The State of Gravitational Wave Detection with Pulsar Timing Arrays

Scott Ransom
National Radio Astronomy Observatory / University of Virginia
Millisecond pulsars (MSPs) as detectors for nanoHz GWs from Super-Massive Black Hole Binaries (SMBHBs)
Gravitational wave physics experiments

Strain $h$

- Cosmic Microwave Background
  - Primordial gravitational waves

- Pulsar Timing Arrays
  - Supermassive black hole binaries and mergers
  - Primordial gravitational waves

- Space-based Interferometers
  - Stellar mass compact binaries
  - Supermassive black hole mergers

- Ground-based Interferometers
  - Neutron star mergers
  - Black hole mergers

All three experiments measure changes in light travel times between objects due to GWs.
What’s a Millisecond Pulsar?

- Rapidly Rotating Neutron Star! (300-700 times/sec!)
- Size of city:
  - $R \sim 10-15$ km
- Mass greater than Sun:
  - $M \sim 1.4-2.0 \, M_{\text{sun}}$
- Strong Magnetic Fields:
  - $B \sim 10^8-10^9$ Gauss
- Pulses are from a "lighthouse" type effect
- “Spin-down” power up to 1000s times more than the Sun's total output!

Credit: Bill Saxton, NRAO/AUI/NSF
Millisecond Pulsars: via “Recycling”

Supernova produces a neutron star

Picture credits: Bill Saxton, NRAO/AUI/NSF
Millisecond Pulsars: via “Recycling”

Supernova produces a neutron star

Red Giant transfers matter to neutron star

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Millisecond Pulsars: via “Recycling”

Supernova produces a neutron star

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Millisecond Pulsar emerges with a white dwarf companion

Picture credits: Bill Saxton, NRAO/AUI/NSF
Pulsar Timing:
Unambiguously account for every rotation of a pulsar over years
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Pulse Measurements
(TOAs: Times of Arrival)

Observation 1
Pulses
Time
Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years

Observation 1

Pulses

Time

Obs 2

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Unambiguously account for every rotation of a pulsar over years

**Pulse Measurements**

(TOAs: Times of Arrival)

**Measurement - Model = Timing Residuals**

Predict each pulse to ~200 ns over 2 yrs!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecliptic longitude (λ)</td>
<td>245.78827556(5)°</td>
</tr>
<tr>
<td>Ecliptic latitude (β)</td>
<td>−1.256744(2)°</td>
</tr>
<tr>
<td>Proper motion in λ</td>
<td>9.79(7) mas yr⁻¹</td>
</tr>
<tr>
<td>Proper motion in β</td>
<td>−30(3) mas yr⁻¹</td>
</tr>
<tr>
<td>Parallax</td>
<td>0.5(6) mas</td>
</tr>
<tr>
<td>Pulsar spin period</td>
<td>3.1508076534271(6) ms</td>
</tr>
<tr>
<td>Period derivative</td>
<td>9.6216(9) × 10⁻²¹ s s⁻¹</td>
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<tr>
<td>Reference epoch (MJD)</td>
<td>53,600</td>
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<tr>
<td>Dispersion measure*</td>
<td>34.4865 pc cm⁻³</td>
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<tr>
<td>Orbital period</td>
<td>8.6866194196(2) d</td>
</tr>
<tr>
<td>Projected semimajor axis</td>
<td>11.2911975(2) light s</td>
</tr>
<tr>
<td>First Laplace parameter (esin ω)</td>
<td>1.1(3) × 10⁻⁷</td>
</tr>
<tr>
<td>Second Laplace parameter (ecos ω)</td>
<td>−1.29(3) × 10⁻⁶</td>
</tr>
<tr>
<td>Companion mass</td>
<td>0.500(6)M☉</td>
</tr>
<tr>
<td>Sine of inclination angle</td>
<td>0.999894(5)</td>
</tr>
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<td>Epoch of ascending node (MJD)</td>
<td>52,331.1701098(3)</td>
</tr>
<tr>
<td>Span of timing data (MJD)</td>
<td>52,469–55,330</td>
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<tr>
<td>Number of TOAs†</td>
<td>2,206 (454, 1,752)</td>
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<tr>
<td>Root mean squared TOA residual</td>
<td>1.1 µs</td>
</tr>
<tr>
<td>Right ascension (J2000)</td>
<td>16 h 14 min 36.5051(5) s</td>
</tr>
<tr>
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<td>−22° 30’ 31.081(7)''</td>
</tr>
<tr>
<td>Orbital eccentricity (e)</td>
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<tr>
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<td>89.17(2)°</td>
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<td>Dispersion-derived distance‡</td>
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<tr>
<td>Surface magnetic field</td>
<td>1.8 × 10⁸ G</td>
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<td>Characteristic age</td>
<td>5.2 Gyr</td>
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<td>Spin-down luminosity</td>
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Highly circular orbit has a radius of \(~3.4\) million km (\(~5\) x Solar radius or \(~9\) x Earth-Moon distance).

