Detecting Gravitational Waves (and doing other cool physics) with Millisecond Pulsars

NANOGrav

Scott Ransom
What's a Pulsar?

Rotating Neutron Star!

Size of city:

\[ R \sim 10-20 \text{ km} \]

Mass greater than Sun:

\[ M \sim 1.4 M_{\text{sun}} \]

Strong Magnetic Fields:

\[ B \sim 10^8-10^{14} \text{ Gauss} \]

Pulses are from a "lighthouse" type effect

"Spin-down" power up to 10,000 times more than the Sun's total output!

Weak but broadband radio sources
Pulsar Flavors

**Young PSRs**
(high B, fast spin, very energetic)

**Normal PSRs**
(average B, slow spin)

**Millisecond PSRs**
(low B, very fast, very old, very stable spin, best for basic physics tests)
Millisecond Pulsars are Very Precise Clocks

**PSR B1937+21**

At midnight on 5 Dec, 1998:

\[ P = 1.5578064688197945 \text{ ms} \]
\[ +/- 0.0000000000000004 \text{ ms} \]

The last digit changes by about 1 per second!

This extreme precision is what allows us to **use pulsars as tools** to do unique physics!
How are millisecond pulsars made?

Binary system of supergiant and a normal star

Supernova produces a neutron star

Red Giant transfers matter to neutron star

Millisecond Pulsar emerges with a white dwarf companion
Physics from Pulsars
(see Blandford, 1992, PTRSLA, 341, 177 for a review)

- Newtonian and relativistic dynamics (e.g. binary pulsars)
- **Gravitational wave physics** (e.g. binaries, MSP timing)
- Physics at nuclear density (e.g. NS equations of state)
- Astrophysics (e.g. stellar masses and evolution)
- Plasma physics (e.g. magnetospheres, pulsar eclipses)
- Fluid dynamics (e.g. supernovae collapse)
- Magnetohydrodynamics (MHD; e.g. pulsar winds)
- Relativistic electrodynamics (e.g. pulsar magnetospheres)
- Atomic physics (e.g. NS atmospheres)
- Solid state physics (e.g. NS crust properties)
Pulsar Timing

- All of the science is from long-term timing
- Account for every rotation of the pulsar
- Fit the arrival times to a polynomial model after transforming the time:

\[ T = t - t_0 + \Delta_C - D/f^2 + \Delta_{R\odot} + \Delta_{E\odot} - \Delta_{S\odot} - \Delta_R - \Delta_E - \Delta_S \]

- Accounts for pulsar spin, orbital, and astrometric parameters and Roemer, Einstein, and Shapiro delays in the Solar System and pulsar system
- Extraordinary precision for MSP timing
Pulsar Timing

- All of the science is from long-term timing
- Account for every rotation of the pulsar
- Fit the arrival times to
  - Accounts for pulsar spin, orbital, and astrometric parameters and Roemer, Einstein, and Shapiro delays in the Solar System and pulsar system
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“Folding” Pulsar Data for Timing

Original time series

Shift and add the pulses

A strong “average” profile that can be cross correlated to get a Time-of-Arrival (TOA)
The science is in the residuals!

RMS precision $\sim 10^{-5}$-$10^{-3}$ P

(a) **“Good” Timing Solution**

(b) Uncorrected spin-down

(c) Position error

(d) Proper motion
Timing Sensitivity

Timing precision depends on:
- Sensitivity (A/T_{sys})
- Pulse width (w)
- Pulsar flux density (S)
- Instrumentation

\[
\sigma_{\text{TOA}} \sim \frac{w}{\text{SNR}} \propto \frac{w}{S_{\text{PSR}}} \sqrt{\frac{1}{Bt_{\text{int}}}} \frac{T_{\text{sys}}}{A}
\]

Jenet & Demorest 2010, in prep.
Precision Timing Example

- **Astrometric Params**
  - RA, DEC, $\mu$, $\pi$

- **Spin Params**
  - $\dot{P}_{\text{spin}}$, $P_{\text{spin}}$

- **Keplerian Orbital Params**
  - $P_{\text{orb}}$, $x$, $e$, $\omega$, $T_0$

- **Post-Keplerian Params**
  - $\dot{\omega}$, $\gamma$, $\dot{P}_{\text{orb}}$, $r$, $s$

$\sim$100 ns RMS timing residuals!

Recent work (e.g. Verbiest et al 2009) shows this is sustainable over 5+ yrs for several MSPs.

