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Pulsar timing arrays

R. N. Manchester*
CSIRO Astronomy and Space Science, PO Box 76, Epping NSW 1710, Australia

Abstract. A pulsar timing array (PTA) consists of an array of pulsars, widely distributed on the sky, with precise timing observations extending over many years for each pulsar. Such timing data sets have the potential to enable a direct detection of low-frequency gravitational waves and to establish an independent pulsar-based timescale. Three main PTAs currently exist, based in Europe, North America and Australia respectively. Data from the three PTAs are being combined to form an International Pulsar Timing Array (IPTA). These PTAs and recent results from them are described.

Keywords : pulsars – gravitational waves

1. Introduction

Direct detection of the gravitational waves (GWs) predicted by Einstein's general theory of relativity is a major goal of current science. Pulsars have already given firm evidence for the existence of GWs through observations of the orbital decay of double-neutron-star systems such as the Hulse-Taylor binary pulsar (PSR B1913+16; Weisberg et al. 2010). However, because of the tiny amplitude of GWs from astronomical sources (or anything else), their direct detection has remained elusive, despite huge efforts over many decades. Most current GW detection systems employ laser interferometers, e.g., the United States LIGO system (Abbott et al. 2009). These systems are sensitive to GWs with frequencies in the range 10 Hz – 1 kHz, with coalescing double-neutron-star systems as the most likely detectable astrophysical source.

With their highly stable periods, pulsars also offer the opportunity to make a direct detection of GWs. To discriminate against intrinsic period variations, it is necessary to observe a number pulsars spread across the sky, that is, to form a pulsar timing

*email: dick.manchester@csiro.au

array (PTA) Foster & Backer (1990). GWs passing over the pulsars produce uncorrelated period modulations but GWs passing over the Earth produce a signal which is correlated between the different pulsars. This is the key to GW detection by a PTA. Only millisecond pulsars (MSPs) have sufficient timing precision and period stability to be useful for PTA projects.

The most likely source for GW detection by a PTA is a largely isotropic background of GWs emitted by binary super-massive black holes in distant galaxies (Sesana et al. 2008). Because of the "red" nature of the expected signal in the pulsar timing residuals ($P(f) \sim f^{-13/3}$), the sensitivity of a PTA is highest for $f \sim 1/T$, where T is the data span. For existing PTAs, T is typically years to decades, so they are most sensitive to GW with frequecies in the 1 – 10 nHz range. PTA GW-detection projects are therefore complementary to laser-interfometer projects.

GWs are not the only correlated signals that PTAs are sensitive to. Instabilities in the reference clock used for the pulsar timing observations will affect the apparent period of all pulsars in the same way. Thought of as a spatial pattern on the sky, a clock error has a *monopole* signaure. Another source of correlated signals is errors in the solar-system ephemeris used to correct observed pulse times of arrival (ToAs) to the solar-system barycentre, an essential step in all pulsar timing analyses (Hobbs et al. 2006). An ephemeris error is effectively an error in the assumed Earth position – this will produce a ToA error of opposite sign for pulsars on opposite sides of the sky, so it has a *dipole* spatial signature. Because of the quadrupole nature of GWs, the pulsar timing signal is anti-correlated for pulsars that are in perpendicular directions and correlated for pulsars which are close together on the sky or on opposite sides of the sky, i.e., a *quadrupolar* signature. For an isotropic background of GWs, the correlation depends only on the angle between the pulsar directions, not on the pulsar directions themselves (Hellings & Downs 1983). In principle, these different spatial signatures can be used to separate signals from these three sources of correlated timing fluctuations.

2. Pulsar timing arrays

There are three main PTAs currently operating. The European Pulsar Timing Array (EPTA) uses four large radio telescopes in Europe (at Efflesberg, Nançay, Westerbork and Jodrell Bank) and will soon be joined by the new 64-m radio telescope in Sardinia (Kramer & Champion 2013). Currently these telescopes are used independently, but under the LEAP project all five telescopes will be operated as a phased array with a collecting area equivalent to that of a 194-m diameter single dish. The EPTA currently is observing about 40 MSPs with 19 having data spans in excess of five years (Kramer & Champion 2013). The majority of observations are at frequencies around 1.4 GHz and typical ToA uncertainties are a few μs.

The North American PTA, known as NANOGrav, uses data from the Green Bank

100-m telescope and the Arecibo telescope at frequencies between 430 MHz and 2 GHz (McLaughlin 2013). About 36 MSPs are currently being observed, with about 23 having data spans in excess of five years; the longest data span, albeit with some large gaps, is about 28 years for PSR B1939+21. The median ToA uncertainty for the better-timed pulsars at frequencies around 1.4 GHz is about 0.4 μs.

The third major PTA is the Parkes Pulsar Timing Array (PPTA) based on the Parkes 64-m radio telescope in Australia (Manchester et al. 2013; Hobbs 2013). Currently 24 MSPs are being observed, with 20 having data spans in excess of five years with the longest being about 17 years. Observations are regularly made in three bands: 50 cm ($\sim$ 0.7 GHz), 20cm ($\sim$ 1.4 GHz) and 10cm ($\sim$ 3 GHz). For the 20 cm band, the median ToA uncertainty is approximately 0.6 μs.

Multi-frequency observations are necessary to correct for variations in interstellar dispersion delays which are proportional to ν^{-2}. Typical observed DM variations over timescales of months to years are $\sim 10^{-3}$ cm^{-3} pc (Keith et al. 2013). A variation of 10^{-4} cm^{-3} pc corresponds to a change in dispersion delay of 212 ns at 1.4 GHz, several times the rms timing residual for the better-timed pulsars, illustrating the need for the correction.