What is the difference in length between the semi-major and semi-minor axes?

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Demorest et al. 2010, Nature
Ask the right question...

Highly circular orbit has a radius of \( \sim 3.4 \text{ million km} \) (~5 x Solar radius or ~9 x Earth-Moon distance)

What is the difference in length between the semi-major and semi-minor axes?

| Orbital period | 8.6866194196(2) d |
| Projected semimajor axis | 11.2911975(2) light s |
| First Laplace parameter (esin \( \omega \)) | 1.1(3) \times 10^{-6} |
| Second Laplace parameter (ecos \( \omega \)) | \(-1.29(3) \times 10^{-6}\) |
| Companion mass | 0.500(6) \( M_\odot \) |
| 52,331.1701098(3) | 0.999894(5) |
| 52,469–55,330 | 52,331.1701098(3) |
| 2,206 (454, 1,752) | 52,469–55,330 |
| 1.1 \( \mu \)s | 2,206 (454, 1,752) |

...get a spectacular answer!

2.8 +/- 0.2 mm!

Right ascension (J2000) | 16 h 14 min 36.5051(5) s |
Declination (J2000) | 22° 30' 31.001(7)'' |
Orbital eccentricity (e) | 89.17(2) |
Inclination angle | \( 1.97(4) M_\odot \) |
Pulsar mass | 1.2 kpc |
Dispersion-derived distance‡ | \( >0.9 \text{ kpc} \) |
Parallax distance | \( 1.8 \times 10^8 \text{ G} \) |
Surface magnetic field | 52 Gyr |
Characteristic age | 5.2 Gyr |
Spin-down luminosity | Demorest et al. 2010, Nature |
The Binary Pulsar: B1913+16
Three post-Keplerian Observables: $\dot{\omega}$, $\gamma$, $\dot{P}_{\text{orb}}$

Indirect detection of Gravitational Radiation!

From Weisberg & Taylor, 2003
Direct Gravitational Wave Detection (Pulsar Timing Array)

- Looking for nHz freq gravitational waves from super massive black hole binaries
- Need good MSPs:
  - Significance scales with the number of MSPs being timed
- Must time 20+ pulsars for 10+ years at precision of ~100 nanosec!

For more information, see nanograv.org

Australia  
Europe  
North America
<table>
<thead>
<tr>
<th>Telescopes</th>
<th>Arecibo GBT</th>
<th>Nancay Effelsberg Westerbork Jodrell Bank Sardinia RT</th>
<th>Parkes</th>
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<tr>
<td>Observing Time</td>
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<td>~5x+</td>
<td>~3x</td>
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<tr>
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<td>Sensitivity</td>
<td>Cadence Phased Array (LEAP)</td>
<td>Cadence Unique Pulsars Single telescope</td>
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<tr>
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Major releases / limits from each PTA have just come out!
NANOGrav 9-yr Data
Where do these GWs come from?

