Re-visiting gravitational wave events via pulsars

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By now many gravitational wave (GW) signals have been detected by LIGO and Virgo, with the waves reaching earth directly from their respective sources. These waves will also travel to different pulsars and will cause (tiny) transient deformations in the pulsar shape. Some of us have recently shown that the resultant transient change in the pulsar moment of inertia may leave an observable imprint on the pulsar signals as detected on earth, especially at resonance. The pulsars may thus act as remotely stationed Weber gravitational wave detectors. This allows us to revisit the past GW events via pulsars. We give here a list of specific pulsars whose future signals will carry the imprints of past GW events, to be specific we constrain it within 50 years. Some interesting cases are, supernova SN1987A with earliest perturbed signals from pulsars J0709-5923 and B0559-57 expected to reach earth in 2023 and 2024 respectively, Crab supernova, with perturbed signal arrival date from pulsar J1856-3754 in 2057, and GW170814 event with its imprints on the signals on the pulsar J0437-4715 reaching earth between 2035-2043. Even the earliest recorded supernova SN185 event may become observable again via pulsar J0900-3144 with the perturbed pulsar signal reaching us sometime between 2033-2066. Importantly, even though the strength of the signal will depend on the interior properties of the pulsar, the expected dates of signal arrival are completely model independent, depending only on the locations of the source and the relevant pulsar.

INTRODUCTION

Detection of gravitational waves (GW) has opened a new chapter in observational astronomy. A number of GW sources have been detected by LIGO and Virgo1 ranging from coalescing black holes (BH) to binary neutron star (BNS) mergers. A BNS merger allows much better localization of the source due to electromagnetic radiations accompanying the GW signal. The same is not true for BH mergers where GW source localization is very hard with very few GW detectors. Recently some of us have proposed2 that sensitive monitoring of pulsars can be used to detect the arrival of GW signals on those pulsars. This possibility arises due to deformations caused by the gravitational wave (GW) passing through a pulsar leading to a transient variation in its moment of inertia. This affects the extremely accurately measured spin rate of the pulsar as well as its pulse profile (due to induced wobbling depending on the source direction). The effect will be most pronounced at resonance. We thus proposed that the pulsars, in this sense, act as remotely stationed Weber detectors of gravitational waves whose signal can be monitored on earth2.

This allows for a new possibility of detecting signals of GW events (or any other astrophysical event affecting pulsar moment of inertia such as phase transitions occurring inside a pulsar as discussed in3). Further, this allows us the possibility of re-visiting past GW events, e.g. those which have already been detected by GW detectors. This can give further information about the GW source, and also new information about the relevant pulsar interior (in the manner its pulses carry the imprints of the GW signal). This also will allow for better triangulation of the original source location which is of crucial importance for black hole mergers which only emit gravitational waves. Particularly important are the cases of those events whose GW signal detection has been missed. For example, many supernova events have been identified within our galaxy from astronomical records around the world. Any GW emission from these events should have relatively strong effects on the galactic pulsars. (Especially for type-II supernova4 with estimated GW strain amplitude reaching as high as $10^{-20}$ at a distance of 10 kpc from the source4, though even for Type Ia supernova the GW signal may be strong5.) Observing these pulsars in future (or, from the past recorded pulse data) has the possibility of identifying the signals of these supernova events hidden in the pulsar signal. In this paper we have analyzed specific GW events which have been detected so far1, as well as specific supernova events which are available from astronomical records6. We then consider the locations of a list of pulsars (a total of 2659 pulsars) from ref.7 and calculate the arrival time of perturbed signals on earth. We limit listing of results here to those pulsars whose signals will reach earth within 50 years. We mention some interesting cases for the earliest signal arrival dates. For supernova SN1987A8, we find that perturbed signals from pulsars J0709-5923 and B0559-57 are expected to reach earth on 5/9/2023 and 7/8/2024 respectively, with many more pulsar signals expected in subsequent years. We give the date of earliest signal arrival in days and months also even though the error estimates (from errors in source and pulsar location) are in years. This is only meant to reflect the exactly known date of the source, and to illustrate the possibility that with improvements in various observations (source and pulsar locations), in principle, a very precise date of
signal arrival on earth could be predicted. We will give error estimates, wherever available, in the table below. For Crab supernova \[9\], we find the signal arrival date from pulsar J1856-3754 in March 2057 with error of one year (from the error in Crab source distance). Among the merger events detected by LIGO/Virgo, GW170814 event will have its imprints on the signals on the pulsar J0437-4715 reaching earth between 2035-2043.

