactic Center (GC) are important probes of General Relativity, star formation, stellar dynamics, stellar evolution, the interstellar medium, and the supermassive black hole accretion flow. In particular, a pulsar in orbit around the GC black hole, Sgr A*, will provide an unprecedented probe of black hole physics and General Relativity, measuring black hole mass, spin, and quadrupole moment, and testing the Kerr metric at sensitivities orders of magnitude better than any other method. The rich recent star formation history and abundant population of high mass stars indicate that thousands of pulsars should be present in the GC. After years of searching, however, only a small number of pulsars in the central tens of parsecs are known. Most important among these is the GC magnetar, the first pulsar found to orbit a supermassive black hole; it has provided the community with an unprecedented tool for characterizing the environment and population of GC pulsars, which points toward the need for high sensitivity observations at radio frequencies up to 30 GHz. These capabilities are necessary to overcome the competing effects of strong interstellar scattering, bright GC background, and steep pulsar spectra, creating for the first time the opportunity to discover millisecond pulsars and pulsars in short-period binaries, as well as survey the full population of slow pulsars.

1 Scientific Goals

The Galactic Center (GC) black hole Sgr A* is one of the best astrophysical laboratories for the study of black holes (BHs) and General Relativity (GR). New technologies across the electromagnetic spectrum and the multi-messenger parameter-space are creating the opportunity to measure BH mass, spin, and quadrupole moment as well as test the Kerr metric. Stellar astrometry in the near infrared has measured the gravitational redshift (GRAVITY Collaboration et al., 2018), and Event Horizon Telescope (EHT) imaging has the potential to test spacetime properties on scales of a few Schwarzschild radii (Doeleman et al., 2008). These discoveries will continue in the context of LIGO/VIRGO discovery and characterization of BH and neutron star binaries (Abbott et al., 2016). Timing of a pulsar in a short period ($\lesssim 1\,\mathrm{yr}$) orbit around Sgr A* would provide an unprecedented capability for probing BH properties, giving results that are orders of magnitude more accurate than existing or planned capabilities. This accuracy comes from the extraordinary timing precision that can be achieved for pulsars, which has been used extensively for characterization of stellar-mass binaries (e.g., Demorest et al., 2010).

Based on the high star formation rate and density of massive stars, the GC is expected to contain many pulsars. However, this large population has been mostly inaccessible to current telescopes due to sensitivity limitations. The six pulsars discovered in the central $30'$ (≈ 70 pc) of the Galaxy have been slow ($P_{\rm spin} \gtrsim 100$ ms), isolated, and bright. The most spectacular of these, PSR J1745−2900, is a transient magnetar located only 0.1 pc in projection from Sgr A*. The population of millisecond pulsars (MSPs), which are the most prized targets for dynamical studies, has not been probed at all by existing observations.

The next generation of radio telescopes will have the sensitivity and frequency coverage needed to discover and monitor a large fraction of the GC pulsar population. There is an enormous potential for discovery in the next decade and the chance to study BHs with high precision by timing a pulsar in a short-period bound orbit to Sgr A*. Progress in the discovery of GC pulsars requires a radio telescope with substantially increased sensitivity at frequencies of 10s of GHz, such as the proposed ngVLA (Selina et al., 2018).

Specific science goals are:

- **Probing the Properties of Sgr A***: Pulsars orbiting Sgr A* will be superb probes for studying the properties of the central BH. Timing even a slowly rotating pulsar in a short-period orbit is sufficient to (1) Measure the mass of Sgr A* with a precision of $\sim 1 M_\odot$(!); (2) Test the cosmic censorship conjecture to a precision of about 0.1%; and (3) Test the no-hair theorem to a precision of 1%. These tests are possible even with a modest timing precision of 100 μs due to the large mass of Sgr A* and through the measurement of relativistic and classical spin-orbit coupling, including the detection of frame-dragging. As will be explained further (§3), a pulsar in orbit around Sgr A* would allow for a range of unique tests of different gravitational symmetries.
- **Characterizing the GC Pulsar Population & Elucidating the Black Hole Reservoir**: Finding GC pulsars will also give 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, including measurements of the central magnetic field and black hole accretion flow using Faraday rotation, a powerful technique for understanding the accretion flow onto the nearest SMBH (Eatough et al., 2013). Proper motions of young pulsars

