Relativity & magnetospheric physics with the double pulsar system

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A double pulsar system - a few years ago?!

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The double pulsar today - one of astronomy’s holy grails
The Double Pulsar System: Outline

- Introduction to pulsars
- Discovery and basic properties of the double pulsar
- Interactions - probing magnetospheres and winds
- Testing general relativity in the strong-field regime
- The ultimate fate of the double pulsar system
- Future prospects

Principle collaborators:

Maura McLaughlin, Michael Kramer, Andrew Lyne, Ingrid Stairs, Andrea Possenti, Marta Burgay, Dick Manchester, Paulo Freire, Fernando Camilo
The Double Pulsar System: Pulsars - What are they?

- Pulsars are compact, highly magnetized neutron stars formed in supernova explosions of massive stars.

Supernova remnant Messier 1

Jocelyn Bell, Cambridge UK
The Double Pulsar System: Pulsars - What are they?
The Double Pulsar System: Pulsars - How do they work?
The Double Pulsar System: Pulsars - History

Currently about 1700 pulsars known
The Double Pulsar System: Telescopes used...
The Double Pulsar System: Pulsars - Population

- Globular Cluster: 3
- Binary: 20
- Planets: 15 Millisecond
- SNRs: 4
- LMC: 1
- SMC: 1
- ~1400 "normal" pulsars
The Double Pulsar System: Discovery

- PSR J0737-3039 (with spin period of 22 ms and 2.4-hr eccentric orbit) discovered in April 2003 in the Parkes Multibeam High Latitude Survey (Burgay et al. 2003, Nature, 426, 531).

- Timing indicated that the companion must be another neutron star.

![Pulse profile of A](image1)

![Parkes Multibeam Receiver](image2)
The Double Pulsar System: Discovery

- In October 2003, analysis of data taken for studies of PSR J0737-3039 (now “A”) shows presence of 2.7-s pulsations.

- Identical dispersion measure to A and period variations as expected for A’s measured orbit show that this is indeed A’s companion.

- In agreement with simple evolutionary models in which:
  - A is first-born, recycled neutron star (short period, low B)
  - B is younger, normal neutron star (long period, high B)

- The following movie shows how we think such a system formed...
### The Double Pulsar System: Summary

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar period (ms)</td>
<td>22.7</td>
<td>2774</td>
</tr>
<tr>
<td>Stellar mass (solar masses)</td>
<td>1.34</td>
<td>1.25</td>
</tr>
<tr>
<td>Projected semi-major axis (lt-s)</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Surface magnetic field strength (Gauss)</td>
<td>$6 \times 10^9$</td>
<td>$2 \times 10^{12}$</td>
</tr>
<tr>
<td>Energy loss rate due to spin-down (ergs/s)</td>
<td>$5800 \times 10^{30}$</td>
<td>$2 \times 10^{30}$</td>
</tr>
<tr>
<td>Distance (pc)</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Orbital inclination (degrees)</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Orbital period (hours)</td>
<td>2.45</td>
<td></td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.088</td>
<td></td>
</tr>
</tbody>
</table>

First double pulsar system ever, and most extreme and relativistic pulsar binary system ever! (Lyne et al. 2004, Science, 303, 1153)
The Double Pulsar System: Interactions - Geometry

\[ R_{LC} = \frac{cP}{2\pi} \]

B’s light cylinder is 100 times that of A.

A’s energy loss due to spindown is 3000 times that of B.
The Double Pulsar System: Interactions - Geometry

- A large portion of a pulsar’s energy is in the form of a relativistic wind of ionized particles. A’s wind will distort B’s magnetosphere into a cometary shape much like the Sun does the Earth’s.
The Double Pulsar System: Interactions - Geometry

- A large portion of a pulsar’s energy is in the form of a relativistic wind of ionized particles. A’s wind will distort B’s magnetosphere into a cometary shape much like the Sun does the Earth’s.

• B clearly visible at 2 orbital phases and very weak otherwise.  
• Profile changes from strong main pulse and weak precursor to strong single pulse to roughly-equal double pulse.  
• These patterns are stable across observing frequency.
The Double Pulsar System: Interactions - A on B

Pulse profile of A
A is “jumpstarting” pulsar B.

Currently examining evolution of B’s on/off patterns to test this model.
The Double Pulsar System: Interactions - A on B

Green Bank Telescope

The Double Pulsar System: Interactions - A on B

Single pulses from B

Green Bank Telescope

The Double Pulsar System: Interactions - A on B

Single pulses from B

and from A!

Green Bank Telescope

The Double Pulsar System: Interactions - A on B

- A appears to be a "normal" MSP.
- However, we see a strange "drifting" behavior in B’s pulses.

Green Bank Telescope

The Double Pulsar System: Interactions - A on B

Predicted arrival times of A pulses at B


Direct evidence for modulation of B’s emission by A’s radiation!!
The Double Pulsar System: Interactions - A on B

- Drifting only seen at some orbital phases.

The Double Pulsar System: Interactions - A on B

- Drifting only seen at some orbital phases.
- These are the phases where we see the cometary B magnetosphere from the side.
- Further studies will allow us to probe the cometary B magnetosphere further and to learn about A’s wind.
The Double Pulsar System: Interactions - B on A

- A is eclipsed for ~ 30 s once per orbit.

- This corresponds to an occulting region of size 0.05 lt-s (15,000 km), or 10% of the light-cylinder radius of B.