We first recall basic results from ref. \[2\]. Deformations in the shape of neutron star (NS) result from the changes in the Riemann curvature tensor $R_{\mu \nu \lambda \rho}$ as the metric undergoes periodic variations due to gravitational wave passing through the NS. This induces a change in its quadrupole moment $Q_{ij}$ which can be written in the following form \[11\]:

$$Q_{ij} = -\lambda_d E_{ij},$$  \hspace{1cm} (1)

Here $E_{ij}$ is the external tidal field. $\lambda_d$ is the tidal deformability which can be expressed in terms of the radius $R$ of the neutron star and the second love number $k_2$,

$$\lambda_d = \frac{2}{3} k_2 \frac{R^5}{G}.$$ \hspace{1cm} (2)

The value of $k_2$ is constrained to be in the range $k_2 \simeq 0.05 - 0.15$ from the observations of the recent BNS merger \[12\]. By writing $E_{ij} = R_{ij00}$ in terms of the GW strain amplitude $h$ for a specific polarization and using transverse traceless (TT) gauge, one gets \[13\]:

$$E_{xx} = -E_{yy} = \frac{2\pi^2 \hbar c^2}{\lambda^2},$$ \hspace{1cm} (3)

Here $\lambda$ is the wavelength of GW, and we use $h$ to denote the GW strain amplitude $h_+$ for the + polarization. By taking an initial spherical shape and considering ellipsoidal deformation, Eq.(1) gives the resulting change in the quadrupole moment tensor. Using that we calculate the change in the moment of inertia tensor for a neutron star of mass $M$ as \[2\]

$$\frac{\Delta I_{xx}}{I} = - \frac{\Delta I_{yy}}{I} \simeq \frac{k_2}{3} \frac{R^2 c^2}{GM^2} \Delta h$$ \hspace{1cm} (4)

We take sample values with $M = 1.0M_\odot$ and $R = 10$ km, and use $k_2 = 0.1$. To get high sensitivity $\lambda$ needs to be small, at the same time validity of Eqn.(1) requires $\lambda$ to be much larger than NS radius $R$. For the astrophysical source of GW, we consider binary NS merger (such as the one observed by LIGO and Virgo) with the highest value of GW frequency being about 1 kHz (thus retaining the validity of Eqn.(1)). We then get,

$$\frac{\Delta I_{xx}}{I} \simeq 10^{-2} h.$$ \hspace{1cm} (5)

The BNS merger detected by LIGO-Virgo had peak strength of the signal $h \simeq 10^{-19}$ \[12\] with the source distance estimated to be about 130 million light years. Considering the prototype pulsar detector to be at a distance of, say, a thousand light years from the GW source, resulting value of $h$ at the pulsar-detector location will get enhanced to $h \simeq 10^{-14}$. With most pulsars in our galaxy located inside dense globular clusters, such a situation is not very unlikely. As we emphasized in \[2\], this should provide motivation for detailed and precision studies of pulsars very far away, especially extra-galactic pulsars.

Fractional changes in the spin rate $\nu$ of the pulsar will be the same as the fractional change in the MI. Thus, we estimate changes in the spin rate of the pulsar for this case to be

$$\frac{\Delta \nu}{\nu} = \frac{\Delta I}{I} \simeq 10^{-16}.$$ \hspace{1cm} (6)

Here, we have written $\Delta I$ for the change in the relevant component of MI. Pulse timings of many millisecond pulsars have been measured to an accuracy better than $10^{-15}$ seconds. Thus spin rate changes of order given above are close to the detectable limits by precision measurements of the pulses of such pulsars. Note that, at resonance, the neutron star Weber detector will exhibit ringing effect. Thus, even for a GW pulse, its effect will be present in the pulsar signal for a much longer duration allowing folding of a large number of pulses to achieve desired accuracy. If the source-pulsar distance is smaller, for example, when both are in the same globular cluster, then the signal strength can be much larger.

