But wait! There's More!

A wealth of science from millisecond pulsars

Scott Ransom
National Radio Astronomy Observatory / University of Virginia
What’s a Millisecond Pulsar?

- **Rapidly Rotating Neutron Star!** (300-700 times/sec!)
- **Size of city:**
  - $R \sim 10-15 \text{ km}$
- **Mass greater than Sun:**
  - $M \sim 1.4-2.0 \text{ M}_\text{sun}$
- **Strong Magnetic Fields:**
  - $B \sim 10^8-10^9 \text{ Gauss}$
- **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
Only 2-3% of known pulsars are “interesting” for basic/astro physics individually.

In Galaxy, we know:
~160 binary MSPs
~40 isolated MSPs
~40 binary part-recyc
~20 isolated part-recyc

Definitions:
Part-recycled:  
\[ P > 20 \text{ ms}, \ B < 3 \times 10^{10} \text{ G} \]
MSP:  
\[ P < 20 \text{ ms}, \ B < 10^9 \text{ G} \]
Millisecond Pulsars: via “Recycling”

Supernova produces a neutron star

Red Giant transfers matter to neutron star

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

Pulse Measurements
(TOAs: Times of Arrival)

Observation 1
Pulses

Obs 2
Model
(prediction)

Obs 3

Measurement - Model = Timing Residuals

Predict each pulse to ~200 ns over 2 yrs!

Table 1 | Physical parameters for PSR J1614-2230

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecliptic longitude ($\lambda$)</td>
<td>245.78827556(5)$^\circ$</td>
</tr>
<tr>
<td>Ecliptic latitude ($\beta$)</td>
<td>$-1.256744(2)^\circ$</td>
</tr>
<tr>
<td>Proper motion in $\lambda$</td>
<td>9.79(7) mas yr$^{-1}$</td>
</tr>
<tr>
<td>Proper motion in $\beta$</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) $\times 10^{-21}$ s s$^{-1}$</td>
</tr>
<tr>
<td>Reference epoch (MJD)</td>
<td>53,600</td>
</tr>
<tr>
<td>Dispersion measure*</td>
<td>34.4865 pc cm$^{-3}$</td>
</tr>
<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 ($\text{esin} \omega$)</td>
<td>$1.1(3) \times 10^{-7}$</td>
</tr>
<tr>
<td>Second Laplace parameter ($\text{ecos} \omega$)</td>
<td>$-1.29(3) \times 10^{-6}$</td>
</tr>
<tr>
<td>Companion mass</td>
<td>0.500(6)$M_\odot$</td>
</tr>
<tr>
<td>Sine of inclination angle</td>
<td>0.999894(5)</td>
</tr>
<tr>
<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>
</tr>
<tr>
<td>Number of TOAs†</td>
<td>2,206 (454, 1,752)</td>
</tr>
<tr>
<td>Root mean squared TOA residual</td>
<td>1.1 $\mu$s</td>
</tr>
<tr>
<td>Right ascension (J2000)</td>
<td>16 h 14 min 36.5051(5) s</td>
</tr>
<tr>
<td>Declination (J2000)</td>
<td>$-22^\circ 30' 31.081(7)''$</td>
</tr>
<tr>
<td>Orbital eccentricity ($e$)</td>
<td>$1.30(4) \times 10^{-6}$</td>
</tr>
<tr>
<td>Inclination angle</td>
<td>89.17(2)$^\circ$</td>
</tr>
<tr>
<td>Pulsar mass</td>
<td>1.97(4)$M_\odot$</td>
</tr>
<tr>
<td>Dispersion-derived distance‡</td>
<td>1.2 kpc</td>
</tr>
<tr>
<td>Parallax distance</td>
<td>$&gt;0.9$ kpc</td>
</tr>
<tr>
<td>Surface magnetic field</td>
<td>$1.8 \times 10^8$ G</td>
</tr>
<tr>
<td>Characteristic age</td>
<td>5.2 Gyr</td>
</tr>
<tr>
<td>Spin-down luminosity</td>
<td>Demorest et al. 2010, Nature</td>
</tr>
</tbody>
</table>
The measured difference between the semi-major and semi-minor axes is: 

\[ 2.8 \pm 0.2 \text{ mm}! \]  

