PULSAR TIMING ARRAYS AND GRAVITATIONAL WAVES : THE FIRST STEPS TOWARDS DETECTION?

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Abstract. PTA (Pulsar Timing Array) experiments use the natural clock properties of pulsars as a detector of gravitational waves. In practice, perturbations in the regularity of pulse arrival times are analysed and a quadrupole signature is sought that spatially correlates all the measurements amongst the pulsars. The PTAs are sensitive in the frequency domain ranging from 10^{-9} to 10^{-6} Hz, which targets in particular the population of supermassive binary black holes. In January of this year, the US consortium NANOGrav announced the first detection of a common signal across all the pulsars in the network, but without showing evidence for spatial coherence, closely followed by the other two consortia, Australia (PPTA) and Europe (EPTA). I will review these results, focusing on the methodology and on the analysis of foregrounds, and I will detail the astrophysical constraints expected in the years to come.

Keywords: pulsars, gravitational waves, black-holes, galaxy formation

1 Introduction

In France, Pulsar Timing Array (PTA) activities are hosted in two laboratories, LPC2E and APC, and are closely connected to the Nançay Radio Observatory where the dedicated instrumentation is developed and the timing observations are performed at high cadence with the decimetric Nançay Radio Telescope (NRT). There are also connexions with people in Femto-ST and Geoazur, for the link to clock metrology and Solar System Ephemerides. This long term program has been jointly supported for many years by PNCG, PNHE and Paris Observatory Scientific Council and has also received recently funding from DIM-ACAV+ and ANR. This year, there has been a renewed interest for PTA experiments, with the publication and forthcoming press releases by the North American consortium NANOGrav in January 2021 (Arzoumanian et al. (2020)) announcing that they found "possible first hints of low-frequency gravitational wave background". Indeed what happened is that the three international consortia, European Pulsar Timing Array (EPTA), Parkes Pulsar Timing Array (PPTA) and NANOGrav, contemporaneously and independently detected a red noise component shared by all the pulsars in their respective timing array (see respectively: Chen et al. (2021, submitted), Goncharov et al. (2021) and Arzoumanian et al. (2020)). As we will see, this signal has the main caracteristics in amplitude and spectral index of what we expect from the emission of a Super Massive Binary Black Hole population, but the three groups are still missing the detection of a spatial correlation of the signal, which would be the irrefutable proof that it is indeed of gravitational origin. Note that there are also other identified sources of gravitational background emission in the PTA frequency range, which are e.g. the emission from a network of cosmic string loops (Kibble (1976), Sanidas et al. (2012)), relic emission produced by quantum fluctuations of the gravitational field in the inflationary era (Caprini et al. (2010)), or the signature of a first-order phase transition in the primordial universe (Lasky et al. (2016); Grishchuk (2005)). At the time of the SF2A 2021 conference, more that three dozen of articles about the interpretation of this "possible" gravitational wave signal have been submitted to astro-ph since the first claim early this year.

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At the world wide level, continental PTA consortia are organised under a common umbrella organisation named the International Pulsar Timing Array. In addition to the three founding groups mentioned above, the Indian consortium InPTA recently formed and joined the collaboration, and one expects the South Africa and China to join as well in the coming years. There are eight radio telescopes presently participating in the data collection. Five in Europe : Effelsberg (Germany), WSRT (Netherlands), SRT (Italy), Lovell (United Kingdom) and NRT (France) ; one in Australia : Parkes, and two in North America : Arecibo and Green Bank. Arecibo recently collapsed and is being replaced by contributions from VLA and CHIME. GMRT (India) has started a high precision timing programme 3 years ago and MeerKAT (South Africa) has been gathering high quality data since 2.5 years and both are preparing their own first release to participate in the common effort. China will join with three radio telescopes : QTT, JRT and the giant FAST.

The PTA experiment has a long history. The first reference is certainly from Sazhin (1978), who proposed that "ultralong gravitational waves" could be detected by their perturbation on electromagnetic pulses propagation. A bit more than a year later, Detweiler (1979) showed that given published pulsar data, one can set an amplitude upper limit of 10^{-11} to the energy density of a stochastic gravitational wave background with periods 1 year. In 1982, Hellings & Downs (1983) further updated this limit and for the first time they calculated the expected spatial correlation of the signal as a function of the angular separation of pulsar pairs. PTA science was born.

