Science with pulsars

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Let’s start at the beginning

08:35:20.61 - 45:10:34.87

Animation: Michael Kramer

- Formation of the beam
- Propagation through the magnetosphere
- Propagation through the interstellar medium
- Propagation through the interplanetary medium
- The pulsar’s astrometric, pulse and orbital parameters
- ...
- gravitational waves passing the Earth and/or the pulsar
Structure of talk

• Part 1: Introduction to pulsar timing
• Part 2: Uncorrelated timing residuals
• Part 3: Monopolar correlations
• Part 4: Dipolar correlations
• Part 5: Quadrupolar correlations
• Part 6: Where is Parkes?

• (Use data from the Jodrell Bank Observatory and Parkes Pulsar Timing Array project)
Pulsar timing

Slide from D. Champion

TOA (measured using the observatory clock)

Model

Residual

Fold

CSIRO. Measuring the mass of Jupiter using pulsars

- Obtain pulse arrival times at observatory
- Model for pulsar spin down
- Form timing residuals – how good is the timing model at predicting the arrival times
- Improve timing model

\[
F_0 = 245.4261197483027 \pm 0.00000000000005 \text{ Hz}
\]

\[
F_1 = -5.38188 \times 10^{-16} \pm 4 \times 10^{-21} \text{ Hz/s}
\]
Details: Roemer delay

\[ \Delta t = \Delta_C + \Delta_A + \Delta_{E\oplus} + \Delta_{R\oplus} + \Delta_{S\oplus} - \frac{D}{f^2} + \Delta_{VP} + \Delta_B \]

- The Roemer delay is the vacuum light travel time between the pulse arriving at the observatory and the equivalent arrival time at the SSB.

**K = Unit vector pointing at pulsar. Obtained from RA, DEC, PMRA, PMDEC**

**R is vector from observatory to SSB. Use JPL ephemeris, observatory coordinates and earth orientation parameters**

**Use observatory coordinate file to know position of observatory**
Example timing residuals
Jodrell Bank Observatory data

Hobbs et al. (2010), MNRAS
A few simulations

GW background  Spin-down irregularities  Clock noise

• With one pulsar you cannot (normally) tell what unmodelled physical effect is causing the residuals

Simulated data
Spin-down irregularities

RA = 24 h

No angular signature

Dec = -90°
Terrestrial time standard irregularities

Monopolar signature

Dec = -90°
Errors in the planetary ephemerides - e.g. error in the mass of Jupiter
What if gravitational waves exist?

Quadrapolar signature

Dec = $-90^\circ$
Part 2: Uncorrelated residuals

- Part 1: Introduction to pulsar timing
- Part 2: Uncorrelated timing residuals
- Part 3: Monopolar correlations
- Part 4: Dipolar correlations
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- Part 6: Where is Parkes?
Describing the spin-down of pulsars

- Modelling the pulsar spin-down usually requires the pulse frequency, $F$ and its first derivative, $F_1$.
- Residuals shown here have $F_2$ (and higher derivatives) = 0.
Difficulties when categorising timing residuals

- B1746-20
- B1900+01
Difficulties when categorising timing noise: depends on data span

- PSR B1818-04
- Any simple classification scheme would change with data span.
- Most large-scale analyses of timing noise used ~3 yr of data.
Typical pulsar timing residuals over many decades (Jodrell Bank Observatory data)

- Hobbs et al. 2010, MNRAS
- Studied 366 pulsars with data spanning 10->40 years
- Found quasi-periodicities
- Need long datasets to see the oscillations clearly!
- The irregularities in the pulsar spin are not completely “random”!

- Could this be caused by planets, free-precession, asteroid belts, … ???
An interlude: B1931+24

- PSR B1931+24 has been reported to undergo “extreme nulling” events (Kramer et al. 2006)
- Normal pulsar for 5 to 10 days
- Switches off for up to 35 days
- The pulsar spin-down rate changes by ~50% between the on and off states (pulsar spinning down faster when “on”)

(Note: PSR J1832+0029 has recently been discovered - “on” for approx 1 year and then “off” for approx 2 years)
Discovery of a two state process in many pulsars

• Lyne, Hobbs, Kramer, Stairs, Stappers, Science 24 June 2010
• We show that timing behaviour often results from typically two different spin-down rates.
• Show correlated pulse shape variations => magnetospheric origin
• In theory can use the observed pulse shape to correct the “pulsar clock”
Why is this important?

• Conclusion: pulsar timing noise is magnetospheric in origin – get correlated spin down changes with pulse profile. Timing noise is a two-state process

• "Mankind's best clocks all need corrections, perhaps for the effects of changing temperature, atmospheric pressure, humidity or local magnetic field. Here, we have found a potential means of correcting an astrophysical clock". – Andrew Lyne

• => reduce the time taken to detect gravitational waves!

