The Parkes Pulsar Timing Array Project

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Summary

• What is a Pulsar Timing Array?
• The Parkes Pulsar Timing Array project
• The new Pulsar Digital Filterbank: PDFB2
• DM variations and implications for the ISM
• Limits on the GW background from pulsar timing
• Future prospects
A Pulsar Timing Array

• A pulsar timing array is a long-term program of frequent precision timing observations of a large sample of pulsars widely distributed on the celestial sphere

• To allow correction for propagation delays, observations at two or more frequencies are required

• Such observations can in principle detect the stochastic gravitational wave background in our Galaxy
  
  ➢ Gravitational waves passing over the pulsars are uncorrelated
  
  ➢ Gravitational waves passing over Earth produce a correlated signal in the TOA residuals for all pulsars

• A timing array can also detect instabilities in terrestrial time standards - establish a pulsar timescale - and improve Solar system parameters

  Idea first discussed by Romani (1989) and Foster & Backer (1990)
Clock errors

All pulsars have the same TOA variations: monopole signature

Solar-System ephemeris errors

Dipole signature

Gravitational waves

Quadrupole signature

Can separate these effects provided there is a sufficient number of widely distributed pulsars
Detecting a Stochastic GW Background

Simulation using Parkes Pulsar Timing Array (PPTA) pulsars with GW background from binary black holes in galaxies

(Rick Jenet, George Hobbs)
The Parkes Pulsar Timing Array Project

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The PPTA Project: Goals

- To detect gravitational waves of astrophysical origin
- To establish a pulsar-based timescale and to investigate irregularities in terrestrial timescales
- To improve the Solar System ephemeris - detect TNOs?

To achieve these goals we need ~weekly observations of ~20 MSPs over at least five years with TOA precisions of ~100 ns for ~10 pulsars and < 1 µs for rest

- Modelling and detection algorithms for GW signals
- Measurement and correction for interstellar and Solar System propagation effects
- Implementation of radio-frequency interference mitigation techniques
- Development of international collaborations - EPTA, NAPTA, China. Coordinated observations, increased sky coverage, collaboration on analysis and interpretation
Sky Distribution of Millisecond Pulsars

P < 20 ms and not in globular clusters

- Red stars: Parkes TA pulsar
- Yellow circles: P = 2 ms
- Orange circles: P = 5 ms
- Filled: S1400 > 2 mJy
PPTA Pulsars

- 20 MSPs - all in Galactic disk except J1824-2452 (B1821-24) in M28
- Three years of timing data at 2-3 week intervals and at three frequencies
- Backends: WBC (1 GHz bw but limited time and frequency resolution, 2-bit sampling), PDFB1 (256 MHz, 8-bit), CPSR2 (2 x 64 MHz, 2-bit, baseband recording)
- Data uncorrected for DM variations, calibration errors and low-level RFI
- Eight pulsars with rms timing residuals < 1 µs, all < 3.5 µs

Still have a way to go!

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<th>Period (ms)</th>
<th>DM (cm⁻³ pc)</th>
<th>Orbital Period (d)</th>
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PDFB2 First Light @ 10cm (PSR B1749-28) - 16 March 2007

Digital Filterbank

• 1 GHz bandwidth, 9-bit sampling, up to 2048 frequency channels
• Based on ATNF CABB board - 7 FPGAs, 2 GB on-board memory
• 4 ms minimum period for 4 poln x 2048 bins x 2048 channels
• Search mode has 1 - 16 bits/sample, integration period 1
  µs - 1 ms
• Baseband mode: Front-end for APSR. Up to 64 contiguous baseband outputs over 1 GHz;
  2, 4 or 8 bits/samp
• Outputs on 16 March, 512 MHz bandwidth
• 1 GHz bandwidth mid-April
• Baseband mode, RFI mitigation (2 boards) ~ June 2007

- Baseband mode
- Outputs over 1 GHz
- Commissioning
- 1 GHz bandwidth
- Baseband mode
Raw PDFB2 spectrum: 512 MHz bw centred at 1550 MHz
Dispersion Measure Variations

- $\Delta DM$ from 10/50cm or 20/50cm observation pairs - data smoothed and interpolated
- Variations observed in most of PPTA pulsars,
  $\Delta DM$ typically a few $10^{-3}$ cm$^{-3}$ pc
- Effect of Solar wind observed in pulsars with low ecliptic latitude

Post-fit residuals:
- Uncorrected TOAs
- Corrected TOAs
- Corrected parameters, Uncorrected TOAs
DM Structure Functions

