Pulsar Timing in Extreme Mass Ratio Binaries

Tom Kimpson w/, Kinwah Wu, Silvia Zane.
July 10, 2019

Mullard Space Science Laboratory, UCL
A Problem

GR is incomplete

- Field equations = Non-unique
- Breaks down: Singularities + Quantum Gravity
• Extreme Mass Ratio Binary (EMRB)
• Event Horizon Clock
A precision, strong-field probe

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

Gravity Probe B

MICROSCOPE

Sun

Hulse-Taylor

Double PSR

S2

EMRB
Scientific prospects

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 $\lesssim 100$ AU
Detection Prospects

- Closest semi-major axis $\lesssim 100$ AU

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

(\text{Mathisson 1937, Papetrou 1951, Dixon 1974} )
Spin Couplings

- Spin-spin
- Spin-orbit
- Spin-curvature
Orbital Dynamics: circular
Orbital Dynamics: eccentric
Spin Precession

The diagram illustrates the concept of spin precession. The precession is depicted as an elliptical path, with arrows indicating the direction of rotation. The plot on the right shows the variation of $S_y$ with $S_x$, demonstrating the precessional motion in a coordinate system.
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
Summary

- PSR-EMRB = precision strong-gravity probes
- Require fully relativistic $t - \nu$ model
- Open question: How good are current methods?

References:
Questions?
Putting it all together...

- Pulsar emission \( \neq \) isotropic
- Find intersection with radiation point
  \[ x^i_{\text{rad}} = R_{PSR} \hat{n} + x^i_{\text{pulsar}} \]
- \( \hat{n} = \hat{n}(S_\theta(\tau), \psi) \)
Aberration

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