2 Pulsar Timing Arrays: principles

What do pulsar timers measure exactly ? We measure at the telescope a series of pulsations with an observed period P due to the rotation of the neutron star, and we observe a variation δP of this period or of rotation frequency $\delta\nu$ with time. The integration of this $\delta\nu$ all along the signal pathway from the pulse emission to its reception is called the timing residual.

$$r(t) = \int_0^t \frac{\nu(t') - \nu_0}{\nu_0} dt' \tag{2.1}$$

In practice we assume that we know sufficiently well the pulsar, its environment, the material present along its line of sight and the Earth motion, that we can model any Doppler shift and dispersion of the signal, so that only the unknown, e.g. the gravitational perturbation we are looking for, remains. One writes:

$$\frac{\nu(t) - \nu_0}{\nu_0} = \frac{1}{2} \frac{\hat{n}^i_\alpha \hat{n}^j_\alpha}{1 + \hat{n}_\alpha . \hat{k}} \Delta h_{ij} \tag{2.2}$$

where $\hat{n}_\alpha$ is the direction of the pulsar i or j, $\hat{k}$ is the direction of a gravitational source, and $\Delta h_{ij} = h_{ij}(t_p) - h_{ij}(t_E)$ is the wave amplitude difference at the pulsar location (t_p) and at the Earth (t_E).

Let us summarize: the Earth and the distant pulsar are considered as free masses whose position responds to changes in the local metric of space time. The passage of a gravitational wave produces fluctuations in the arrival times of the individual pulses, so that with timing uncertainties dt ($\sim$100 ns), a cadence of a few days and total observation time spans T ($\sim$25 years), PTA are sensitive to amplitudes $\sim dt/T \sim 1.3\ 10^{-16}$ and to frequencies $f \sim 1/T \sim 10^{-9}$ - 10^{-6} Hz (see Fig. 1, left panel).

3 The recent results by NANOGrav, PPTA and EPTA

3.1 *A first detection of the stochastic background?*

Fig. 1 (right panel) shows the free spectrum of the PTA residuals along gravitational wave frequencies, as measured respectively by NANOGrav (blue violins, from Arzoumanian et al. (2020)) and EPTA (orange violins, from Chen et al. (2021, submitted)). The power is measured in frequency bins centered successively on $1/T$, $2/T$, ... N_{bin}/T, where T is the total time span covered by the PTA observations. The EPTA has longer time series, thus it reaches lower frequency bins. The full lines show the actual power law describing the red noise fitted from respectively the lowest 5 (NANOGrav) and 30 (EPTA) frequency bins. The European results show a shallower spectral index (-0.39 vs -1.26) and a bit higher amplitude (e.g. 2.95 10^{-15} vs 1.92 10^{-15}, at fixed α = -2/3) with respect to NANOGrav. Both experiments use completely independent data. They use also different analysis pipelines, different MCMC samplers and different models for Solar System Ephemerides uncertainties. Considering our own results from the EPTA analysis, we obtained a robust estimation of the significance of the common red noise detection by comparing bayesian evidences for different models. The Bayes factor is around 1000 in favor of a common red noise or gravitational wave background, with respect to a simple model considering only individual pulsar timing noise. By comparison, the false detection resulting from a clock reference error or a Solar System Ephemerides bias is granted a Bayes factor of respectively 5 and 100 only with respect to the simple model.