Table 1 PSR J0437–4715 physical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right ascension, $\alpha$ (J2000)</td>
<td>$04^{h}37^{m}15^{s}.7865145(7)$</td>
</tr>
<tr>
<td>Declination, $\delta$ (J2000)</td>
<td>$-47^{\circ}15\arcmin08.461584(8)$</td>
</tr>
<tr>
<td>$\mu_\alpha$ (mas yr$^{-1}$)</td>
<td>121.438(6)</td>
</tr>
<tr>
<td>$\mu_\delta$ (mas yr$^{-1}$)</td>
<td>$-71.438(7)$</td>
</tr>
<tr>
<td>Annual parallax, $\pi$ (mas)</td>
<td>7.19(14)</td>
</tr>
<tr>
<td>Pulse period, $P$ (ms)</td>
<td>5.757451831072007(8)</td>
</tr>
<tr>
<td>Reference epoch (MJD)</td>
<td>51194.0</td>
</tr>
<tr>
<td>Period derivative, $\dot{P}$ ($10^{-20}$)</td>
<td>5.72906(5)</td>
</tr>
<tr>
<td>Orbital period, $P_b$ (days)</td>
<td>5.741046(3)</td>
</tr>
<tr>
<td>$x$ (s)</td>
<td>3.36669157(14)</td>
</tr>
<tr>
<td>Orbital eccentricity, $e$</td>
<td>0.000019186(5)</td>
</tr>
<tr>
<td>Epoch of periastron, $T_0$ (MJD)</td>
<td>51194.6239(8)</td>
</tr>
<tr>
<td>Longitude of periastron, $\omega$ ($^\circ$)</td>
<td>1.20(5)</td>
</tr>
<tr>
<td>Longitude of ascension, $\Omega$ ($^\circ$)</td>
<td>238(4)</td>
</tr>
<tr>
<td>Orbital inclination, $i$ ($^\circ$)</td>
<td>42.75(9)</td>
</tr>
<tr>
<td>Companion mass, $m_2$ ($M_\odot$)</td>
<td>0.236(17)</td>
</tr>
<tr>
<td>$\dot{P}_b$ ($10^{-12}$)</td>
<td>3.64(17)</td>
</tr>
<tr>
<td>$\dot{\omega}$ ($^\circ$ yr$^{-1}$)</td>
<td>0.016(10)</td>
</tr>
</tbody>
</table>

van Straten et al., 2001
Nature, 412, 158
Post-Keplerian Orbital Parameters

General Relativity gives:

\[
\dot{\omega} = 3 \left( \frac{P_b}{2\pi} \right)^{-5/3} (T_\odot M)^{2/3} (1 - e^2)^{-1}
\]  
(Advance of Periastron)

\[
\gamma = e \left( \frac{P_b}{2\pi} \right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2 (m_1 + 2m_2)
\]  
(Grav redshift + time dilation)

\[
\dot{P}_b = -\frac{192\pi}{5} \left( \frac{P_b}{2\pi} \right)^{-5/3} \left( 1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right) (1 - e^2)^{-7/2} T_\odot^{5/3} m_1 m_2 M^{-1/3}
\]  
(Shapiro delay: “range” and “shape”)

\[
r = T_\odot m_2
\]

\[
s = x \left( \frac{P_b}{2\pi} \right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1}
\]

where: \( T_\odot \equiv GM_\odot/c^3 = 4.925490947 \) μs, \( M = m_1 + m_2 \), and \( s \equiv \sin(i) \)

These are only functions of:
- the (precisely!) known Keplerian orbital parameters \( P_b, e, \) asin(\( i \))
- the mass of the pulsar \( m_1 \) and the mass of the companion \( m_2 \)
The Binary Pulsar: B1913+16


**NS-NS Binary**

- $P_{\text{psr}} = 59.03$ ms
- $P_{\text{orb}} = 7.752$ hrs
- $a \sin(i)/c = 2.342$ lt-s
- $e = 0.6171$
- $\dot{\omega} = 4.2$ deg/yr
- $M_c = 1.3874(7) \, M_\odot$
- $M_p = 1.4411(7) \, M_\odot$
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
High-precision MSP Timing for Gravitational Wave Detection

- The best MSPs (timing precisions between 50-200 ns RMS) can be used to search for nHz gravitational waves
  - $\nu_{gw} \sim 1/$yrs to 1/weeks
  - $h \sim \sigma_{TOA} / T \sim 10^{-15}$
- Sensitivity comparable and complementary to Adv. LIGO and LISA!
- Need best pulsars, instruments, and telescopes!