Coalescing Super-Massive Black Holes

- Basically all galaxies have them
- Masses of $10^6 – 10^9 \, M_\odot$
- Galaxy mergers lead to BH mergers
- When BHs within 1pc, GWs are main energy loss
- For total mass $M/(1+z)$, distance $d_L$, and SMBH orbital freq $f$, the induced timing residuals are:

$$
\Delta \tau \sim 10 \, \text{ns} \left( \frac{1 \, \text{Gpc}}{d_L} \right) \left( \frac{M}{10^9 \, M_\odot} \right)^{5/3} \left( \frac{10^{-7} \, \text{Hz}}{f} \right)^{1/3}
$$

Potentially measurable with a single MSP!
So where do these GWs come from?

3C66B
At z = 0.02
Orbital period 1.05 yrs
Total mass $5.4 \times 10^{10} M_\odot$
(Sudou et al 2003)

Predicted timing residuals
Ruled out by MSP observations

So where do these GWs come from?

Possible binary SMBH with ~5 year orbital period... just needs to be ~10x closer!

Graham et al, 2015, *Nature*
Stochastic GW Backgrounds

An ensemble of many individual GWs, from different directions and at different amplitudes and frequencies

Characteristic strain spectrum is (basically) a power law:

$$h_c(f) = A \left( \frac{f}{yr^{-1}} \right)^{\alpha}$$

But see Sesana et al 2008, 2010, ...

Table 1: The expected parameters for predicted stochastic backgrounds

<table>
<thead>
<tr>
<th>Model</th>
<th>$A$</th>
<th>$\alpha$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supermassive black holes</td>
<td>$10^{-15} - 10^{-14}$</td>
<td>$-2/3$</td>
<td>Jaffe &amp; Backer (2003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wyithe &amp; Loeb (2003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Enoki et al. (2004)</td>
</tr>
<tr>
<td>Relic GWs</td>
<td>$10^{-17} - 10^{-15}$</td>
<td>$-1 - -0.8$</td>
<td>Grishchuk (2005)</td>
</tr>
<tr>
<td>Cosmic String</td>
<td>$10^{-16} - 10^{-14}$</td>
<td>$-7/6$</td>
<td>Maggiore (2000)</td>
</tr>
</tbody>
</table>

The amplitude is the only unknown for each model

A Pulsar Timing Array (PTA)

Timing residuals due to a GW have two components:

“Pulsar components” are uncorrelated between MSPs
“Earth components” are correlated between MSPs

\[
\frac{\delta \nu}{\nu} = - \mathcal{H}_{ij} \left[ h_{ij}(t_e, x_e^i) - h_{ij}(t_p, x_p^i) \right]
\]

Signal in Residuals
Clock errors: monopole
Ephemeris errors: dipole
GW signal: quadrupole

e.g. Hellings & Downs, 1983, ApJL, 265, 39;
Where are the GWs?

Current power-law models in tension. Maybe environmental effects? (stars, gas, eccentricity, ...)


Shannon et al. 2015, Science, 349, 1522 arXiv:1509.07320

McWilliams et al. (2014) Model

Sesana et al. (2013) Model

Characteristic Strain $|h_c(\nu)|$

Frequency [Hz]
Latest models don’t show a problem...

- From Illustris cosmological simulations
- Assuming efficient MBH mergers and power law evolution
- About 30% below the best observational limit

Kelley, Blecha, & Herrnquist 2016, sub., arXiv:1606.01900
Latest models don’t show a problem...

- From Illustris cosmological simulations
- Including environmental effects (dynamical friction, stellar scattering, viscous circumbinary disk), but no eccen (yet)

Kelley, Blecha, & Herrnquist 2016, sub., arXiv:1606.01900
So what about the future?

Newest models suggest background must be $> \sim 3 \times 10^{-15}$

(e.g. Kelley, Blecha, & Herrnquist 2016)
So what about the future?

Combined as IPTA, likely factor of ~2 improvement in GW sensitivity

Newest models suggest background must be > ~3x10^{-15} (e.g. Kelley, Blecha, & Herrnquist 2016)

95% upper limit

50% Detection prob

95% Detection prob

95% Detection prob

Combined as IPTA, likely factor of ~2 improvement in GW sensitivity

bound must be > ~3x10^{-15} (Herrnquist 2016)
How to do better?

