SPECIAL PURPOSE PULSAR TELESCOPE FOR THE DETECTION OF COSMIC GRAVITATIONAL WAVES

Shou-Guan Wang
National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

Zong-Hong Zhu*
National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
National Astronomical Observatory, 2-21-1, Osawa, Mitaka, Tokyo 181-8588, Japan

Zhen-Long Zou
National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

Yuan-Zhong Zhang
Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080, China

Pulsars can be used to search for stochastic backgrounds of gravitational waves of cosmological origin within the very low frequency band (VLF), $10^{-7}$ to $10^{-9}$ Hz. We propose to construct a special 50 m radio telescope. Regular timing measurements of about 10 strong millisecond pulsars will perhaps allow the detection of gravitational waves within VLF or at least will give a more stringent upper limits.

1. Introduction

Because a background of relic particles gives a snapshot of the state of the universe at the time when these particles decoupled from the primordial plasma, relic gravitational waves (gravitons) are a potential source of informations on the state of the very early universe and the physics at correspondingly high energies, which can not be accessed experimentally in any other way\(^1\). The photons of the cosmic microwave background (CMB) give us a snapshot of the state of the universe at $t \sim 3 \times 10^5$ years after the big-bang, while the gravitons of the stochastic gravitational wave background (SGWB) encode in its spectrum the information of the universe at $t \sim 10^{-44}$ seconds. These properties make the detection of SGWB very

*Email: zong-hong.zhu@nao.ac.jp zhuzh@bao.ac.cn
interesting, which is the main purpose of the proposal discussed here.

A SGWB can be characterized by its energy distribution in frequency, especially
the dimensionless quantity

$$\Omega_{gw}(f) := \frac{1}{\rho_{\text{critical}}} \frac{d\rho_{gw}}{d\ln f},$$

(1)

where $\rho_{\text{critical}} = \frac{3c^2H_0^2}{8\pi G}$ is the critical energy density required (today) to close
the universe (the Hubble constant $H_0 = 100h_{100}\text{ km sec}^{-1}\text{ Mpc}^{-1} = 3.2 \times 10^{-18}h_{100}$
Hz). Up to now, there have been three observational constraints on SGWB
spectrum\textsuperscript{2,3}: (i) The strongest observational constraint on $\Omega_{gw}(f)$ comes from the
high degree of isotropy observed in the CMB, $\Omega_{gw}(f) h_{100}^2 < 7 \times 10^{-11} (H_0/f)^2$ for
$H_0 < f < 30H_0$. (ii) The second comes from the standard model of big-bang nucleosynthesis,
$\int_{f>10^{-8} \text{ Hz}} d\ln f \Omega_{gw}(f) h_{100}^2 < 10^{-5}$. (iii) The last observational constraint
comes from monitoring the radio pulses emitted by a number of stable millisecond
pulsars for a decade, $\Omega_{gw}(f = 10^{-8} \text{ Hz}) h_{100}^2 < 10^{-8}$.

In order to get a lower constraint on SGWB spectrum or even directly detect
SGWB within the very low frequency band (VLF), $10^{-7}$ to $10^{-9}$ Hz, we propose to
construct a special 50 m radio telescope at National Astronomical Observatories,
Chinese Academy of Sciences (NAOC) to monitor about 10 strong millisecond
pulsars. After reviewing the basics of pulsars as probes for gravitational wave (section
2), we present our research plan in details (section 3).

2. Pulsar timing array as efficient gravitational wave detectors

Pulsars have been believed to be extremely stable natural clocks. Detweiler\textsuperscript{4} had
shown that measurements of pulse arrival time (TOA) may be used to search for
gravitational waves with a period on the order of years. For SGWB, his found

$$\rho_{gw} = \frac{243 \pi^3 f^4 \langle R^2(t) \rangle}{208 G},$$

(2)

where the residual $R(t)$ is the difference between observed and expected TOA. The
span of measurements $T$ should be longer than $1/f$ (with $1/f = a$ few years, the
measurements may be taken at intervals of say, 10-20 days).

