Probing the Spacetime Around Sgr A* with Radio Pulsars

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Massive Stars Orbiting Sgr A*

- Near-IR observations have revealed roughly two dozen stars within \( \sim 0.5'' \) of Sgr A*.

- Dynamics \( \Rightarrow \) black hole of mass \( (3-4) \times 10^6 M_\odot \).

- Spectral evidence suggests that many of the stars have masses of \( 10-20 \, M_\odot \).

Massive stars leave neutron-star remnants . . .

*Radio pulsars!*
Number of Pulsars

- Steady-state population of $\sim 10$–100 massive stars with orbital periods of $\lesssim 100 \text{ yr}$.

- Stellar lifetimes of $\sim 10^7 \text{ yr} \Rightarrow$ NS birthrate of $10^{-6}$–$10^{-5} \text{ yr}^{-1}$.

- Characteristic pulsar lifetime of $(1$–$5) \times 10^8 \text{ yr} \Rightarrow \sim 100$–5000 active radio pulsars.

What is the detectable fraction?
Take the steady-state assumption further, and use the statistics of the Galactic pulsar population:

- **400-MHz luminosity function**: \( p(L_{400}) \propto L_{400}^{-2} \).
- **Luminosity to flux**: \( L_{\nu} \approx D^2 S_{\nu} \).
- **Spectrum**: \( S_{\nu} \propto \nu^{-\alpha} \).
- **Spectral slopes**: \( p(\alpha) \propto \begin{cases} \exp\left[-(\alpha - \langle\alpha\rangle)^2/2\sigma_\alpha\right] & \alpha > 0 \\ 0 & \alpha < 0 \end{cases} \)

\( \langle\alpha\rangle \approx 1.7, \sigma_\alpha \approx 0.8 \)
Extreme radio-wave scattering:

- Angular broadening of $\simeq 1'' \left( \frac{\nu}{\text{GHz}} \right)^{-2}$ for Sgr A*.

- Temporal smearing of $\sim 300 \text{ s} \left( \frac{\nu}{\text{GHz}} \right)^{-4}$ vs pulse period of $P_p \sim 1 \text{ s}$.

- Optimum observing frequency: $\nu' \simeq 7 \text{ GHz} \left( \alpha^{1/2} P_p \right)^{-1/4}$ (Cordes & Lazio 1997).

- Pulsed flux sensitivity (e.g., GBT):

$$S_{\text{min}} \simeq 20-40 \mu\text{Jy} \left[ \frac{\epsilon}{0.05} \cdot \frac{1\text{ GHz}}{\Delta \nu} \cdot \frac{1\text{ hr}}{t_{\text{int}}} \right]^{1/2}$$
Detectable Fraction

<table>
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<th>$S_{\text{min}}$ ($\mu$Jy)</th>
<th>$\nu$ (GHz)</th>
<th>$F_{\text{det}}$ (%)</th>
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<td>50</td>
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- Detectable fraction $\sim 1\%$.
- Not much variation with $\nu$.

Several tens of pulsars may orbit Sgr A* with $P_{\text{orb}} \lesssim 100$ yr and $S > S_{\text{min}}$. The beaming fraction is $\approx 0.2$, and so perhaps a few pulsars will be detectable with current telescopes.
Pulsar Timing

Analysis of pulse arrival times reveals the dynamics of a pulsar orbiting Sgr A*.

- Arrival-time precisions are $\delta t \sim (10^{-3} - 10^{-2}) P_p$, or $\sim 1$–10 ms.

- The RMS timing precision is then $\sim \delta t / \sqrt{N}$, which is $\lesssim 1$ ms for $N \sim 100$.

- Pulsar spin-down model: $\phi = \nu_p T + \dot{\nu}_p T^2 / 2 + \ldots$

- Time delays: $t - t_0 = T + \sum_i \Delta_i$. 
Relativistic Gravity

Largest post-Keplerian timing residuals:

(1) Einstein
(2) First-order Shapiro
(3) Frame-Dragging
(4) Second-order Shapiro
Other Issues

- Probe the accretion flow onto the black hole via dispersion-measure variations.
- Dynamics of the Sgr A* cluster. Gravitational perturbations may be evident in the timing residuals.
- Radio imaging and astrometry. It may be possible to measure the precession of the orbit and determine the spin of the black hole in 3-D.