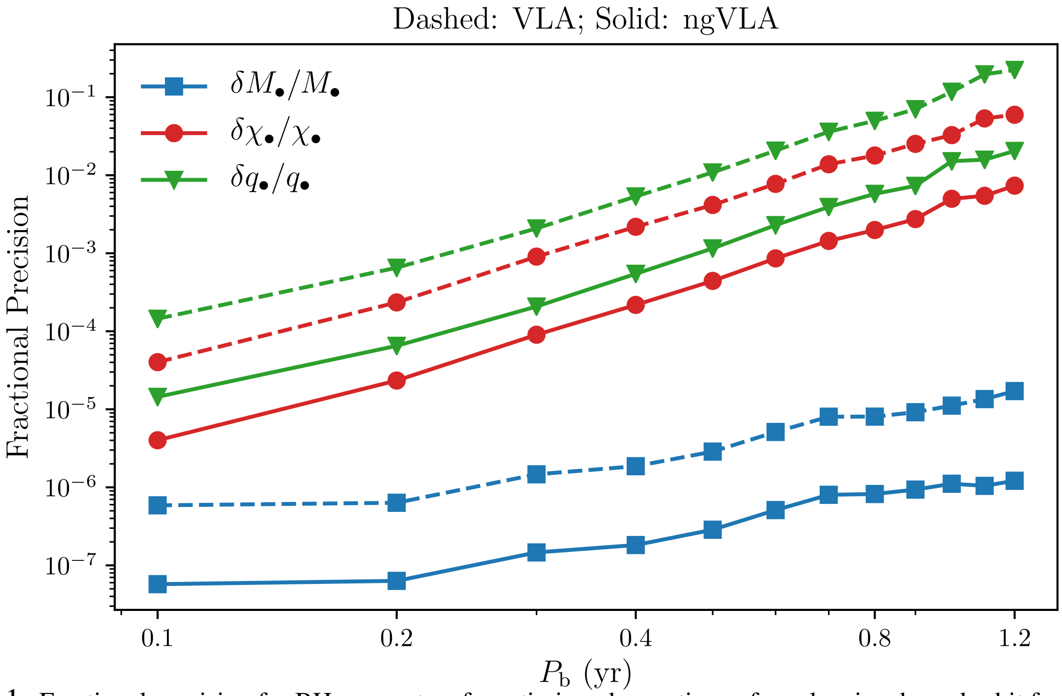

Figure 1: Fractional precision for BH parameters from timing observations of a pulsar in a bound orbit for the VLA (dashed lines) and for the ngVLA (solid lines). Constraints are given for BH mass ($M_\bullet$), spin ($\chi_\bullet$), and quadrupole ($q_\bullet$). These constraints were calculated for a $P = 0.5$ s pulsar with orbital eccentricity $e = 0.8$ and timing residuals of $\sigma_{\mathrm{TOA}} = 1$ ms and 0.1 ms for the VLA and ngVLA, respectively. Simulations assume weekly observations over a 5 yr interval.

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).

2 Precise Black Hole Parameters with Pulsars

The spacetime around Sgr A* can be mapped using pulsar timing. By measuring the times of arrival (TOAs) of pulses from pulsars and comparing them to a timing model, orbital and relativistic parameters can be determined with exquisite precision. As TOA uncertainties (σ_{TOA}) scale inversely with telescope sensitivity, the radio telescopes planned for the next decade can provide up to an order of magnitude improvement in timing precision.

As an example of the power of next generation telescopes, we consider ngVLA observations of a pulsar orbiting Sgr A*. Building on work by Wex & Kopeikin (1999) and Liu et al. (2012), we have numerically integrated simulated pulsar orbits around Sgr A* and extracted BH parameters from timing observations. Figure 1 shows estimates of the uncertainty in BH mass, spin, and quadrupole moment for a set of pulsar orbits to be timed with the VLA and the ngVLA.

Relativistic effects are best measured when the observational duration is greater than the orbital period, but constraints on GR and BH properties can still be obtained for longer period systems. We consider the case of a pulsar with a 15 yr orbital period observed over a 5 yr interval during pericenter passage. The BH mass can be measured with the ngVLA to a fractional precision of order 10^{-5}. Lense-Thirring precession parameters will be found with a signal-to-noise ratio between 10 and 1000, depending on the details of the orbit and the observations. At large radii, perturbations to the pulsar orbit through stellar interactions will limit the accuracy with which GR constraints can be made. Next generation adaptive optics on large optical telescopes imaging the stellar cluster may enable modeling of these perturbations.

3 Uniqueness of Pulsars for Probing Black Hole Physics

A number of current experiments seek to characterize properties of the SMBH and GR. These include the millimeter-wavelength imaging of Sgr A* with the EHT 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). In the following, we discuss some of these aspects.

EHT constraints will result primarily from modeling static and time-domain images of the immediate region of Sgr A*, to a radius of $\sim 10R_{\rm S}$ (Psaltis, 2018). The gravity theory under consideration (e.g., GR) 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. Pulsar observations are an important and sensitive complement to EHT observations (Psaltis et al., 2016). Pulsar precision tests, in the far field of the BH ($\gg R_S$), could confirm a theory or identify a deviation from GR.