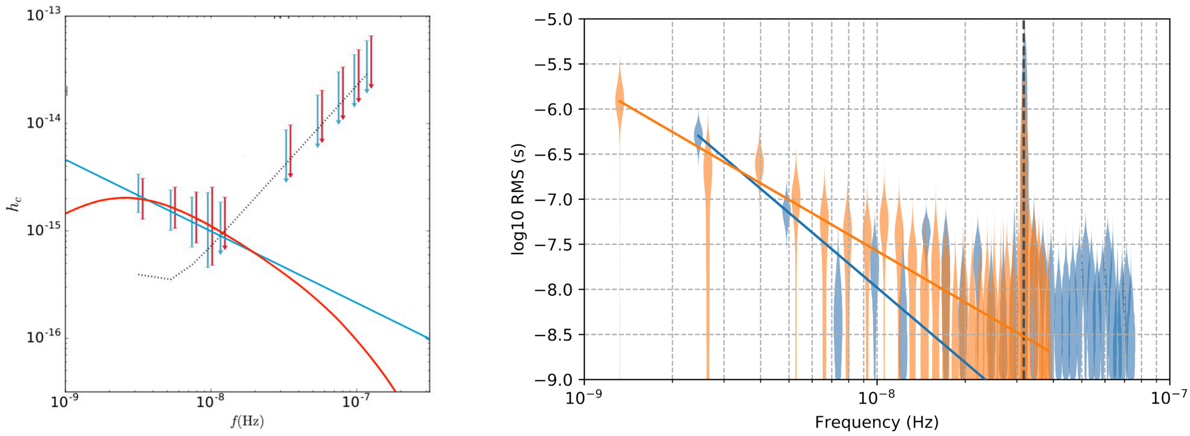

Fig. 1. Left: We illustrate here the principles of PTA stochastic gravitational wave background detection. On the vertical axis, hc is the strain amplitude and the frequencies along the horizontal axis range from 10^{-9} to 2 10^{-7} Hz. The blue line shows the expected power law spectrum $h_c(f) = A(f/yr^{-1})^{\alpha}$ with slope α = -2/3 for a population of super massive black hole binaries with circular orbits and energy loss dominated by gravitational emission. The red curve shows the same spectrum for a more realistic population, including eccentricity of the orbits and energy loss contribution from interactions with central stars and gas. The dotted line shows the PTA sensitivity curve. Above $\sim 10^{-8}$ Hz, the signal is not detected and PTA measurements only provide us with an upper limit. At lower frequencies instead, the signal is detected and one could even start to differentiate the two models of population. **Right:** We show here the recent PTA measurement from Arzoumanian et al. (2020) (red violins, NANOGrav) and Chen et al. (2021, submitted) (blue violins, EPTA). Below $\sim 10^{-8}$ Hz, we actually detect a clear signal in the form of low frequency correlated noise in the timing residuals. Straight full lines represent the respective fitted power law to the lowest 5 (NANOGrav) and 30 (EPTA) frequency bins.

In Fig. 2 (left), one compares the measured power law parameters (common red noise amplitude and index) from PTA experiments to the prediction from astrophysical models. These models describe a population of Super Massive Black Hole Binaries emitting low frequency gravitational waves in the context of hierarchical galaxy and large scale structure formation in a ΛCDM universe (prediction from Middleton et al 2021). One considers here the astrophysical parameters describing: the galaxy stellar mass function, the galaxy pair fraction, the merger time scale, the black-hole to bulge mass ratio, the binary BH eccentricity and the galaxy central stellar density. Among those, it is the merger rate, the merger time scale and the normalization of BH-bulge mass relation, which will be the first parameters to be constrained by a sensitivity limit or a robust detection of the GW background.

3.2 An essential diagnostic: the spatial correlation of the signal

However, the quadrupole nature of gravitational wave emission implies that the Earth term of the stochastic signal is necessarily spatially correlated between all pulsars and follows a well defined signature. Hellings & Downs (1983) showed that the overlap reduction function, which depends both on the sky position of the sources and on the antenna pattern (i.e. the relative position of the pulsars in the array) writes in a unique way as a function of the pulsar angular separations. This signature is an essential diagnostic. Let us emphasise here that **up to now, none of the PTA experiments has detected such a spatial correlation**, which would be the actual smoking gun of a gravitational wave background (see Fig. 2, right panel, for the NANOGrav result). **So no-one can yet claim a detection**. In order to get a detection, each consortium needs to extend its data set:

