The double pulsar system:

A unique lab for relativistic plasma physics and tests of general relativity

Michael Kramer
Bad Honnef – 15th May 2006
Outline

- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- Moment-of-inertia
- Frame-dragging
- Summary
Outline

• The double pulsar
• A plasma & gravity lab
• Precision tests of GR
• Moment-of-inertia
• Frame-dragging
• Summary

Collaborators

and N. Wex
Outline

• The double pulsar
• A plasma & gravity lab
• Precision tests of GR
• Moment-of-inertia
• Frame-dragging
• Summary

Collaborators

and N. Wex
The double pulsar

PSR J0737-3039 discovered in April 2003 at Parkes in high-latitude survey (Burgay et al. 2006):

J0737-3039
The first double pulsar system

- A young 2.77-s pulsar in a 2.4-hr orbit with an old 22-ms pulsar.
- Orbit size ~ Sun, with orbital velocities of 1 Million km/h!
- Ideal lab for gravitational physics and understanding pulsars.

Burgay et al. (2003), Lyne et al. (2004)
### Basic parameters

<table>
<thead>
<tr>
<th>A:</th>
<th>B:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>$22.7 \text{ ms}$</td>
</tr>
<tr>
<td>$\dot{P}$</td>
<td>$1.7 \times 10^{-18}$</td>
</tr>
<tr>
<td>Char. age</td>
<td>$200 \text{ Myr}$</td>
</tr>
<tr>
<td>$B_{\text{surf}}$</td>
<td>$6 \times 10^9 \text{ G}$</td>
</tr>
<tr>
<td>$R_{\text{LC}}$</td>
<td>$1,080 \text{ km}$</td>
</tr>
<tr>
<td>$B_{\text{LC}}$</td>
<td>$5 \times 10^3 \text{ G}$</td>
</tr>
<tr>
<td>$\frac{dE}{dt}$</td>
<td>$6 \times 10^{33} \text{ erg s}^{-1}$</td>
</tr>
<tr>
<td>Mean $V_{\text{orb}}$</td>
<td>$301 \text{ km s}^{-1}$</td>
</tr>
</tbody>
</table>
Birth & Rebirth in the double pulsar

1. First pulsar is born in Supernova explosion
2. First pulsar is spun up by mass transfer from companion
3. Second pulsar is born in Supernova explosion

Dramatic confirmation of evolutionary theories!
The life of pulsars
Outline

• The double pulsar
• A plasma & gravity lab
• Precision tests of GR
• Moment-of-inertia
• Frame-dragging
• Summary
Outline

• The double pulsar
• A plasma & gravity lab
• Precision tests of GR
• Moment-of-inertia
• Frame-dragging
• Summary
An energetic pulsar wind from A interacts with B. The emission from B is affected. B is only visible for short parts of the orbit!
Orbital modulation of “B” emission

Two bright intervals near inferior conjunction:

1.4 GHz

Effelsberg 4.85 GHz
Direct modulation of B’s emission by A

McLaughlin et al. (2004a)
Huge precession of orbit!

Orbit precesses by 17 deg/yr!

• Measured within a few days of observations!
• One full revolution in about 20 years!
  (compared to 3 Million years for Mercury)

Remember Mercury:
\[ \dot{\omega} = 0.00012 \text{deg/yr} \]
Orbit is shrinking by 7mm per day!

- Change in orbital period due shrinking orbit
- Neutron stars will collide in 85 Million years due to gravitational wave emission!

- Discovery boosts expected LIGO detection rates by almost an order of magnitude...!
Pulsar clock slows down near companion!

Clocks are running slower in deep gravitational fields

Pulsars’ separation is changing during orbit:

Pulsars are running slower and faster during orbit by about 380 microseconds! (grav.redshift + 2nd order Doppler)
Space-time is curved near pulsar

Pulses of A are delayed when propagating through curved space-time near B:
Space-time is curved near pulsar Pulses of A are delayed when propagating through curved space-time near B:

\[ s = \sin(i) = 0.99978 \pm 0.00012 \]
Space-time is curved near pulsar

Pulses of A are delayed when propagating through curved space-time near B:

System is seen edge-on!
Space-time is curved near pulsar

Also, eclipses of A:

Orbital phase

last for ~27 sec

System is seen edge-on!

\[ i = 88.7 \text{ deg} \]

To Earth

30,000km
Eclipses of A

At superior conjunction lasting for ~27 sec

System is seen edge-on!