Highly circular orbit has a radius of \(~3.4 \text{ million km}\) (~5 x Solar radius or ~9 x Earth-Moon distance)
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
Gravitational Wave Detection with a Pulsar Timing Array

- Need very good MSPs
- Significance scales directly with the number of MSPs being timed. Lack of good MSPs is currently the biggest limitation
- Must time the pulsars for 5-10 years at a precision of ~100 nano-seconds!
<table>
<thead>
<tr>
<th>Telescopes</th>
<th>Arecibo</th>
<th>Nancay Effelsberg Westerbork Jodrell Bank Sardinia RT</th>
<th>Parkes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observing Time</td>
<td>1x</td>
<td>~5x+</td>
<td>~3x</td>
</tr>
<tr>
<td>Advantages</td>
<td>Sensitivity</td>
<td>Cadence Phased Array (LEAP)</td>
<td>Cadence Unique Pulsars Single telescope</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Sky coverage Oversubscription Telescope threats</td>
<td>Systematics</td>
<td>Sensitivity Telescope threat</td>
</tr>
<tr>
<td>Telescopes</td>
<td>Arecibo</td>
<td>GBT</td>
<td>Nancay</td>
</tr>
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<tr>
<td>Disadvantages</td>
<td>Sky coverage</td>
<td>Oversubscription</td>
<td>Telescope threats</td>
</tr>
</tbody>
</table>

Major releases / limits from each PTA coming out now!
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 $5.4 \times 10^{10} \text{M}_\odot$
(Sudou et al 2003)

Predicted timing residuals
Ruled out by MSP observations

So where do these GWs come from?

Radio Galaxy 3C66B
VLA 20cm image

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

Graham et al, 2015, *Nature*

PG 1302-102

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

Santiago Lombeyda / Caltech

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

\[ \frac{\delta \nu}{\nu} = -\mathcal{H}_{ij} \left[ h_{ij}(t_e, x^i_e) - h_{ij}(t_p, x^i_p) \right] \]

**Signal in Residuals**

- Clock errors: monopole
- Ephemeris errors: dipole
- GW signal: **quadrupole**

So what's the status? **Looking good!**

New results from EPTA and PPTA in here. Predictions are more optimistic than before due to merger-driven growth of BCGs (e.g. McWilliams et al 2012, Sesana 2012).

We are already in astrophysically interesting territory!
So what's the status?

Looking good!

New results from EPTA and PPTA in here. Predictions are more optimistic than before due to merger-driven growth of BCGs (e.g. McWilliams et al 2012, Sesana 2012). Combined as IPTA, likely factor of ~2 improvement in GW sensitivity.
Timing Sensitivity

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

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

R. Jenet & P. Demorest
Timing Sensitivity

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- Instrumentation

Limited by telescopes / receivers

Searches: New MSPs

Bandwidth + time resolution

Now

R. Jenet & P. Demorest
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(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!

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

See Siemens et al. 2013, CQG
Year
Numbers have:
more than quadrupled in last 10 yrs
doubled in last ~4 years

Why?
Rise in computing capability,
sensitive new radio surveys,
\textit{Fermi}!
Currently ~65 new Radio/gamma-ray MSPs because of *Fermi*!

~10-20% of them look like they will be “good timers”
~30% are strange eclipsing systems, like “Black-Widows”
Recent exotics: “Missing Links”

**J1023+0038**: Previously (over last 10 yrs) detected in FIRST, optical images/ spectra, and X-rays and identified as a strange CV or a quiescent LMXB

1.69 ms PSR in 4.75 hr binary

Evidence for accretion!

LMXB <-> MSP link!


PSR J0348+0432

- 39.1 ms GBT Driftscan pulsar
- 2.4hr relativistic orbit with WD
- He WD is \( \sim 10,120 \text{K} \), \( \log(g) \sim 6.0 \)
- Mass ratio of 11.70 +/- 0.13
- Orbital period decay coming...

NS mass \( \sim 2.01(4) \text{ Msun} \)
(interesting tests of GR)

Antoniadis et al Science, 2013, 340, 448
“Black Widow” J1311-3430

- 94-min orbit gamma-ray MSP
- Similar analysis to B1957+21
- Radial vel curve: 609(8) km/s amplitude
- Mpsr > 2.1 Msun (!)


More to come? Lots of Black Widows...
Recent exotics: Triple Systems (?)