• => make the best use of future telescopes such as ASKAP, SKA …

Unanswered questions:

• Why do the pulsars have this two state process?
• Are glitches and timing noise linked?
• Do all pulsars show this two state timing noise? Do millisecond pulsars exhibit different timing noise?
• How fast can the pulsar switch between the two modes?
Part 3: Correlated timing residuals: monopole

- Part 1: Introduction to pulsar timing
- Part 2: Uncorrelated timing residuals
- Part 3: Monopolar correlations
- Part 4: Dipolar correlations
- Part 5: Quadrupolar correlations

Now using observations of millisecond pulsars obtained as part of the Parkes Pulsar Timing Array project … timing precisions of <100ns (equiv 30m) are obtained for some pulsars.
Time standards

- Pulsar observations referred to a realisation of terrestrial time: TT(TAI)
- Post-corrected time standard TT(BIPM2010) can be used
It’s hard (page 11)

• Must deal with:
  • Different data spans for different pulsars
  • Different timing model fits being applied
  • Different sampling for different pulsars (and all sampling is irregular)
  • Variable error bars (between pulsars and within a given pulsar data set)
  • Unexplained pulsar timing irregularities
  • Other phenomena that may cause correlated signals (i.e., a gravitational wave background signal has a correlated component)
  • …
Consider two pulsar data sets.
• Have different data spans
• Fit for the pulse frequency and its derivative
• Add in realistic amounts of noise
An example (page 16)

• Add in some unexplained timing irregularities
Technique:
(Hobbs et al., in preparation)

• Define clock function to be simple Fourier expansion:

\[ f(t) = \sum A_k \cos(k\omega_0 t) + B_k \sin(k\omega_0 t) \]

(note: can use other functional forms if needed)

• Carry out a standard least-squares fit of pulsar timing model parameters + f(t) as usual, except:

- simultaneously fit to multiple pulsars
- use measurement of the covariance in the residuals for a given pulsar as part of the least-squares-fit fit (to deal with timing noise)

\[ \vec{P}_{est} = (M^T C^{-1} M)^{-1} M^T C^{-1} \vec{R} \]

Timing residuals

Covariance matrix of the residuals

Pulsar timing model
Testing: can we recover TAI-TT(BIPM2010) \times 10?

- Simulate 10x expected TAI-TT(BIPM2010) in real pulsar data
Final result (no simulations)
EPT-TT(TAI) and TT(BIPM2010)-TT(TAI)

Clock difference (sec)

1 μs
Summary of part 3:

- Can recover recent deviations between TT(BIPM2010) and TT(TAI) using pulsar observations
- Have significant deviation from TT (BIPM2010) prior to the year 1999
- Can not (currently) distinguish between errors in TT(BIPM2010) and errors in the time transfer from the Parkes observatory
- New data sets should significantly improve the results
- New pulsar discoveries and improved observing techniques are significantly improving the precision with which pulsars can be timed.
- Pulsars may be able to provide confirmation/addition to Earth-based timestands on timescales of years and decades.

Unanswered questions:

- Can we prove that the deviation from TT prior to 1999 is caused by errors in TT(BIPM2010)?
- Can we use the pulsar timescale to improve our timing precision?
- Can we include pulsar data in the creation of TT(BIPM2010) to improve terrestrial time.
- Can any other affects mimic clock errors?
Part 4: Correlated timing residuals: dipole

- Part 1: Introduction to pulsar timing
- Part 2: Uncorrelated timing residuals
- Part 3: Monopolar correlations
- Part 4: Dipolar correlations
- Part 5: Quadrupolar correlations
Measuring planetary masses

- Use International Pulsar Timing Array data from Parkes, Effelsberg, Nancay and Arecibo.
- A planetary mass error will lead to incorrect determination of the Solar System barycentre => correlated pulsar timing residuals
- Can fit to multiple pulsars simultaneously to search for such a signal
### Measuring Planetary Mass

- Use data from Parkes, Arecibo, Effelsberg and Nancay

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<td>$2.858858(14) \times 10^{-4}$</td>
</tr>
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Summary of part 4

• Can measure planetary masses with pulsar timing
• New data sets will significantly improve the precision

• **Unanswered questions:**

• Can we identify an unknown TNO? (Have a summer student this year trying to rule out “nemesis” – a postulated large mass in our solar system)
• Can we realistically simulate the effects of perturbing a planetary mass?
• Can we search for unknown planets/asteroids around the pulsars?
Part 5: Correlated timing residuals: quadrupole