The observed $R(t)_{\text{obs}}$ consists of deviations caused by various effects. Some of
them are systematic, such as the uncertainties in the position and proper motion
of pulsars, errors in the positions of barycenter. While others are random, for
example, propagation delays caused by interstellar turbulence, relativistic effects
by intervening massive objects, irregularities occurred in pulsar parameters, or in
reference clock. Some of these effects could be modeled or be estimated, and hence
be corrected. The resulted $\langle R^2(t) \rangle$ is therefore the mixture of three components:
(1) the remaining effects left over after the correction; (2) pulse timing noise which
is related with (a) signal-to-noise ratio of pulsar observation, (b) pulse shape and
the definition of arrival time, and (c) method in obtaining the arrival time; (3)
background gravitational waves. Thus the quantity $\langle R^2(t) \rangle$ from pulsar timing observations produces an upper limit on the energy density of SGWB.

Following Detweiler’s work, a number of observations had been made over a decade due to the advent of the discovery of millisecond pulsars. Millisecond pulsars have high stability and sharp pulses, therefore the precision of timing measurements is extraordinary high, reaching 0.1 $\mu$s sometimes. A millisecond pulsar, besides its extraordinary high inertia which warrants high stability, the shape of its pulses being so sharp has caused a great increase in the precision of timing measurements. As a result, the energy density of SGWB in the frequency range around 0.5 cycle/year was found to be $\rho < 10^{-6} \rho_{\text{critical}}$ (see eg. Ref 5).

This result is encouraging. In particular, a much better sensitivity will be obtained if one can use two or more pulsars as coincident detectors. Such a “pulsar timing array” could be a very efficient SGWB detector. To quantify this, consider the Doppler shift from the $i$th pulsar in the array

$$\frac{\Delta \nu_i(t)}{\nu_i} = \alpha_i s(t) + n_i(t)$$

(3)

where $s(t)$ is the GW signal, $\alpha_i$ a geometrical factor depending on the line-of-sight direction, and $n_i(t)$ contains the noise intrinsic to the pulsar timing. The cross-correlation between two pulsars then gives

$$\alpha_i \alpha_j \langle s^2(t) \rangle + \alpha_i \langle sn_i \rangle + \alpha_j \langle sn_j \rangle + \langle n_i n_j \rangle$$

(4)

and, since the timing noises from different pulsars are uncorrelated, increasing the observation time will limit the cross-correlation towards $\alpha_i \alpha_j \langle s^2(t) \rangle$.

Unfortunately, the galactic millisecond pulsars known around 1990, for which timing data have been taken already, were concentrated in almost the same region of the sky, and correlation analysis of these data does not improve much the result. Now the known millisecond pulsars are much more uniformly distributed on the sky. It is the right time to construct such a “pulsar timing array”. The Berkeley pulsar group led by Don Backer has been working on this direction for a few years.

3. A special 50 m radio telescope at NAOC

We propose to construct a special 50m radio telescope at NAOC, devoted to pulsar timing measurement. It will work on low frequencies, with 1400 MHz as the highest (so that the instruments will not be very expensive). At least 10 strong millisecond pulsars can be chosen from the 27 candidates listed in Table 1 for regular timing measurements. Each object should be observed 1 hour every day. With the best receiving system today, accumulation of 15 day’s measurements will have a sensitivity of about 0.05 mJy, so that a signal-to-noise ratio above 10 is expected for these pulsars.
Table 1. 27 candidates to be observed with 50 m telescope ($S_{400} > 10mJy$)