- **PSR J1903+0327**: Arecibo PALFA survey found distant 2 ms pulsar in 95 day **highly eccentric orbit** around a main sequence star.
- Shapiro delay + precession gives high-precision mass: 1.67 +/- 0.02 Msun PSR
- Binary now, but likely a triple **origin**

  Champion et al. 2008, Science

- Triple dynamics are complicated. **Small number of true triples should exist.**

An MSP in a stellar triple system!

- **PSR J0337+1715**: In 2012, from the GBT Driftscan survey, a 2.7 ms PSR in a hierarchical triple system!
  - 1.6 day inner binary with hot WD
  - 327 day outer orbit with cool WD
  - Very strong 3-body effects...

Ransom et al. 2014, *Nature*, 505, 520
**PSR J0337+1715 Triple System**

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

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

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

**Figure credit:**
Jason Hessels
Inner White Dwarf
~18-19 mag
GALEX (UV)
SDSS (Opt)
WIYN (IR)
Spitzer (IR)
Teff = 15,800K \log(g) = 5.82
Therefore He WD of 0.15-0.2 Msun
RVs give mass ratio of 7.32+/-0.08
W/ timing masses, gives ~6% radius:
D = 1,300 +/- 80 pc
Neutron Star ($1.4378(13) \text{ M}_{\odot}$) and White Dwarf (0.19751(15) M_{\odot}) orbited by another White Dwarf (0.4101(3) M_{\odot})

Will provide the best test (by far?) of the Strong Equivalence Principle

Also: Archibald et al. 2015 in prep.
(Weak) Equivalence Principle:
Inertial Mass = Gravitational Mass
(regardless of object)

From BBC's “Human Universe” Ep. 4, with Brian Cox
Strong Equivalence Principle

- Gravitational and inertial masses are equal
- Composition, shape, mass, location etc doesn't matter
- This applies to objects with strong self-gravity as well:
  - Gravitational binding energy gravitates!
    \[ \epsilon \sim \frac{GM}{Rc^2} \sim 0.1 \text{ for NS} \]
  - Only GR embodies this
- Tested via the Nordtvedt parameter, \( \eta \):

\[
\left( \frac{m_{\text{grav}}}{m_{\text{inertial}}} \right) = 1 + \Delta = 1 + \eta \epsilon + \mathcal{O}(\epsilon^2).
\]
Strong Equivalence Principle

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  \[ \left( \frac{m_{\text{grav}}}{m_{\text{inertial}}} \right) = 1 + \Delta = 1 + \eta \epsilon + O(\epsilon^2). \]

Lunar Laser Ranging (LLR) has constrained: \( |\eta \epsilon| < 2 \times 10^{-13} \), corresponding to \( |\eta| < 4 \times 10^{-4} \), given weak gravity of Solar System bodies

Müller, Hofmann, Biskupek, 2012, CQGrav
Here is signal we are looking for (Constraint on $\eta \sim 100x$ smaller than limit by LLR)
Here is signal we are looking for
(Constraint on $\eta \sim 100x$ smaller than limit by LLR)

- New PPN Lagrangian (Nortvedt) based timing solution
- All timing be computed without TEMPO/TEMPO2
- Still working on removing possible data systematics
- We have lots of data (~38,000 TOAs!)

Hopefully a result this summer.... (Archibald et al)
J0337+1715 scalar-tensor constraints

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

- Prediction is ~1-2 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 2,000 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!
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

• Many amazing (and bright!) pulsars to be found in the Galaxy: we know of <10% of total

• Radio pulsars can, do, and will make extremely important contributions to **basic physics**
  • Direct detection of gravitational radiation
  • High precision tests of gravitational theories
  • Probes the nature of matter at supra-nuclear densities
  • Study the advanced stages of stellar+binary evolution

• But we are sensitivity limited (Need big scopes!)
  • FAST in China, MeerKAT in S.Africa, eventually SKA?
  • Losing GBT and/or Arecibo would be **bad** for PSRs
Orbital Animation

PSR J0337+17
MJD 55930.9
4 TOAs

\[ P_o = 327 \text{ day} \]
\[ P_i = 1.6 \text{ day} \]
\[ m_p = 1.438 \, M_\odot \]
\[ m_1 = 0.198 \, M_\odot \]
\[ m_2 = 0.410 \, M_\odot \]

AO  GBT  WSRT

video by Anne Archibald