- Part 1: Introduction to pulsar timing
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- Part 6: Where is Parkes?
Part 2: Details of the detection method. Single GW sources

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

\[ R(t) = -\int_0^t \frac{\delta \nu(t)}{\nu} dt \]
Orbital Motion in the Radio Galaxy 3C 66B: Evidence for a Supermassive Black Hole Binary

Hiroshi Sudou, Satoru Iguchi, Yasuhiro Murata, Yoshiaki Taniguchi

- $M_t = 5.4 \times 10^{10} \, M_{\text{solar}}$
- Mass ratio = .1
- $M_{\text{chirp}} = 1.3 \times 10^{10} \, M_{\text{solar}}$
- Orbital period = $1.05 \pm .03$ yrs
- Distance = 85 Mpc ($H=75 \, \text{km/s/Mpc}$)
- $h \approx M_{\text{chirp}}^{5/3} \, \Omega^{2/3} / D \approx 10^{-12}$
- $R = h / \Omega = 2 \, \mu \text{s}$
Application to 3C66B: Jenet et al. (2004)

Application to 3C66B


Data from Kaspi et al. 1994
New technique – Our first “map of sky in GWs” - Hobbs et al. (in prep)

- Use same technique as the pulsar time scale, but search for a quadrupolar signal.
Detecting the stochastic background

\[ R(t, \hat{k}) = - \int_0^t \sum_{s=0}^{N-1} \mathcal{H}(\hat{k}, \hat{\eta}_s)^{ij} (h_{ij}(t_e, x_e, \hat{\eta}_s) - h_{ij}(t_e - d, x_p, \hat{\eta}_s)) dt_e \]

This is the same for all pulsars.

This depends on the pulsar.

- The induced timing residuals for different pulsars will be correlated
The expected correlation function

Simulated data

Detection/limits on the background

- Yardley et al. (2011) providing details on detecting the background
- No detection yet made

Current data sets are ruling out a few cosmic string models

The square kilometre array should detect GWs or rule out most models

GW frequencies between $10^{-9}$ and $10^{-8}$ Hz - complementary to LIGO and LISA
And now for something completely different …

Pulsar navigation

• Normal pulsar timing:
  - set of pulse arrival times
  - initial model of pulsar
  - know telescope position
  - know clock

  -> improved model of pulsar
  -> timing residuals

• Do it backwards
  - set of pulse arrival times
  - “perfect” model of pulsar

  -> get telescope position
  -> determine time of observation

Can we create an astronomical “gps” system?
Pulsar navigation

- **K** = Unit vector pointing at pulsar. Obtained from RA, DEC, PMRA, PMDEC
- **R** = Vector from observatory to SSB. Use JPL ephemeris, observatory coordinates and Earth orientation parameters
- Use observatory coordinate file to know position of observatory

CSIRO. Gravitational wave detection
Pulsar navigation: assume that you are on the Earth’s surface

- Parkes observations
Pulsar navigation: assume that you are on the Earth’s surface

• Parkes observations
Pulsar navigation: assume that you are on the Earth’s surface

• Parkes observations
Pulsar navigation: assume that you are on the Earth’s surface

- Parkes observations
Pulsar navigation: assume that you are on the Earth’s surface

- Parkes observations ... correct to within a few kilometres

CSIRO. Gravitational wave detection
Pulsar navigation: in 3D
Conclusion

- Pulsars can be used to study many different aspects of astronomy and astrophysics
- The pulsar timing array projects are providing high quality data sets on large numbers of pulsars
- We have a better understanding of pulsar timing irregularities
- We have found errors in the terrestrial time standards
- The International Pulsar Timing Array has the best published mass of the Jovian system
- We have techniques developed and ready that should be able to detect GWs.
- However, we need some confidence that merging supermassive black holes actually exist!
Unanswered questions

• **Timing irregularities:**
  - Why do the pulsars have this two state process?
  - Are glitches and timing noise linked?
  - Do all pulsars show this two state timing noise? Do millisecond pulsars exhibit different timing noise?
  - How fast can the pulsar switch between the two modes?

• **Clocks:**
  - Can we prove that the deviation from TT prior to 1999 is caused by errors in TT (BIPM2010)?
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  - Can anything else mimic clock errors?

• **Planets:**
  - Can we identify an unknown TNO?
  - Can we realistically simulate the effects of perturbing a planetary mass?
  - Can we search for unknown planets/asteroids around the pulsars?

• **Gravitational waves/galaxies**
  - What do our upper bounds on GW emission imply for e.g. galaxy merger rates, the rate of expansion in the inflationary era and cosmic strings?
  - Can we find a black hole binary system with ~1 pc separation?
  - Can we undertake a coherent search to identify single source of GWs?
  - Can we find burst GW sources?