| Name     | Gal-L | Gal-B | Period (ms) | Distance (kpc) | $S_{400}$(mJy) |
|-----------|-------|-------|-------------|----------------|----------------|
| J0034-0634 | 111.49 | -68.07 | 1.8771818543796 | 0.98 | 17 |
| J0613-0200 | 210.41 | +21.09 | 3.478770781510 | 2.02 | 2e+01 |
| J0751+1807* | 202.73 | +13.50 | 5.25574001198 | 0.517 | 3e+01 |
| J1012+5307 | 160.35 | +50.86 | 16.452929681440 | 0.599 | 2e+01 |
| J1022+1001* | 231.79 | +51.10 | 6.215319388187 | 0.624 | 2e+01 |
| J1300+1240* | 311.30 | +75.41 | 7.987204795504 | 0.738 | 9.0 |
| J1455-3330 | 330.72 | +22.56 | 11.075750876440 | 1.8 | 2e+01 |
| J1623-2631 | 350.98 | +15.96 | 4.6216414465630 | 4.86 | 8e+01 |
| J1643-1224 | 28.75 | +25.22 | 4.5079352273380 | 0.892 | 4e+01 |
| J1713-2304 | 3.14 | +6.02 | 8.1227979128499 | 0.506 | 4e+01 |
| J1744-1134 | 14.79 | +9.18 | 4.07454587512695 | 0.166 | 18 |
| J1748-2446A | 3.84 | +1.70 | 11.563148398585999401 | 7.1 | - |
| J1804-2717 | 3.51 | -2.74 | 9.343030681150 | 1.17 | 15 |
| J1823-3021A | 2.79 | -7.91 | 5.440002278840 | 8 | 16 |
| J1824-2452 | 7.80 | -5.58 | 3.0543146293528 | 5.5 | 4e+01 |
| J1857+0943* | 42.29 | +3.06 | 5.36210045404154 | 1 | 3e+01 |
| J1911-1114 | 25.14 | -9.58 | 3.6257455713977 | 1.59 | 31 |
| J1939+2134* | 57.51 | -0.29 | 1.5578064924327 | 9.65 | 2e+02 |
| J1955+2908 | 65.84 | +0.44 | 6.1331664887299 | 5.39 | 2e+01 |
| J1959+2048 | 59.20 | -4.70 | 1.60740168490632 | 1.53 | 2e+01 |
| J2019+2425* | 64.75 | -6.62 | 3.9345240796636 | 0.912 | 2e+01 |
| J2051-0827 | 39.19 | -30.41 | 4.50864174335 | 1.28 | 2e+01 |
| J2124-3358 | 10.93 | -45.44 | 4.93111485914810 | 0.248 | 17 |
| J2145-0750 | 47.78 | -42.08 | 16.05242365840991 | 0.5 | 100 |
| J2229+2634* | 87.69 | -26.28 | 2.9778192947192 | 1.43 | 1e+01 |
| J2317+1439* | 91.36 | -42.36 | 3.4452510710225 | 1.89 | 2e+01 |

*–Being observed by USA groups

In addition to what mentioned above, multi-object observation strategy is of importance for the detection of SGWB in the following senses: Consider a number of pulsars separated at different parts in the sky, gravitational wave from any direction sweeping across the Earth will be marked by the change of the rates of local clock at a frequency $f$. Owing to the quadrupole character of the gravitational radiation, such effect will exactly in two pulsar data if their directions are 180° apart. So that $R(t)$, in the form of random fluctuations, contained in the record of timing measurements of a pulsar would have an exactly similar shape with the $R(t)$ record of a pulsar. As the period of the gravitational wave $1/f$ being very long, observations of two pulsars within a time interval of one day can be thought as nearly simultaneous. $R(t)_{obs}$ of the two records, when cross-correlated, will reveal the existence quantitatively of the background gravitational waves. In practice, we will have a number of pairs of pulsars at different separation angles, by the same principle, cross-correlations performed to the $R(t)_{obs}$ of all the pairs will produce a better result than that from a single pair.

Finally, we would like to remark that, among these sources of perturbations contained in $R(t)$, many of them are of interest in their own right. The timing measurement data of these objects may be used to, for examples, (1) improve the
ephemeris, (2) monitor the intrinsic perturbations of pulsars, (3) establish a time standard for long time scales.

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