Credit: D. Backer

E.g. Detweiler, 1979
Hellings & Downs, 1983
Pulsars and GW Basics

Flat space metric with perturbations

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]

Frequency shifts occur along the photon path based on the G-wave

\[ \frac{\delta \omega}{\omega} = \frac{1}{2\xi^0 k^0} \int_{s_0}^{s_1} h_{ij,s} \, ds \]

Integral turns out to only be based on the metric at the Pulsar (then) and Earth (now)

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

Integrate over the frequency shifts in time to get the timing residuals

\[ R(t) = -\int_0^t \frac{\delta \nu(t)}{\nu} \, dt \]
So 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

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

The amplitude is the only unknown for each model

<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>

Best Single Pulsar Limits

Power spectrum of induced timing residuals:

\[ P(f) = \frac{1}{12\pi^2} \frac{1}{f^3} h_c(f)^2 \]

\[ \Omega_{gw}(f) = \frac{2}{3} \frac{\pi^2}{H_0^2} f^2 h_c(f)^2 \]


Demorest 2007, PhD Thesis

<table>
<thead>
<tr>
<th>Source(s)</th>
<th>C/I</th>
<th>T (yr)</th>
<th>( \Omega_{GW}(1/T)h^2 )</th>
<th>( h_c(1 \text{ yr}^{-1}) )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1133+16, B1237+25, B1604–00, B2045–16</td>
<td>C</td>
<td>12</td>
<td>( &lt; 1 \times 10^{-4} )</td>
<td>( &lt; 9.1 \times 10^{-13} )</td>
<td>Hellings and Downs (1983)</td>
</tr>
<tr>
<td>B1855+09, B1937+21</td>
<td>I</td>
<td>8</td>
<td>( &lt; 6 \times 10^{-8} )</td>
<td>( &lt; 1.9 \times 10^{-14} )</td>
<td>Kaspi et al. (1994)</td>
</tr>
<tr>
<td>B1855+09, ...</td>
<td>I</td>
<td>8</td>
<td>( &lt; 2 \times 10^{-8} )</td>
<td>( &lt; 1.1 \times 10^{-14} )</td>
<td>Jenet et al. (2006)</td>
</tr>
<tr>
<td>J1713+0747, B1855+09</td>
<td>I</td>
<td>20</td>
<td>( &lt; 2 \times 10^{-9} )</td>
<td>( &lt; 4.9 \times 10^{-15} )</td>
<td>Lommen et al. (2007)</td>
</tr>
</tbody>
</table>
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

![Two-point correlation function](image)

**Signal in Residuals**

Clock errors: **monopole**

Ephemeris errors: **dipole**

GW signal: **quadrupole**

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GW Detection with a Pulsar Timing Array

- Need good MSPs and lots of time (patience)
- Significance scales linearly with the number of MSPs

**Canonical PTA:**
- Bi-weekly, multi-freq obs for 5-10 years
- ~20-40 MSPs with ~100 ns timing RMS
- This is not easy...

\[
\text{SNR} \propto \frac{A^2}{\sigma^2} N_{\text{PSRs}} N_{\text{TOAs}} T^{-2\alpha+2}
\]

\[
\text{SNR}_{\text{SMBHs}} \propto \frac{A^2}{\sigma^2} N_{\text{PSRs}} N_{\text{TOAs}} T^{10/3}
\]
NANOGraV

- About **22 members** from North America
- Observing ~20 MSPs
- Using **Arecibo** and the **GBT** via 2 large projects (PI Paul Demorest)
- 2 obs freqs at GBT, 2-3 at Arecibo per PSR
- RMS residuals from ~100ns to 1.5us
- First 4 years of data limit $h_c(1\text{yr}^{-1}) < 7 \times 10^{-15}$ comparable to 20yrs of single MSP

http://nanograv.org
NANOGRAV improvement with time...