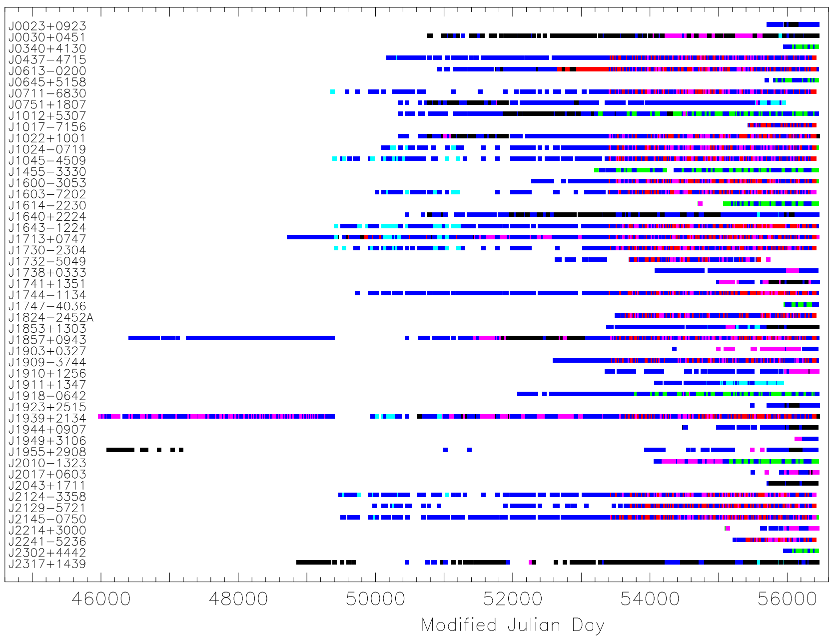

Figure 1. Distribution of ToAs for the 50 pulsars in the IPTA data set. Band centre frequencies are represented by colours: black: $\nu < 0.5$ GHz, red: 0.5 GHz $< \nu < 0.75$ GHz, green: 0.75 GHz $< \nu < 1$ GHz, blue: 1 GHz $< \nu < 1.5$ GHz, aqua: 1.5 GHz $< \nu < 2$ GHz and pink: 2 GHz $< \nu < 4$ GHz. (Manchester 2013)

3. Limits on the GW background

Each of the three PTAs has recently published a limit on the strength of the GW background in the Galaxy. For the EPTA, van Haasteren et al. (2011) used Bayesian methods to set a 95% confidence limit on the GW characteristic strain of 6×10^{-15} at a wave frequency of 1 yr^{-1} based on observations of seven MSPs. This limit and the others quoted below assume an intrinsic GW spectrum $P_g(f) \sim f^{-2/3}$ through the frequency range of interest. For the NANOGrav project, Demorest et al. (2013) used observations of 17 MSPs with data spans of about five years to give a limit of $7{\times}10^{-15}$. More recently, Shannon et al. (2013) used PPTA observations of six MSPs with data spans of up to 17 years (extended to 25 years for PSR B1855+09; Kaspi et al. 1994) to set an upper limit of 2.4×10^{-15}. This limit is the first to seriously challenge current physical models for galaxy evolution and black-hole formation in the early Universe. PPTA data have also been used to define the first pulsar-based timescale that has a stability comparable to that of international atomic timescales (Hobbs et al. 2012).

4. The international pulsar timing array

Progress toward essentially all PTA objectives is enhanced by increasing the number and data span of precisely timed pulsars in the data set. Ultimately this will come from PTAs based on sensitive new instruments such as the FAST radio telescope in China (Nan et al. 2011) and the Square Kilometre Array (Lazio 2013). But in the shorter term, the most practical and effective way of achieving this is to combine the data sets of the existing PTAs. The International Pulsar Timing Array (IPTA) project (Manchester 2013) has been set up for this purpose. As illustrated in Figure 1, the IPTA data set contains 50 MSPs with data spans of up to 28 years. Combining observations made with many different telescopes and processed in different ways to form a uniform data set is a non-trivial problem and is currently a work-in-progress.

References

Abbott B. P., Abbott R., Adhikari et al., 2009, Rep. Prog. Phys., 72, 076901
Demorest P. B., Ferdman R. D., Gonzalez et al., 2013, ApJ, 762, 94
Foster R. S., Backer D. C., 1990, ApJ, 361, 300
Hellings R. W., Downs G. S., 1983, ApJ, 265, L39
Hobbs G., 2013, Classical and Quantum Gravity, 30, 224007
Hobbs G., Coles W., Manchester R. N., et al., 2012, MNRAS, 427, 2780
Hobbs G. B., Edwards R. T., Manchester R. N., 2006, MNRAS, 369, 655
Kaspi V. M., Taylor J. H., Ryba M., 1994, ApJ, 428, 713
Keith M. J., Coles W., Shannon et al., 2013, MNRAS, 429, 2161
Kramer M., Champion D. J., 2013, Classical and Quantum Gravity, 30, 224009
Lazio T. J. W., 2013, Classical and Quantum Gravity, 30, 224011
Manchester R. N., Hobbs G., Bailes M., et al., 2013, PASA, 30, 17
Manchester R. N., 2013, Classical and Quantum Gravity, 30, 224010

McLaughlin M. A., 2013, Classical and Quantum Gravity, 30, 224008
Nan R., Li D., Jin C., et al., 2011, Intl. J. of Mod. Phys. D, 20, 989
Sesana A., Vecchio A., Colacino C. N., 2008, MNRAS, 390, 192
Shannon R. M., Ravi V., Coles W. A., et al., 2013, Science, 342, 334
van Haasteren R., Levin Y., Janssen G. H., et al., 2011, MNRAS, 414, 3117
Weisberg J. M., Nice D. J., Taylor J. H., 2010, ApJ, 722, 1030