Gravity with the SKA

Strong-field tests of gravity using Pulsars and Black Holes

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Outline

• Pulsars
• Past and present successes
• A giant leap - the power of the SKA
• Transforming our knowledge of fundamental physics, particularly:
  - Strong-field tests of gravity
  - Gravitational wave astronomy

Searching & Timing: see Jim
Gravitational Waves: see Rick
A frequently asked question, still...
Testing Einstein

Experiments made in Solar System provide accurate tests...but only in weak gravitational field!

In strong gravitational fields, physics may be different!

Compute energy in gravitational field:

\[ \varepsilon = \frac{E_{\text{gravity}}}{mc^2} \]

Neutron stars & Black Holes:

\[ \varepsilon_{NS} \approx 0.15 \]
\[ \varepsilon_{BH} \approx 0.5 \]

Solar system:

\[ \varepsilon_{Sun} \approx 0.0000001 \]
\[ \varepsilon_{Earth} \approx 0.00000000001 \]
\[ \varepsilon_{Moon} \approx 0.0000000000001 \]

Radiative aspects need to be tested too!
Pulsars are extreme objects...

- Cosmic lighthouses ...
- Precise clocks ...
- Almost Black Holes ...
- Objects of extreme matter ...
  - 10x nuclear density
  - \( B \sim B_q = 4.4 \times 10^{13} \) Gauss
  - Voltage drops \( \sim 10^{12} \) V
  - \( F_{EM} = 10^{10-12} F_g \)
  - High-temperature & superfluid superconductor
- Massive stable flywheels \( \Rightarrow \) superb cosmic clocks
  e.g. period of B1937+21:

\[
P = 0.0015578064924327 \pm 0.000000000000000004 \text{ s}
\]

Precision tools for a wide range of fundamental physics and astrophysics
The importance of pulsar tests
Strong-field tests using pulsars...

Various approaches:

Parameterized Post-Newtonian (PPN)

Binary pulsars

Theory-independent or phenomenological:
Parameterized Post-Keplerian approach

Theory-dependent:
Beyond usual post-Newtonian parameters, used for classes of tensor-scalar theories
### Parametrized post-Newtonian (PPN)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>How much space curvature per unit mass?</td>
<td>$1 \gamma^{-1} &lt; 2 \times 10^{-3}$</td>
<td>Viking ranging (time delay)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td></td>
<td>$1 \gamma^{-1} &lt; 3 \times 10^{-4}$</td>
<td>VLBI (light deflect.)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>How much “non-linearity” in the superposition law?</td>
<td>$1 \beta^{-1} &lt; 3 \times 10^{-3}$</td>
<td>Perihelion shift</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Preferred-location effects?</td>
<td>$0</td>
<td>\xi</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>Preferred-frame effects? Orbital polarization</td>
<td>$0 \alpha_1 &lt; 10^{-4}$</td>
<td>Lunar ranging (weak)</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td></td>
<td>$0 \alpha_1 &lt; 1.2 \times 10^{-4}$</td>
<td>Pulsars (strong)</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>Preferred-frame effects? Spin precession</td>
<td>$0 \alpha_2 &lt; 4 \times 10^{-7}$</td>
<td>Solar alignment</td>
</tr>
<tr>
<td>$\alpha_3$</td>
<td>Preferred-frame effects? Violation of conversation of total momentum</td>
<td>$0 \alpha_3 &lt; 4.0 \times 10^{-20}$</td>
<td>Pulsars</td>
</tr>
</tbody>
</table>

**Plus:** limits on violation of SEP: $|\Delta| < 5.5 \times 10^{-3}$
...already a success story: The first binary pulsar

Hulse & Taylor (1974)

PSR B1913+16

1.9 Mill. km

unseen

$M_c = 1.39 \, M_\odot$

$M_p = 1.44 \, M_\odot$

$P = 59\, \text{ms}$

$P_b = 7.8\, \text{h}$

$e = 0.617$

Weisberg & Taylor (2004)

- Orbit shrinks every day by 1cm
- Confirmation of existence of gravitational waves
Tests of General Relativity

Elegant method to test any theory of gravity:
(Damour & Taylor '92)

Relativistic corrections to Keplerian orbits measured
• All corrections can be written as function of the pulsar masses
• Only one true combination of $m_A$ and $m_B$ should exist

Single unique point in a $m_A - m_B$ diagram!
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$N_{pk} - 2$ tests possible
...already a success story:
The first double pulsar

- most relativistic systems
- most over-constrained system:
  - Five PK params
  - Theory independent mass ratio

\( s = \sin(i) = 0.9997 \pm 0.0002 \)

Testing GR:
\[
\frac{S_{\text{exp}}}{S_{\text{obs}}} = 1.000 \pm 0.001
\]