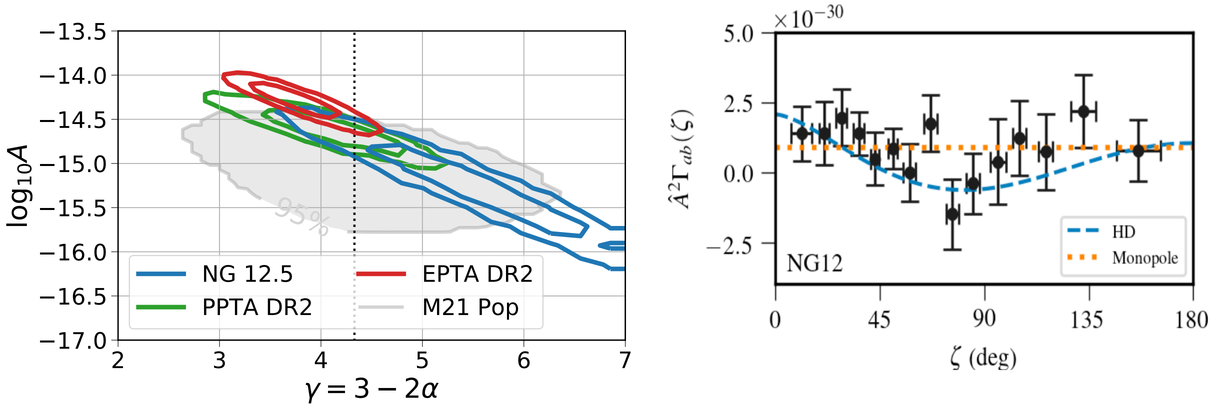

Fig. 2. Left: Contour plot corresponding to the posterior chains for the common-spectrum amplitude and spectral index obtained by the three regional consortia (NANOGrav in blue, EPTA in red, PPTA in green). The vertical dotted line corresponds to the spectral index expected for the emission from a population of Super Massive Black Hole Binaries in circular orbits. The grey area is obtained from Middleton et al. (2021) and shows the 95% confidence contour from astrophysical model predictions for the same population. **Right:** Hellings & Downs (HD) angular correlation measured from the NANOGrav 12.5 years sample (Arzoumanian et al. (2020)). The blue curve shows the expected quadrupolar signature. The orange horizontal line shows the fit of a monopole expected e.g. from clock reference systematics.

NANOGrav and PPTA to have essentially longer time spans, EPTA to add more pulsars in the analysis (i.e. include at least 25 pulsars instead of the 6 best timers only) in order in particular to better sample the spatial correlation. The data set should be completed and analyzed by mid-2022. After that, the full combination of the international data set will bring the ultimate confirmation, allowing to enhance both sensitivity and sky coverage.

3.3 Dealing with foregrounds and systematics

Of course, there are plenty of foreground noises that need to be characterised and correctly modelled before being able to access the GW signal in the timing residuals. Those noises are of different nature. We need to consider first the white or time un-correlated noise in each pulsar residual time series. Its origin can be instrumental (e.g. receiver gain instability, calibration uncertainty) or astrophysical (e.g. pulse jitter, related to the statistics of emission in the pulsar magnetosphere). We then have to deal with various time correlated or ”red” noises that mimic or hide the gravitational emission signature at low frequencies. These ones come primarily from the dispersion measure (DM) variations (a secular change in electron content along the line of sight due to the relative motion of the Earth and the pulsar) and from long term variations of the neutron star rotation (either due to small bodies gravitational perturbations, variations in radiated energy or series of micro-glitches, presence of an unknown long orbital period companion). The former is chromatic with observed radio frequency and can be distinguished from the latter by using multi-band or multi-telescope observations. It can be modeled by a simple power law, but often requires custom modelization to take into account peculiar events (e.g. a lense effect due to a plasma bubble along the line of sight) or secondary variations due to multi-propagation changes or scintillation. The intrinsic or rotation noise is specific to each pulsar and can span a wide range of amplitudes. Fig. 3 shows an example of single pulsar noise analysis, with posterior plots for amplitude and spectral indices of both intrinsic red noise and chromatic DM noise.

Finally, Solar System planetary Ephemerides (SSE) play a crucial role in the timing process as they are used to transpose the timing residuals measured at the telescope to the barycentre of the Solar System (SSB), i.e. to correct for the Roemer delays. Any inaccuracy in such Roemer delays will impact all the pulsars of the array and will induce a spatial correlation that insidiously mimics the imprint of a GW background. To deal with this, the various consortia carefully compare the results from different SSE solutions (using JPL - Folkner & Park (2018) - , INPOP - Fienga et al. (2019) - or PMOE - Li et al. (2008)) and some have developed their own bayesian model of SSE uncertainties to be included in the full GW analysis. The difficulty is that SSE are built from space probe data to optimize the measurements of planets' positions, orbital velocities and masses,