Note complementarity with LIGO and LISA
Magenta and cyan curves show what happens if we improve our ability to time the pulsars by factors of \(~3\) and \(10\).
So how do we improve?
(in approx order of difficulty)

- Patience...
- International PTA
- New instrumentation (more BW)
- Find more and better MSPs
- Better timing algorithms
- Improved understanding of the systematics. e.g. interstellar medium (ISM) effects
- Bigger telescopes (i.e. FAST and SKA)
International PTA

Green Bank, West Virginia
Westerbork, The Netherlands
Effelsberg, Germany
Pune, India
Arecibo, Puerto Rico
Goostrey, United Kingdom
Nancay, France
San Basilio, Italy
Parkes, Australia
International PTA (5yr campaign)

\[ \text{SNR}_{\text{SMBHs}} \propto \frac{A^2}{\sigma^2} N_{\text{PSRs}} N_{\text{TOAs}} T^{10/3} \]

Graph showing the detection significance vs. GWB Amplitude for different projects: NANOGrav, IPTA, EPTA, PPTA.
GUPPI: A Pulsar “Dream Machine” for the GBT

800 MHz BW coherent de-dispersion backend
9x more BW ~ 3x more sensitive
High dynamic range (8-bit sampling) with full polarization
Large improvement in timing precision and “control” of ISM effects
“CASPER” FPGA-based technology from Berkeley
Ready by end of 2009!

e.g. Parsons et al 2006; http://seti.berkeley.edu/casper/

CASPER “iBob” with 2xADC boards (2Gsps each)
CASPER “BEE2” compute board with 5 fast FPGAs
GUPPI: A Pulsar “Dream Machine” for the GBT

- 800 MHz BW coherent de-dispersion backend
- 9x more BW ~ 3x more sensitive
- High dynamic range (8-bit sampling) with full polarization
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Galactic ISM: electrons and radio waves...

- Turbulent, Ionized ISM causes several time and radio frequency dependent effects:
  - Dispersion
  - Faraday Rotation
  - Multi-path propagation
    - Scintillation
    - Scattering
- Some effects are removable, others aren't (yet?)...
- Much work ongoing in this area (see recent papers by Stinebring, Walker, Demorest, Cordes, Shannon, Rickett etc)

From Cordes and Lazio 2001 (NE2001)
Dispersion

Lower frequency radio waves are delayed with respect to higher frequency radio waves by the ionized interstellar medium

$$\Delta t \propto DM \nu^2$$

($DM =$ Dispersion Measure)

Coherent Dedispersion exactly removes this effect

**PSR B1937+21**

$P = 1.56 \text{ ms}$
Pulse Broadening and Scintillation

Multipath causes freq dependent pulse broadening and scintillation.
More MSPs

- Several large-scale searches for pulsars ongoing around the world: (GBT, Arecibo, Parkes, Effelsberg)
- MSPs are prime target: know ~1% of total in Galaxy
- Many bright and high-precision MSPs have yet to be discovered – some are very nearby
- Lots of “secondary” science
PSR J1903+0327 with Arecibo P-ALFA

This thing is weird.

- Fully recycled PSR
- Highly eccentric orbit
- Massive likely main-sequence star companion
- Massive NS (1.7 Msun)
- High precision timing despite being distant and in Galactic plane

Champion et al. 2008, Science, 320, 1309
PSR J1023+0038 is a “Missing Link” (w/ GBT)

Previously (over last 10 yrs) detected in FIRST, optical images/spectra, and X-rays and identified as a strange CV or a quiescent LMXB!

4.75 hr binary!
Evidence for accretion!
“Nasty” eclipses...

Archibald et al. 2009, Science, 324, 1411
Very recently... Bright Fermi UnIDd Sources

Bright Radio Binary MSPs!

Ransom et al. in prep
MSPs and GWs Summary

• Radio pulsars can potentially directly detect nHz frequency gravitational waves

• A detection with current facilities is possible (maybe even likely) in the next 5-15 years
  - Currently limits from single pulsars and initial PTAs are $A \sim 10^{-14}$ or slightly below (strain amplitude)
  - Arecibo buys us 5 yrs, 3x more obs buys us 3 yrs

• More and better MSPs for quicker detection

• With future very large radio telescopes (e.g. SKA) and many more MSPs, detailed study of nHz GWs is likely ($A \sim 10^{-17}$)

• nanograv.org and white papers for more info
Arecibo and the IPTA

37 IPTA Pulsars, $A = 2 \times 10^{-15}$

- 22@200ns, 15@40ns (IPTA w Arecibo), 50 pts/yr
- 37@200ns (IPTA w/o Arecibo), 50 pts/yr
- 22@200ns, 15@40ns (IPTA w Arecibo), 12 pts/yr
- 37@200ns (IPTA w/o Arecibo), 12 pts/yr

F. Jenet
The known MSPs are local objects (and are almost isotropically distributed on the sky.)