Kramer et al. (in prep)
Double Pulsar: Tests of GR

December 2003 (Lyne et al. 2004)
Double Pulsar: Tests of GR

Kramer et al. in prep.
...already a success story: Scalar-Tensor Theories

Scalarisation

Solar-system and future binary-pulsar constraints on tensor–scalar theories

Damour (priv. comm.)

\[ |\alpha_0| \]

Solar-system and pre-2003 binary-pulsar constraints on tensor–scalar theories

\[ J_{0737-3039} \]

+ 1% accurate $\dot{P}$

\[ J_{1141-6545} \]

+ 1% accurate $\dot{P}$

1534+12

SEP tests

0655+64

1913+16

0655+64

solar system

general relativity

Damour (priv. comm.)
The is more to do:

- The remaining “holy grail”: a pulsar – black hole system!
- Wanted: millisecond pulsar around black hole

"...a binary pulsar with a black-hole companion has the potential of providing a superb new probe of relativistic gravity. The discriminating power of this probe might supersede all its present and foreseeable competitors...

(Damour & Esposito-Farese 1998)
Galactic Census with the SKA

- Blind survey for pulsars will discover PSR-BH systems!
- Timing of discovered binary and millisecond pulsars to very high precision:
  - “Find them!”
  - “Time them!”
  - “VLBI them!”

Benefiting from SKA twice:
- **Unique sensitivity**: many pulsars, ~10,000–20,000 incl. many rare & exotic systems!
- Not just a continuation of what has been done before - Complete new quality of science possible!
Pulsar Science with the SKA

Very wide range of applications:

- **Galactic probes:**
  - Interstellar medium/magnetic field
  - Star formation history
  - Dynamics
  - Population via distances (ISM, VLBI)

- **Electron distribution**

- **Movement in potential**

  - Galactic Centre
Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars: Formation & Population
  Turbulent magnetized IGM

Search nearby galaxies!

Giant pulses

Reach the local group!
Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- **Relativistic plasma physics:** Radio emission
  Resolving magnetospheres
  Relation to high-energies
Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics
- **Extreme Dense Matter Physics:**
  - Ultra-strong B-fields
  - Equations-of-State
  - Core collapses
  - Variation of $G$
Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics
- Extreme Dense Matter Physics

- Multi-wavelength studies: Photonic windows
Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics
- Extreme Dense Matter Physics

- Multi-wavelength studies: Photonic windows
  Non-photonic windows
Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics
- Extreme Dense Matter Physics
- Multi-wavelength studies
- **Exotic systems:** planets
  - millisecond pulsars
  - relativistic binaries
  - double pulsars
  - PSR-BH systems

3. Holy Grail: PSR-BH
Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics
- Extreme Dense Matter Physics
- Multi-wavelength studies
- Exotic systems

- **Gravitational physics:**
  - Strong-field tests
  - BH properties
  - Gravitational Waves
Black Hole spin:

- Astrophysical black holes are expected to rotate

\[ \chi = \frac{c S}{G M^2} \]

- Result is relativistic spin-orbit coupling
- Visible as a precession of the orbit:
  Measure higher order derivatives of secular changes in semi-major axis and longitude of periastron \( \dot{\omega}, \dot{x}, \ddot{x} \)

- Not easy! It is not possible today!
- Requires SKA sensitivity!

See Wex & Kopeikin (1999)
Black Hole properties

Black Hole quadrupole moment:

- Spinning black holes are oblate

\[ q \equiv \frac{c^4}{G^2} \frac{Q}{M^3} \]

- Result is classical spin-orbit coupling
- Visible as transient signals in timing residuals
- Even more difficult!
- Requires SKA!

Wex & Kopeikin (1999):
For all compact massive, BH-like objects, we’ll be able to measure spin very precisely.

In GR, for Kerr-BH we expect:

\[ \chi \leq 1 \]

But if we measure

\[ \chi > 1 \iff \text{Event Horizon vanishes} \iff \text{Naked singularity!} \]

Then: either GR is wrong or Censorship Conjecture is violated!
• If we measure

\[ q \neq -\chi^2 \]

either GR is wrong, i.e. “no-hair” theorem is violated
or we have discovered a new kind of object, e.g. a Boson star with

\[ q \leq -10\chi^2 \]
Fundamental Physics with the SKA

Pulsars discovered and observed with the SKA...

- complement studies in other windows
- probe wide range of physical problems
- New science possible – not just the same:
  - Was Einstein right?
  - What are the Black Hole properties?
  - Do naked singularities exist?
  - Do Black Holes have “hairs”?

Work to be done: 2PN timing formula
Calibration techniques
Means to handle blind survey
Efficient timing methods
(LOTS of data, LOTS of pulsars)
The SKA sky!