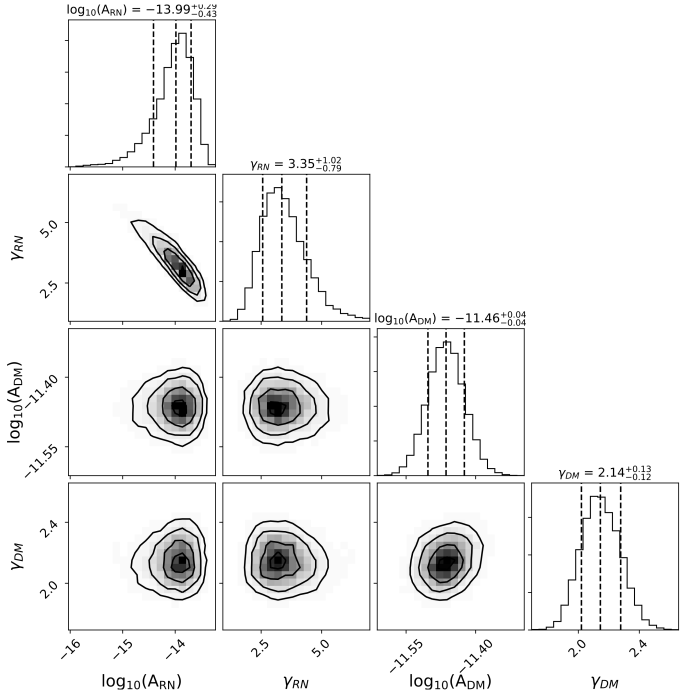

Fig. 3. Posterior distribution of intrinsic red noise (RN) and chromatic noise (DM) for the EPTA pulsar PSR J1600-3053. Each red noise component is modelled with a power law as $S \sim A^2(f/1yr^{-1})^{-\gamma}$. Courtesy of Aurélien Chalumeau (PhD student at LPC2E, Chalumeau et al 2021 in prep)

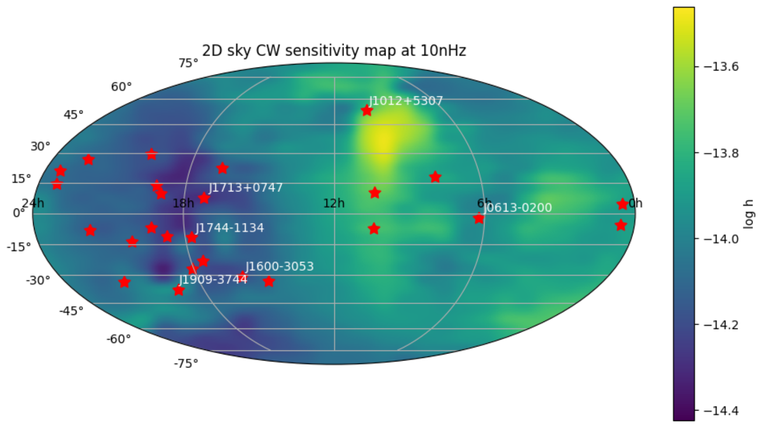

Fig. 4. 2D sky continuous wave sensitivity map at the fixed frequency of 10 nHz, derived from the analysis of EPTA first data release (Desvignes et al. (2016)), extended with 9 years of recent wide band NRT data. Red stars show the positions of the EPTA pulsars. The color scale denotes the span in strain hc in logarithmic scale. Courtesy of Mikel Falxa (PhD student at APC, Falxa et al 2022 in prep)

but not to accurately constrain the position of the SSB.

3.4 The search for individual sources

One expects that PTA measurements will also detect in the near future a few nearby or massive individual binary black-holes, which will show up as continuous wave sources at a single frequency or as a series of harmonics depending on the degree of eccentricity of their orbit. Such a detection is expected to occur as a second step, most probably after the first characterisation of the stochastic background from the whole population. Even without a detection, one can build a whole sky sensitivity map for each frequency bin, given the sky distribution and timing characteristics of the pulsars used in the array. A preliminary such map is shown on Fig. 4, for the GW frequency f = 10 nHz, given the current EPTA pulsar sample (2nd data release, courtesy of Mikel Falxa, PhD student at APC laboratory).

4 Conclusion

To summarize, all PTA consortia have developed independently a complete methodology to properly analyse the pulsar timing residuals and disentangle potential GW emission from various instrumental or astrophysical noise components affecting individual pulsars, as well as consistently taking into account uncertainties coming from SSE systematics. They all detect in their independent data sets the presence of a common process, which is comparable in amplitude and spectral index to the signal expected from a population of Super Massive Black Hole Binaries. However, these convergent results have to be considered with care, since the essential diagnostic of a spatial correlation following Hellings & Downs (1983) signature has not been successful yet. These results are preliminary, based on a sub-sample of available data. The next two years should bring a definitive and robust answer with the extension of the respective data sets and hopefully the global pooling of IPTA data, bringing the ultimate confirmation with much better sensitivity than the separate programmes.

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