To Earth

30,000 km

Lyne et al. (2004)

McLaughlin et al. (2004)
Eclipses of A

Power Spectrum

Eclipse duration vs. frequency

Brenton et al. (in prep)

McLaughlin et al. (2004)
Outline

• The double pulsar
• A plasma & gravity lab
• Precision tests of GR
• Moment-of-inertia
• Frame-dragging
• Summary
Outline

• The double pulsar
• A plasma & gravity lab
• Precision tests of GR
• Moment-of-inertia
• Frame-dragging
• Summary
Testing Einstein

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

In strong gravitational fields, physics may be different!

E.g. additional scalar field may appear in strong fields:

Scalar Charge
(for $\beta_0=-6$)

“Scalarisation”

Damour & Esposito-Farese (1996)
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:

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

Neutron stars & Black Holes:

- \( \mathcal{E}_{NS} \approx 0.15 \)
- \( \mathcal{E}_{BH} \approx 0.5 \)

Solar system:

- \( \mathcal{E}_{Sun} \approx 0.000001 \)
- \( \mathcal{E}_{Earth} \approx 0.0000000001 \)
- \( \mathcal{E}_{Moon} \approx 0.000000000001 \)
Strong-field tests with binary pulsars

Elegant method to test (falsify!) any theory of gravity
(Damour & Taylor ’92)

Effects can be described as Post-Keplerian params as function of only the observed Keplerian params and the masses of pulsar and companion, eg in GR:

\[ \dot{\omega} = 3T_\odot^{2/3} \left( \frac{P_b}{2\pi} \right)^{-5/3} \frac{1}{1-e^2} \left( m_p + m_c \right)^{2/3} \]

\[ PK = f(K, m_p, m_c) \]

\[ m_c = g(K, PK, m_p) \]

\( f, g \) depend on theory!
Strong-field tests with binary pulsars

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

Effects can be described as Post-Keplerian params as function of only the observed Keplerian params and the masses of pulsar and companion, eg in GR:

$$\dot{\omega} = 3T^{2/3}_\odot \left( \frac{P_b}{2\pi} \right)^{-5/3} \frac{1}{1-e^2} (m_p + m_c)^{2/3}$$

$$PK = f(K, m_p, m_c)$$

$$m_c = g(K, PK, m_p)$$

$f, g$ depend on theory!
Strong-field tests with binary pulsars

Elegant method to test (falsify!) any theory of gravity

(Damour & Taylor '92)

Effects can be described as Post-Keplerian params as function of only the observed Keplerian params and the masses of pulsar and companion, eg in GR:

\[
\dot{\omega} = 3T_0^{2/3} \left( \frac{P_b}{2\pi} \right)^{-5/3} \frac{1}{1-e^2} (m_p + m_c)^{2/3}
\]

\[PK = f(K, m_p, m_c)\]

\[m_c = g(K, PK, m_p)\]

\[N_{pk} - 2 \text{ tests possible}\]
Double Pulsar: Tests of GR
Double Pulsar: Tests of GR

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

Kramer et al. in prep.

Graph showing the relationship between Mass A and Mass B with Mass A shown on the x-axis and Mass B shown on the y-axis. The graph includes various lines and markers indicating different parameters such as T, P_b, R, γ, and S. The inset graph focuses on a specific range of Mass A values.
Double Pulsar: Tests of GR

\[ M_B = 1.2489(8)M_\odot \]

\[ M_A = 1.3381(8)M_\odot \]
Kepler's 3rd law:

\[ R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B} \]
Significance of "R"

To 1PN order, Kepler's 3rd law given in generic form as:

\[
a_R = \left( \frac{G_{AB}M_{tot}}{n^2} \right)^{1/3} \left[ 1 - \frac{1}{6} (5\varepsilon + 3 - 2\nu) \left( \frac{G_{AB}M_{tot}}{c^3} \right)^{2/3} \right] = \frac{x_B}{x_A} = \frac{m_A}{m_B}
\]

so that for "any" theory of gravity to 1PN order:

\( R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B} \)

is independent of strong-field effects!

Different to other PK parameters, which all depend on strong-field modified "constants"!

