Pulsar timing in Extreme Mass Ratio Binaries

Tom Kimpson w/, Kinwah Wu, Silvia Zane.
July 2, 2019
Mullard Space Science Laboratory, UCL
GR is incomplete

- Field equations = Non-unique
- Breaks down: Singularities + Quantum Gravity
Strong vs. Weak fields

\[ \epsilon \propto \frac{M}{r} \]

\[ \epsilon \sim 10^{-10} \quad \epsilon \sim 10^{-6} \quad \epsilon \sim 10^{0} \]

Weak Field \quad \text{Strong Field}
How can we probe strong fields?

- Extreme Mass Ratio Binary (EMRB)
- Event Horizon Clock
Strong-field probe

Weak Field

$\epsilon \sim 10^{-10}$

$\epsilon \sim 10^{-6}$

$\epsilon \sim 0.01$

Strong Field

$\epsilon \sim 10^0$
3 important parameters:

\[ M, \chi, Q \]

**Fundamental Physics**

- No Hair Theorem \( (Q = -\chi^2) \)
- Cosmic Censorship Conjecture \( (\chi \leq M^2) \)

**Astrophysics**

- Astrophysical BH = Kerr solution?
- Constrain low end of \( M - \sigma \) relation / Existence of IMBH
Hunting Grounds

- Galactic Centre
- Globular Clusters
Detection Prospects

• Closest semi-major axis $\approx 100$ AU
Detection Prospects

- $\lesssim 10^4$ PSR at $< 1$ pc \cite{Wharton2012, Rajwade2017}
- Closest semi-major axis $\lesssim 100$ AU
- Closest pericentre distance $\sim 2$ AU \cite{Zhang2014}

No such PSR-EMRB yet detected!
Goal: Use the next-generation radio telescopes to time a pulsar in orbit around a massive central black hole.

Require theoretical basis for PSR Timing Signal
This Work: Why?

- Detection. *e.g.* Are our algorithms good enough?
- Modelling. *i.e.* GR predictions vs. observation
This Work: How?

Require theoretical basis for PSR Timing Signal

Behaviour of light + Orbital Dynamics = Timing signal
This Work: How?

Require theoretical basis for PSR Timing Signal

Behaviour of light + Orbital Dynamics = Timing signal
Ray Tracing
This Work: How?

Require theoretical basis for PSR Timing Signal

Behaviour of light + Orbital Dynamics = Timing signal
• Textbook GR: point particles.
• Real pulsars $\neq$ point particles!
Creating the skeleton

$T^\mu_\nu;\nu = 0$

Multipole expansion to dipole order:

$$\frac{Dp^\mu}{d\tau} = -\frac{1}{2} R^\mu_{\nu\alpha\beta} u^\nu s^{\alpha\beta}$$

$$\frac{Ds^{\mu\nu}}{d\tau} = p^\mu u^\nu - p^\nu u^\mu$$

Equations are indeterminate

(Mathisson 1937, Papetrou 1951, Dixon 1974)
Choosing a centre of mass

Multipole expansion defined w.r.t some reference worldline $z^\alpha(\tau)$. Centre of mass is observer dependent.

How to choose a reference worldline?

Spin Couplings

- Spin-spin
- Spin-orbit
- Spin-curvature
Orbital Dynamics: circular
Spin Precession
Putting it all together...

Behaviour of light + Orbital Dynamics = Timing signal
Putting it all together...

Behaviour of light + Orbital Dynamics = Timing signal

Optimization problem

\[ f(\alpha, \beta) \]
Effects to consider

- Gravitational lensing
- Primary/Secondary rays
- Influence of plasma: temporal/spatial dispersion
- Gravitational/Relativistic time dilation
- Orbital Dynamics
- Spin-curvature coupling (+spin-spin, spin-orbit)
- Spin precession
- Relativistic aberration

Photon ToA, pulse profile, intensity, observability
Effects to consider

- Gravitational lensing
- Primary/Secondary rays
- Influence of plasma: temporal/spatial dispersion
- Gravitational/Relativistic time dilation
- Orbital Dynamics
- Spin-curvature coupling (+spin-spin, spin-orbit)
- Spin precession
- Relativistic aberration

Photon ToA, pulse profile, intensity, observability
Gravitational Bending

- Deviation from straight lines
- Primary/Secondary Rays
Plasma: spatial dispersion
• PSR-EMRB = precision strong-gravity probes
• Require fully relativistic $t - \nu$ model
• Open question: How good are current methods?

**References:**
Questions?
• Pulsar emission \( \neq \) isotropic
• Find intersection with radiation point
  \( x^i_{\text{rad}} = R_{\text{PSR}} \hat{n} + x^i_{\text{pulsar}} \)
• \( \hat{n} = \hat{n}(S_\theta(\tau), \psi) \)
Aberration

- ‘Seen’ if $\omega < \omega_c$
- Global $\omega \neq$ Local $\omega$
- Transform to coming frame