Stellar astrometry systems have now measured the black hole mass to less than 1% (GRAVITY Collaboration et al., 2018). Future measurements have the potential to measure orbital precession (Waisberg et al., 2018). The closest star, S2, has a period of 16 yr and recently went through periastron passage. Improved instruments may discover fainter stars in shorter orbits leading to greater precision but detectable and measurable stars have not yet been shown to exist. Further, even submilliarcsecond astrometry provides a length-scale precision $l_\theta \sim D\,\delta\theta \sim 1\,\mathrm{AU}$ that is orders of magnitude less precise than millisecond-accuracy pulsar timing $l_t \sim c\,\delta t \sim 10^{-6}\,\mathrm{AU}$, leading to BH and GR parameter constraints from astrometry that are complementary but correspondingly less accurate. On the other hand, combining stellar astrometry and pulsar timing would provide a unique test for the strong equivalence principle (SEP). SEP states the universality of free fall for self-gravitating bodies, which means that the effective gravitational constant $\mathcal{G}$ is independent of the fractional binding energy of a star (Will, 2018). If the S-stars and the strongly self-gravitating pulsar fall the same in the gravitational field of the supermassive BH Sgr A* then the (gravitating) BH mass determined from stellar orbits has to agree with the mass determined from the pulsar orbit.

Another deviation from GR that can occur if SEP is violated is the dependence of the local gravitational constant G_L on the local gravitational potential sourced by neighboring masses (Will, 2018). A pulsar around Sgr A* would provide a unique test for such an effect. As G_L varies along the pulsar's orbit around Sgr A* the structure of the pulsar and, hence, its moment of inertia will vary, in turn, leading to a change in the pulsar's spin frequency ($\Delta\nu/\nu \propto \Delta G_L/G_L$). As ν is an extremely well measured parameter in pulsar timing, the result is a precise test of such a violation of local position invariance in the gravitational field of an SMBH.

Long-term pulse-profile and polarization measurements of a pulsar in orbit around Sgr A* could be used to test relativistic spin precession in the curved spacetime of a BH. This would be similar to the *Gravity Probe B* satellite experiment, but with a SMBH as the source of spacetime curvature, hence providing a qualitatively very different test.

In the last few years, the observation of gravitational waves (GW) with terrestrial GW detectors has opened up completely new ways to test the properties of BHs. GW astronomy is expected to continue to provide rich and unique information in the coming decade. Gravity tests with a pulsar around Sgr A* are in many ways complementary. Before the expected launch of space based GW detectors in the 2030s, like LISA, GW detectors will only probe stellar mass BHs. Moreover, GW experiments are closely linked to the radiative and highly dynamical properties of gravity, while a pulsar in orbit around Sgr A* is probing the quasi-stationary properties of a gravity theory. Amongst these are precision tests for the coupling of electromagnetic fields to gravity, i.e. the propagation of photons, an aspect that cannot be tested with GW detectors. More generally, pulsar timing, like stellar astrometry, is unique in the range and duration over which gravity can be studied, permitting repeated and deep characterization of GR effects.

4 Pulsar Searching in the GC

The innermost regions of the Galaxy should be a pulsar-rich environment. 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 inner parsec around Sgr A* contains a $10^5\ \mathrm{M}_\odot$ cluster of massive stars with ages ~ 4 to 8 Myr bound to the black hole, which are possible progenitors to neutron stars and pulsars (Blum et al., 2003; Pfuhl et al., 2011). However, despite numerous searches for GC pulsars, only six pulsars have been detected in the central $30'$ (≈ 70 pc) around Sgr A* (Johnston et al., 2006; Deneva et al., 2009; Eatough et al., 2013). Only one of these, a radio-emitting magnetar, is potentially in a bound orbit around the black hole (Bower et al., 2015).

The relatively low number of GC pulsars discovered so far highlights the difficulty of GC pulsar searches with current telescopes. The main challenges of a GC pulsar search arise from the large distance to the target, the strong scattering along the line of sight and the bright GC background. Sgr A* is located at a distance of $D = 8.13 \pm 0.03$ kpc (GRAVITY Collaboration et al., 2018), which is further away than $\approx 80\%$ of known radio pulsars. Pulse broadening caused by multipath propagation along the line of sight presents a significant challenge to GC pulsar searches. The effect of scattering is to convolve the intrinsic pulse shape with an asymmetric pulse broadening function with time scale $\tau_{\rm sc}$. This reduces the sensitivity of a periodicity search when the scattering time exceeds the intrinsic pulse width ($\tau_{\rm sc} \gtrsim W$) and makes pulsars with spin periods $P_{\rm spin} \lesssim \tau_{\rm sc}$ essentially undetectable. For PSR J1745−2900, the pulse broadening time is $\tau_{\rm sc} = 1300\ \mathrm{ms}\ \nu_{\rm GHz}^{-4}$ (Spitler et al., 2014). If other pulsars along this line of sight have similar levels of scattering, then observing frequencies of $\gtrsim 10$ GHz are needed to detect millisecond pulsars. However, pulsars are much fainter at these higher frequencies ($S_\nu \propto \nu^\alpha$, $\alpha \approx -1.4$; Bates et al., 2013), so high instantaneous sensitivity and long exposure times are needed.