Slope = 2

Slope = 5/3

DISS

(You et al. 2007)

Spectral break

$1 \, \mu s$

$100 \, ns$

$\log_{10}[D_{DM}(\tau)]$

time lag (days)

J1045–4509

inner time-scale
Detecting Gravitational Waves with Pulsars

• Observed pulse periods affected by presence of gravitational waves in Galaxy

• For stochastic GW background, effects at pulsar and Earth are uncorrelated

• With observations of one or two pulsars, can only put limit on strength of stochastic GW background

• Best limits are obtained for GW frequencies \( \sim 1/T \) where \( T \) is length of data span

• Analysis of 8-year sequence of Arecibo observations of PSR B1855+09 gives
  \[ \Omega_g = \rho_{GW}/\rho_c < 10^{-7} \]  
  (Kaspi et al. 1994, McHugh et al. 1996)

• Extended 17-year data set gives better limit, but non-uniformity makes quantitative analysis difficult  
  (Lommen 2001, Damour & Vilenkin 2004)
Current and Future Limits on the Stochastic GW Background

- Arecibo data for PSR B1855+09 (Kaspi et al. 1994) plus recent PPTA data
- Monte Carlo methods used to determine detection limit for stochastic background described by $h_c = A(f/1\text{yr})^\alpha$
  (where $\alpha = -2/3$ for SMBH, $\sim -1$ for relic radiation, $\sim -7/6$ for cosmic strings)
  - Current limit: $\Omega_{gw}(1/8 \text{ yr}) \sim 2 \times 10^{-8}$
  - For full PPTA (100ns, 5 yr): $\sim 10^{-10}$
- Currently consistent with all SMBH evolutionary models (e.g., Jaffe & Backer 2003; Wyithe & Loeb 2003, Enoki et al. 2004)
- If no detection with full PPTA, all current models ruled out
- Already limiting EOS of matter in epoch of inflation ($w = p/\varepsilon > -1.3$) and tension in cosmic strings (Grishchuk 2005; Damour & Vilenkin 2005)

(Jenet et al. 2006)
A Pulsar Timescale

- Terrestrial time defined by a weighted average of caesium clocks at time centres around the world
- Comparison of TAI with TT(BIPM03) shows variations of amplitude ~1 µs even after trend removed
- Revisions of TT(BIPM) show variations of ~50 ns
- Pulsar timescale is not absolute, but can reveal irregularities in TAI and other terrestrial timescales
- Current best pulsars give a 10-year stability ($\sigma_z$) better than TT(NIST) - TT(PTB)
- Full PPTA will define a pulsar timescale with precision of ~50 ns or better at 2-weekly intervals and model long-term trends to 5 ns or better
Future Prospects

• PDFB2 (April 2007) has higher time and frequency resolution than PDFB1 and 4x bw - should improve TOAs by factor of 2-3

• Real-time RFI mitigation (June 2007)

• New 10cm/50cm feed, preamps at 700-764 MHz to avoid worst of digital TV in 50cm band (August 2007)

• APSR: Successor to CPSR2, baseband up to 1 GHz bw (late 2007)

• Hope to continue ~2-weekly observations at Parkes for at least another five years. International collaborations are important!

• MIRANDA is not really competitive with Parkes: similar collecting area but higher Tsys, smaller frequency coverage

• SKA will win with raw sensitivity. Searches will give a much larger sample (>100 field MSPs?)

Reducing systematic errors is key to success!
Summary

- Frequent precision timing observations of many pulsars widely distributed on the celestial sphere constitute a pulsar timing array.
- PTA observations with a data span of at least 5 years can detect GW from astrophysical sources (or rule out many current models).
- The Parkes Pulsar Timing Array (PPTA) project has been timing 20 MSPs every 2-3 weeks since mid-2004. Goal is ~100 ns rms residuals on at least half of the sample; currently have eight with rms residuals < 1 µs.
- Much effort is going into improving instrumentation and data analysis techniques and fostering international collaboration.
- Corrections for DM variations are important and give interesting information about large-scale fluctuations in the interstellar electron density.
- A pulsar-based timescale will have better long-term stability than the current best terrestrial timescales based on atomic clocks.
- Current results put a limit of $2 \times 10^{-8}$ on $\Omega_{gw}$ in the Galaxy, limit the tension in cosmic strings and the EOS in the early Universe.
- SKA will herald a new era in the study of gravitational waves!