The above estimates of changes of spin rate of NS have not accounted for resonances for the increase of deformation amplitude. For this discussion, we refer to the earlier paper \[2\] only mentioning the conclusion that there appears a good possibility that the neutron star interior acts like a material of high quality factor $Q$, and the range of frequencies considered here are precisely in the range in which typical neutron stars have various resonant modes. This should allow huge enhancement in the amplitude of deformation, hence in the modification in the pulses of the NS. For example, for the Weber detector, in principle, one could get enormous amplitude enhancement at resonance with $Q$ factor of about $10^6$. Even for a short pulse, the ringing effect for Weber detector operating at resonance helps in tremendously enhancing signal to noise ratio. (Due to this ringing effect, the detector continues to vibrate in the resonant mode for some time even after the passing of the pulse through the detector. This time can be about 10 minutes for a GW burst lasting only a few ms, thereby allowing for separation between the random noise and the signal. In the same way, if the pulsar continues to ring for some time after the GW pulse has passed through it, then the radio pulses will continue to retain this definite frequency signal hidden within. Folding of many pulses may be able to separate this ringing signal.)
We had pointed out in [2] that our proposal provides an opportunity to revisit the gravitational wave events which have already been detected by LIGO/Virgo. For this one should look for specific pulsars which would have been disturbed by these events, and will transmit this disturbance via their pulse signals in any foreseeable future. If these future pulsar events can be predicted with accuracy then a focused effort can be made to detect any possible changes in the signals of these specific pulsars. Any possible such detection will give valuable information about the GW source as well as the neutron star parameters of the relevant pulsar (such as equation of state). Interestingly, this also gives a possibility to actually detect those events whose GW signal detection has been missed. For example, many supernova events have been identified within our galaxy from astronomical records around the world. Any GW emission from these events (especially for type-II supernova [4] with estimated GW strain amplitude reaching as high as $10^{-20}$ at a distance of 10 kpc from the source, see also, [5]) should have relatively strong effects on the galactic pulsars. Observing these pulsars in future (or from past recorded pulse data) has the possibility of identifying the signal of these supernova events hidden in the pulsar signal.

Fig. 1 shows a typical GW event where the emitted GW from the source reach earth directly via path C. These GW also reach a pulsar via path B affecting its structure, hence its pulses. The affected pulses reach earth via path A.

![Figure 1](image_url)

**FIG. 1:** GW from the source reach earth directly via path C. These GW also reach a pulsar via path B affecting its structure, hence its pulses. The affected pulses reach earth via path A.

### TABLE I: GW signal arrival dates for next 50 years

| Source     | Pulsar               | Min. date mm/dd/year | Mean year | Max. year |
|------------|----------------------|-----------------------|-----------|-----------|
| GW150914   | J0736-6304           | 4/24/2031             | 2031      | 2081      |
| GW170814   | J0437-4715           | 1/14/2035             | 2038      | 2043      |
| GW170817   | J1400-1431           | 5/21/2048             | 2048      | 2052      |
| GW170818   | J0437+7225           | 12/2/2031             | 2037      | 2066      |
| SN185      | J0900-3144           | 9/21/2033             | 2038      | 2066      |
| SN1006     | B1944+117            | 7/4/2029              | 2032      | 2035      |
| J0633-1746 | J0633+1746           | 4/10/2032             | 2032      | 2033      |
| J0108-1431 | J1124-3358           | 11/23/2038            | 2034      | 2036      |
| Crab       | J1856-3754           | 3/21/2057             | 2057      | 2058      |
| SN1604     | J1734-3058           | 6/15/2019             | 2029      | 2040      |
| J1753-1956 | J1753-1956           | 1/1/2020              | 2039      | 2060      |
| J1736-3511 | J1736-3511           | 4/24/2025             | 2030      | 2035      |
| J1726-00   | B1726-00             | 2/21/2027             | 2029      | 2031      |
| J1725+04   | (2027-2030), J1725+04 (2031-2040), J1800-0125 (2033-2037), J1832+0029 (2034-2036), J1911-1144 (2035-2038), B1800-21 (2035-2070), J1654-23 (2037-2064), J1851-0053 (2045-2048), J1609-1930 (2054-2060), J1732-02 (2062-2068), J1754-3510 (2063-2074), B1804-12 (2064-2078), J1758-2630 (2065-2101), J1717+03 (2067-2070), SN1885 | J0139+33 | 11/12/2024 | 2024 | 2024 |
| J0230+42   | 11/19/2030           | 2030                   | 2030      | 2030      |
| J1622+4442 | 2/22/2031            | 2031                   | 2031      | 2031      |
| J0103+54   | 4/1/2060             | 2060                   | 2060      | 2060      |
| B2334+61   | 8/9/2064             | 2064                   | 2064      | 2064      |
| J3207+2225 | 7/21/2065            | 2065                   | 2065      | 2065      |
| SN1987A    | J0705-5923           | 7/19/2023              | 2023      | 2023      |
| J0059-57   | 7/8/2024             | 2024                   | 2024      | 2024      |
| J0932-58   | 8/1/2024             | 2024                   | 2024      | 2024      |
| J0621-55   | 11/15/2024           | 2024                   | 2024      | 2024      |
| J0637+1115 | (2028-2029), J0637+1115 (2030), J0656-5449 (2041), J1017-5907 (2050), J017-7156 (2050), B1055-52 (2052), B1014-53 (2055), J0849-6322 (2060), J1000-5149 (2062), B0961-63 (2064), | J0637+1115 | 7/17/2023 | 2023 | 2023 |