(e.g. \( G_{AB} \) differs from \( G^{\text{Newton}} \) depending on strong-field effects)

e.g. Damour & Taylor '92
Double Pulsar: Tests of GR

Kramer et al. in prep.

Mass ratio & 5 PK parameters $\Leftrightarrow 6 - 2 = 4$ potential tests!
More than in any system!
Double Pulsar: Tests of GR

Based on:

\[ R = 1.071 \pm 0.001 \text{ & } \dot{\omega} = 16.8995 \pm 0.0007 \text{ deg/yr} (0.004\%) \]

<table>
<thead>
<tr>
<th>Expected in GR:</th>
<th>Observed:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma = 0.3840 \text{ ms} )</td>
<td>( \gamma = 0.3839 \pm 0.0011 \text{ ms} \ (0.3%) )</td>
</tr>
<tr>
<td>( \frac{dP_b}{dt} = -1.248 \times 10^{-12} )</td>
<td>( \frac{dP_b}{dt} = (-1.252 \pm 0.014) \times 10^{-12} ) (1.2%)</td>
</tr>
<tr>
<td>( r = 6.152 \mu s )</td>
<td>( r = 6.21 \pm 0.24 \mu s ) (4%)</td>
</tr>
<tr>
<td>( s = 0.99987 )</td>
<td>( s = 0.99978 \pm 0.00012 ) (0.01%)</td>
</tr>
</tbody>
</table>

- Best test in strong-field
- Purely non-radiative with fundamentally different constraint!

Kramer et al. to be submitted.
Outline

• The double pulsar
• A plasma & gravity lab
• **Precision tests of GR**
• Moment-of-inertia
• Frame-dragging
• Summary
Outline

- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- Moment-of-inertia
- Frame-dragging
- Summary
Geodetic Precession

- Relativistic Spin-Orbit Coupling
- First prediction for binary pulsar by Damour & Ruffini (1974)
- Precession rate expected in GR:
  \[
  \Omega_p = \left(\frac{2\pi}{P_b}\right)^{5/3} T_{\odot}^{2/3} \frac{m_c (4m_p + 3m_c)}{2(m_p + m_c)^{4/3}} \frac{1}{1 - e^2}, \quad T_{\odot} = GM_\odot c^{-3}
  \]

What effects do we expect to observe?
Effects of Geodetic Precession
The Effects of Geodetic Precession

- Pulsar may not always be visible
- Line-of-Sight will change
- Changes in pulse shape, width and polarization
Geodetic Precession in J0737-3039A

- Precession period of double pulsar only 71/74 years!
- Expect to see effects already!

A

B

not yet seen!

seen!
Spin-orbit coupling

Relativistic spin-orbit coupling contributions to observed periastron advance:

• Formally, spin-orbit coupling enters at 1PN level!
• For binary pulsars however, numerically they are of size of 2PN effects (Wex 1995), so usually they are ignored
• However, for double pulsar, precision in periastron advance measurements has reached 2PN limit!
Spin contributions in Double Pulsar

Total periastron advance at 2PN level: Damour & Schaefer (1988)

\[ k^{tot} = \frac{3 \beta_0^2}{1 - e_T} \left[ 1 + f_0 \beta_0^2 - g_S A \beta_A^A \beta_S^A + g_S B \beta_A^B \beta_S^B \right] \]

1PN 2PN Spin A Spin B

Geometry dependent Neutron star dependent

Assuming 'canonical' values:

1PN = 16.9 deg/yr
2PN = 0.0004 deg/yr
SpinA = 0.0002 deg/yr

Need two other parms with similar precision... Not easy! sin(i), Pbdot?
Neutron star structure

Total periastron advance to 2PN level: Damour & Schaefer (1988)

\[ k_{\text{tot}} = \frac{3 \beta_0^2}{1 - e_T} \left[ 1 + f_0 \beta_0^2 - g_S^A \beta_0^A \beta_S^A + g_S^B \beta_0^B \beta_S^B \right] \]

1PN 2PN Spin A Spin B

Equation-of-State!