- Improved fidelity and systematics – instrumentation
- Better pulsars (right ones are rare) – searches
- PSRs are faint (sensitivity limited) – bigger telescopes

These improvements dramatically help all pulsar science!
Ultra-wideband System (planned)

~0.6-3 GHz in one shot
CASPER-based backend
Improve timing by 20-100%

Bandwidth:
- Improves S/N (as $\sqrt{\text{BW}}$)
- Scintillation protection
- Much better ISM (i.e. DM) removal

ASP / GASP  GUPPI / PUPPI  Wideband

Fig: Paul Demorest
New All-Sky Pulsar Surveys

- All major radio telescopes are conducting all-sky pulsar surveys
- We know of only about 5% of the total pulsars in the Galaxy!
- These generate lots of data:
  - 1000s of hrs, 1000s of channels, 15000kHz sampling: gives more than a Petabyte!
- Requires huge amounts of high performance computing
  - Many times real-time and millions of false positives
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Gravitational wave sensitivity is proportional to the number of MSPs!

\[ h_{c,\text{min}} \propto \sigma N_{\text{PSRs}}^{-1} T^{-1/2} \]

See Siemens et al. 2013, CQG
New Millisecond Pulsars

Numbers have:
quadrupled in last 10 yrs
doubled in last ~3 years

Why?
Rise in computing capability,
sensitive new radio surveys,
Fermi!
Currently ~70 new Radio/gamma-ray MSPs because of *Fermi*!
~10% of them look like they will be “good timers”
**PSR J0337+1715 Triple System**

**Outer Orbit**
- $P_{orb} = 327$ days
- $M_{WD} = 0.41 M_{Sun}$

**Inner Orbit**
- $P_{orb} = 1.6$ days
- $M_{PSR} = 1.44 M_{Sun}$
- $M_{WD} = 0.20 M_{Sun}$

- Pulsar
- "Young, hot" White Dwarf
- "Cool, old" White Dwarf

**Orbital inclinations**
- $39.2^\circ$

**Figure credit:**
Jason Hessels
Neutron Star ($1.4378(13)\text{ Msun}$) and White Dwarf ($0.19751(15)\text{ Msun}$) orbited by another White Dwarf ($0.4101(3)\text{ Msun}$) will provide the best test (by far?) of the Strong Equivalence Principle.


Also: Archibald et al. in prep.
J0337+1715 scalar-tensor constraints

- “$G$” effectively different for NS and WD. They fall in relatively “strong” grav field of outer WD.

- Prediction is $\sim1$-$2$ orders of mag better than other current or future tests (including Lunar Laser Ranging!), and soon! (Archibald et al in prep).

- $T_1(\alpha_0,\beta_0)$ theories
- GR has $\alpha_0=\beta_0=0$
- Jordan–Fierz–Brans–Dicke theory has $\beta_0=0$

N. Wex, private communication
What about the future?

- We only know of about 2,500 out of ~50,000+ pulsars in the Galaxy!
  - Many of them will be “Holy Grails”
    - Sub-MSP, PSR-Black Hole systems, MSP-MSP binary
- Several new huge telescopes...

  We need them because we are sensitivity limited!

MeerKAT (64 dishes, SA)  FAST (500m, China)
Square Kilometer Array

• SKA-1 (650 M€) 2020+, SKA-2 (3-5G€) 2025+
• 2 (or 3) arrays in S. Africa and W. Australia
• Should find most of the pulsars in the Galaxy
  • But will be incredibly difficult – can't record the data!
Summary

• The pulsars are behaving very well
• GW detection at nHz freqs is likely within 10 yrs
• Many amazing (and bright!) pulsars to be found in the Galaxy: we know of ~5% of total
  • Will provide a huge amount of secondary science
• But we are sensitivity limited (Need big scopes!)
  • FAST in China, MeerKAT in S.Africa, eventually SKA?
  • Will be hard to get the time we need on those
  • Losing GBT and/or Arecibo would be bad for PSRs