In the next decade, new instruments and facilities will provide the requisite sensitivity and frequency coverage to detect a large fraction of GC pulsars. Figure 2 shows the distribution of known field pulsars with flux densities scaled to 1.4 GHz and at the distance of the GC. The sensitivty curves are for 1, 3, and $10\times$ the phased VLA (100 m equivalent) at a range of frequencies for both magnetar-like and hyperstrong scattering. For magnetar-like scattering, the next generation telescopes 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 sensitivity of these new facilities will be essential for detecting slow pulsars.

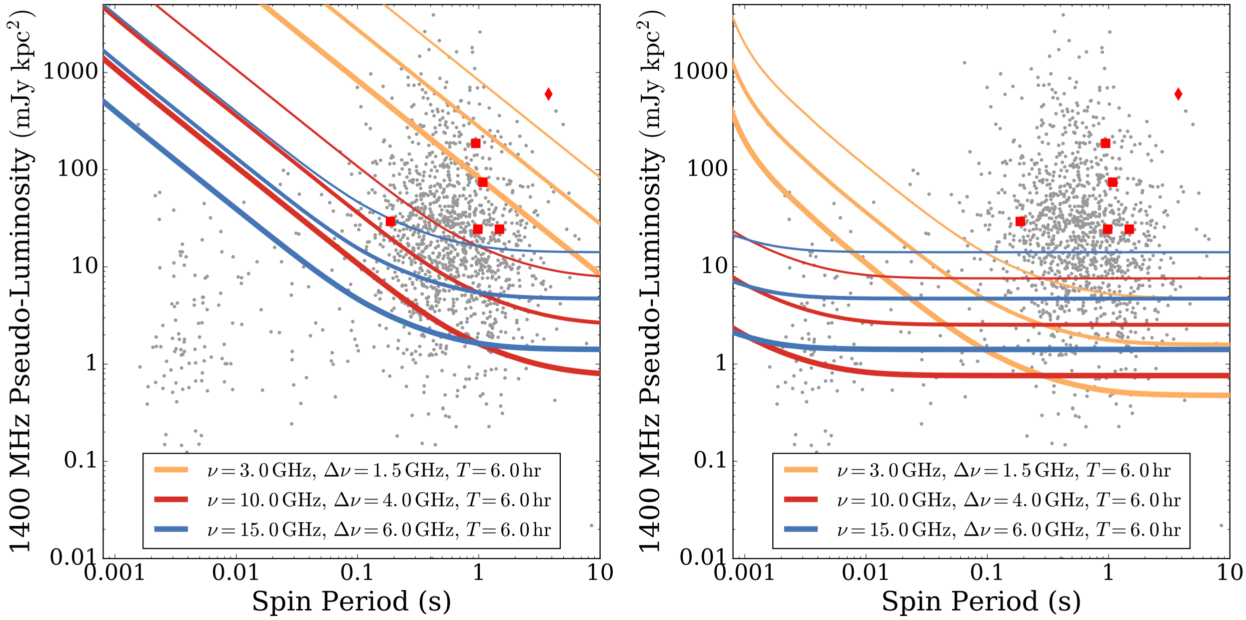

Figure 2: Field and GC pulsars (grey dots and red symbols, respectively) in period–pseudo-luminosity space for hyperstrong scattering (*left*) and magnetar-like scattering (*right*). The red diamond indicates the GC magnetar J1745−2900. Curves show sensitivities of 1, 3, and 10× VLA (thinner to thicker lines) at three frequencies. Sensitivity curves include nominal VLA and ngVLA system performance and scaling for the average pulsar spectral index. The increased sensitivity of the ngVLA is required to have a high confidence of probing into the GC pulsar population.

5 Summary

The discovery and characterization of pulsars in the Galactic Center, the nearest and best studied galactic nucleus, requires an order of magnitude increase in sensitivity at radio frequencies up to 30 GHz. Characterization of the population within the Central Molecular Zone will give new insights into the ISM and stellar populations of one of the Galaxy's most dynamic regions. Conditions within the CMZ are quite unlike elsewhere in the Galaxy (e.g., gas component and magnetization). Pulsars can also be used to understand the accretion system of Sgr A* which is unknown and which seems to be "quiet" in comparison to other galaxies. 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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