Measure NS moment of inertia!!!
Equation of State

- Measurement of $M$ & $I$ better than $M$ & $R$
- Even low precision with important consequences for EOS:
  
  E.g. Lattimer & Schutz (2005)

Already some constraints from mass of B under assumption about supernova explosion (see Podsiadlowski et al. 2005)
Outline

- The double pulsar
- A plasma & gravity lab
- Precision tests of GR
- **Moment-of-inertia**
- Frame-dragging
- Summary
Outline

• The double pulsar
• A plasma & gravity lab
• Precision tests of GR
• Moment-of-inertia
• Frame-dragging
• Summary
New Scientist, Sep. '04

One loose or two?

This argument has been raging for almost 250 years: are the head louse and the body louse distinct species or one and the same creature? A genetic analysis may finally settle the question, and even help when it comes to fighting off the little parasites, which are straining comeback in rich countries.

Linnaeus named the human louse Pediculus humanus in 1758, but later realized there might be two species. Debate has gone on ever since. Those who regard body lice as a separate species point out that they are bigger than head lice and live in clothes rather than in hair. They can also transmit diseases such as typhus and trench fever, something head lice have never been shown to do.

Other experts dismiss these differences and argue that, because head and body lice interbreed if kept together in the lab, they must be the same species. Then again, breeding under artificial conditions is a poor test of a species.

To find out if head and body lice interbreed in the wild, Natalie Lee and Stephen Barker of the University of Queensland in Brisbane, Australia, collected lice from seven boys in Nepal and four girls in Inner Mongolia in China. A form of DNA fingerprinting of 445 lice showed there were two genetically distinct populations. "The head lice were one big family; the body lice were one big family," says Barker.

Further studies on children who shared sleeping quarters showed that the lice travelled from the body of one child to the body of another, or from head to head, but never between the body and head. Evidence is that the two populations were not interbreeding and that head and body lice are different species.

The best way to treat head lice is to use permethrin. Many health authorities, including the US Centers for Disease Control, advise treating clothes and sheets. Other experts say parents should not waste time beating clothes. The latest findings, reported at an entomology conference in Brisbane last month, support the idea that the parents of children with head lice should concentrate on their heads. "Your head louse, shifting to clothes would be like setting up across the desert," says Barker.

Rachel Rosak, Melbourne

Neutron stars steal space probe's glory

It has taken almost 50 years to conceive and build and has cost more than $700 million, but now NASA's Gravity Probe B spacecraft could be upset by telescopes on the ground.

The craft is designed to accurately test Einstein's general theory of relativity. According to the theory, a gyroscope orbiting a massive object such as the Earth should experience two forces that gradually cause it to "precess", just as the Earth's axis of spin is offset from that of the Sun. The stronger force, known as the geodetic effect, is caused by the Earth's warping the fabric of space-time. The other, known as the gravitational effect, is caused by the rotating Earth's dragging space and time with it.

Gravity Probe B, which carries ultra-sensitive gyroscopes, was conceived in the 1950s to measure these forces, but was only launched in April this year. It has yet to take any measurements. Francis Everitt, the physicist in charge of the project at Stanford University, says the probe should produce results by mid-2006.

Meanwhile, astronomers have been studying binary pulsars - two rapidly spinning neutron stars orbiting each other - to measure these effects. The gravitational fields of pulsars are so strong that both of the forces predicted by Einstein should show up relatively clearly in the motion of each pulsar in a binary system, much like that for a gyroscope.

Last week, Egbert W. van Haam of the University of British Columbia in Vancouver and colleagues reported for the first time that the observed precession in a binary pulsar due to the gravitational effect was consistent with that predicted by general relativity (www.ambricap.com/astron/...).

The big prize for Gravity Probe B is now the geodetic effect, which is hundreds of times weaker than the gravitational effect and is unlikely to be seen in the near future by Stanford's team. But earlier this year, astronomers announced the discovery of a binary system in which the pulsars are much closer together than orbit each other every 2.4 hours. The discovery has triggered a hunt of satellites to gather data on the pulsars from radio telescopes all over the world and a hunt through historical records for past observations of the system.

The huge gravitational forces at work in it should make some of the effects predicted by relativity easy to see, says Robert O'Connell, a theoretical physicist at Louisville State University in Better Boise. For instance, the geodetic effect should cause the axis of the pulsars to precess 2500 times faster than the error on Gravity Probe B, says O'Connell.