The GW sources and the relevant pulsars are listed along with the earliest date expected for the perturbed pulsar signal to reach earth (Min. date), the mean value of the year (Mean year) and the maximum year (Max. year). The mean year value corresponds to the exact day and the coordinates listed for the GW event and the relevant pulsar, while minimum and maximum dates are calculated using various errors given for these quantities (wherever available). We give the date of earliest signal arrival in days and months also even though the error estimates are in years. This is only meant to reflect the exactly known date of the source, and to illustrate the possibility that with improvements in various observations (source and pulsar locations), in principle, a very precise date of signal arrival on earth could be predicted.
format pulsar (min year - max year), (e.g. for SN1604, SN1885, and SN1987A). When max year and min year are the same then it is listed as pulsar (year). The error estimates are not very exhaustive here, and more effort is needed to give more reliable estimates for this. But the mean value is calculated with the mean values for distances and coordinates available, giving clear idea that many such events could be observed in very near future. We give the date of earliest signal arrival in days and months also even though the error estimates (from errors in source and pulsar location) are in years. This is only meant to reflect the exactly known date of the source, and to illustrate the possibility that with improvements in various observations (source and pulsar locations), in principle, a very precise date of signal arrival on earth could be predicted. For example, for supernova SN1987A we find that perturbed signals from pulsars J0709-5923 and B0559-57 are expected to reach earth on 5/9/2023 and 7/8/2024 respectively, with many more pulsar signals expected in subsequent years. For Crab supernova, we find the signal arrival date from pulsar J1856-3754 in March 2057 with error of one year (from the error in Crab source distance). Among the merger events detected by LIGO/Virgo, GW170814 event will have its imprints on the signals on the pulsar J0437-4715 reaching earth between 2035-2043. Interestingly, even for the earliest observed supernova SN185 (recorded in the year 185 AD), we have a possibility of observing the original event imprinted on the signal of pulsar J0900-3144 which will reach us sometime between 2033-2066.

In TABLE II, we have presented the data for those past events where signal arrival date lies between 1967-2019. This is with the idea that since the discovery of pulsars, whatever data may have been recorded, in principle, it could be analyzed to identify and imprints of those events. We have avoided listing those events for which the uncertainty (in terms of known errors in locations) is larger than 50 years, even if the earlier dates are within next few years. Including those cases makes the list too large for presentations. Our purpose here is to show the feasibility of this proposal with few test cases where signal arrival date is very likely within a couple of decades.

From Fig.1 we also note that relative directions of the GW propagation and the pulsar spin will lead to different effects on the pulse timing and profile which can be analyzed to get information about source direction even with a single pulsar-detector observation. It also shows an interesting possibility of directly observing any circularly polarized gravitational wave (which could arise in supernova explosion depending on the pre-explosion hydrodynamics) by its direct effect on the spin rate and the pulse profile of the pulsar.

Main conclusion of our paper is that different GW events can be observed again and again via pulsars which are affected by these GW events. This gives a remarkable possibility of visiting past GW events which we missed, e.g. allowing us to observe the actual signal of past supernova events, especially in our galaxy. The most important message here is that the dates which are predicted are completely model independent, simply following from the coordinates of the source and the relevant pulsars. Model details come in estimating the strength of the signal. We have argued that the signal should be in resonance with the pulsar (year), so that we do not miss out the great opportunity of revisiting past events. If this proposal works, it will open up an entirely new way of observing GW events in the sky.

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