- A has “blown away” much of B’s magnetosphere.
The Double Pulsar System: Interactions - B on A

• There is significant modulation of A’s intensity during eclipse.

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• There is significant modulation of A’s intensity during eclipse.

• This modulation is at exactly $0.5P_B$, with longer eclipse at phases when beam of B is pointing towards/away from us.
As expected if eclipse is caused by synchrotron absorption in B’s magnetosheath/sphere.

Further studies of eclipse behavior will allow us to probe A’s wind and B’s magnetosphere (density, shape).
The Double Pulsar System: Testing GR - Method

Was Einstein Right???

“Everything should be made as simple as possible, but not simpler.”
The Double Pulsar System: Testing GR  - Method

Was Einstein Right???

Radio timing yields 5 Keplerian parameters
- $P_B$ - binary period
- $a \sin i$ - semi-major axis
- $e$ - eccentricity
- $\omega$ - longitude of periastron
- $T_0$ - epoch of periastron

We have five measurable relativistic (Post-Keplerian) parameters and only 3 unknowns ($M_A, M_B, i$).

![Einstein](image)

Can measure $M_A, M_B, i$ AND test GR.
The Double Pulsar System: Testing GR - $M_A$ vs $M_B$
The Double Pulsar System: Testing GR - $M_A$ vs $M_B$

\[ f(m_P, m_c) = \frac{(m_c \sin i)^3}{(m_P + m_c)^2} = \frac{4\pi^2 (a_P \sin i)^3}{G \frac{P_b^2}{P}} \]
The Double Pulsar System: Testing GR - $M_A$ vs $M_B$

\[ f(m_p, m_c) = \frac{(m_c \sin i)^3}{(m_p + m_c)^2} = \frac{4\pi^2 (a_p \sin i)^3}{G P_b^2} \]
The Double Pulsar System: Testing GR - $M_A$ vs $M_B$

Mass ratio, theory independent

$$\frac{m_P}{m_p} = \frac{m_c}{m_c}$$
The Double Pulsar System: Testing GR - $M_A$ vs $M_B$

\[ \omega \sim 40 \text{ deg yr}^{-1} \left( \frac{P_b}{\text{hr}} \right)^{-5/3} \left( \frac{1}{1 - e^2} \right) \left( \frac{m_F + m_c}{M_\odot} \right)^{2/3} \]
Gravitational redshift

\[ \gamma \sim 2.4 \text{ ms} \left( \frac{P_b}{\text{hr}} \right)^{1/3} \frac{m_c(m_p + 2m_c)}{(m_p + m_c)^{4/3}} e \]
The Double Pulsar System: Testing GR - $M_A$ vs $M_B$

\[ r \sim 5\mu s \times m_c \]

\[ s = \sin i \sim 0.9 \left( \frac{P_b}{\text{hr}} \right)^{-2/3} x \frac{(m_p + m_c)^{2/3}}{m_c} \]
The Double Pulsar System: Testing GR - $M_A$ vs $M_B$

$M_A \sim 1.335 \, M_{\text{sun}}$

$M_B \sim 1.252 \, M_{\text{sun}}$

$i = 88$ degrees
The Double Pulsar System: Testing GR - $M_A$ vs $M_B$

So far, Einstein is right!!

\[
\frac{s_{\text{obs}}}{s_{GR}} = 1.0001 \pm 0.0022
\]

- Most overconstrained system.
- Most precise determination of neutron star masses ever.
- “B” is the least massive neutron star known.

- Continuing timing observations:
  - 2PPN corrections to PK parameters
  - Contributions of spin-orbit coupling (geodetic precession)
    First measurement of neutron star moment of inertia!
The Double Pulsar System: Testing GR - Timing Update!

\[ \dot{P}_b \sim -4 \times 10^{-12} \left( \frac{P_b}{\text{hr}} \right)^{-5/3} \frac{\left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)}{(1-e^2)^{7/2}} \frac{m_pm_c}{(m_p + m_c)^{1/3}} \]

orbital decay due to gravitational radiation
The Double Pulsar System: Testing GR - GW detection

\[ \dot{P}_b \sim -4 \times 10^{-12} \left( \frac{P_b}{\text{hr}} \right)^{-5/3} \frac{1 + \frac{73}{24} e^2 + \frac{37}{96} e^4}{(1 - e^2)^{7/2}} \frac{m_p m_c}{(m_p + m_c)^{1/3}} \]

\[ \tau_{GW} \sim 10^7 \text{ yr} \left( \frac{P_b}{\text{hr}} \right)^{8/3} \left( \frac{\mu}{M_\odot} \right)^{-1} \left( \frac{M}{M_\odot} \right)^{-2/3} (1 - e^2)^{7/2} \]

- Stars will coalesce in 85 Myr.

- 40 - 660 per year detectable by advanced LIGO (Kalogera et al. 2004, 614, 137)

Watch the following animation....
The Double Pulsar System: Future

• Future radio observations will yield vital insights into pulsar winds and magnetospheres - may aid understanding of Earth/Sun interactions.

• VLBI observations will yield precise distance and velocities, giving even more stringent tests of GR.

• Future radio timing will enable most precise test of GR and most precise measurement of neutron star masses ever

• X-ray/radio continuum studies may allow study of interaction between A’s relativistic wind and B’s magnetosphere.

• Future searches will yield more of these objects and, possibly, a pulsar/black hole binary!