"The gravitational fields of pulsars are so strong that the force predicted by Einstein should show up relatively clearly," says Egbert W. van Haam of the University of British Columbia in Vancouver and colleagues reported for the first time that the observed precession in a binary pulsar due to the gravitational effect was consistent with that predicted by general relativity (www.ambricap.com/astron/...).

The big prize for Gravity Probe B is now the geodetic effect, which is hundreds of times weaker than the gravitational effect and is unlikely to be seen in the near future by Stanford's team. But earlier this year, astronomers announced the discovery of a binary system in which the pulsars are much closer together than orbit each other every 2.4 hours. The discovery has triggered a hunt of satellites to gather data on the pulsars from radio telescopes all over the world and a hunt through historical records for past observations of the system.

The huge gravitational forces at work in it should make some of the effects predicted by relativity easy to see, says Robert O'Connell, a theoretical physicist at Louisville State University in Better Boise. For instance, the geodetic effect should cause the axis of the pulsars to precess 2500 times faster than the error on Gravity Probe B, says O'Connell.

"The gravitational fields of pulsars are so strong that the force predicted by Einstein should show up relatively clearly," says Egbert W. van Haam of the University of British Columbia in Vancouver and colleagues reported for the first time that the observed precession in a binary pulsar due to the gravitational effect was consistent with that predicted by general relativity (www.ambricap.com/astron/...).
Evidence for Frame-dragging Effects

Illustration of frame dragging effects using simple model:

- Following Nordtvedt (1988) look at theories in PPN limit that differ from GR only in PPN parms $\alpha_1, \alpha_2$
- without preferred-frame effects, we get:

(see Nordtvedt 1988, Will 1993)

\[
\begin{align*}
g_{00} &= -1 + 2U - 2U^2 + \ldots \\
g_{0j} &= -\frac{1}{2} (7 + \alpha_1 - \alpha_2) V_j - \frac{1}{2} (1 + \alpha_2) W_j \\
g_{ij} &= (1 + 2U) \delta_{ij}
\end{align*}
\]

Hence, no framing-dragging effects only for $g_{0j} = 0$, or $\alpha_1 = -8$, $\alpha_2 = -1$
Evidence for Frame-dragging Effects

- In this simple framework, one can show that

\[ \dot{\omega}_{\text{obs}} = (1 + \Delta) \dot{\omega}_{\text{GR}} \]

with

\[ \Delta = \frac{1}{6} \left( 2\alpha_1 - \alpha_2 \right) \frac{\mu}{M} \]


- Determine GR value from Shapiro and mass ratio which are independent of frame-dragging effects

- Compare predicted GR value to observed value, obtaining a limit on \( \Delta \) and hence non-existing of frame-dragging
Evidence for Frame-dragging Effects

In our choice of theories, we have 2d-plane for illustration:
Evidence for Frame-dragging Effects

In our choice of theories, we have 2d-plane for illustration:

- GR
- Double Pulsar: $\Delta < 2 \times 10^{-3}$ (95%)
- Effects are clearly seen!
- No Frame-dragging
Evidence for Frame-dragging Effects

Even in this simple framework with only two parameters, one sees that Gravity Probe-B is testing different aspects:

No replacement but comforting complementary evidence!
Outline

The Future
The Square-Kilometre-Array
The "Square-Kilometre-Array"
The "Square-Kilometre-Array"

- The biggest telescope ever built
- Tackling Noble-prize science
- Construction 2012-2020, first science by 2015
- The science case requires: gigantic collecting area, huge field-of-view (FOV), large spatial resolution, multiple, independent FOVs
A Galactic Census of pulsars

- SKA will essentially discover ‘all’ Galactic pulsars!

- Find pulsars around stellar BH and in Galactic Centre
- Measure BH properties: masses, spin & quadrupole moment
- Testing GR description of BHs, such as Cosmic Censorship Conjecture & No-hair theorem

Until then...

- Double pulsar has lived up to all its expectations
- Valuable tool to probe a pulsar magnetosphere
- Most relativistic system ever found
- Unique testbed for theories of gravity
- Best strong-field test of GR ever
- With continuing timing observations precision will continue to improve (“No show-stopper”)
- Double Pulsar will surpass ALL solar system tests!
- Measure relativistic orbital deformation and aberration for the first time soon
- Measure moment of inertia of a neutron star
Final comment...