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THE PAST AND THE FUTURE OF DIRECT SEARCH OF GW FROM PULSARS IN THE ERA OF GW ANTENNAS

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Abstract. In this paper we will give an overview of the past and present status of Gravitational Wave (GW) research associated with pulsars, taking into account the target sensitivity achieved from interferometric laser GW antennas such as Tama, Geo, Ligo and Virgo. We will see that the upper limits obtained with searches for periodic GW begin to be astrophysically interesting by imposing non-trivial constraints on the structure and evolution of the neutron stars. We will give prospects for the future detection of pulsar GW signals, with Advanced Ligo and Advanced Virgo and future enhanced detectors, e.g. the Einstein Telescope.

Keywords: gravitational waves, pulsar, neutron star.

1. Introduction

Efforts to detect gravitational waves started about fifty years ago with Joe Weber's bar detectors [1]. They opened the way to the present day interferometric detectors with useful bandwidths of thousands of hertz, namely 10 Hz ÷ 10 kHz for Virgo [2], 40 Hz ÷ 10 kHz for Ligo [3], 50 Hz ÷ 1.5 kHz for GEO600 [4] and 10 Hz ÷ 10 kHz for the Japanese TAMA [5]. In this paper we will give an overview of the past and present status of research on Gravitational Waves from pulsars. Taking into account all interferometric laser GW antennas Tama, GEO600, LIGO and Virgo, we must note that no direct detection of a GW credited signal has yet been announced, although target sensitivity has been reached for both VIRGO and LIGO (see Fig. 1). Searches for GWs from pulsars did not begin with LIGO and VIRGO. After the discovery of the Crab pulsar optical pulsations at ~ 30 Hz [6] there were a series of pioneering searches for GW emission:

- 1972: Levine and Stebbins [7] used a 30 m laser interferometer (single arm Fabry–Pérot cavity);
- 1978: Hirakawa et al. [8, 9]) searched for the Crab GW emission using a ~ 1000 kg aluminum quadrupole antenna with resonant frequency at 60.2 Hz;
- 1983: Hereld [10] at Caltech used a 40 m interferometer;
- 1983: Hough et al, in Glasgow used a split bar detector [11];
- 1993: Niebauer [12] searched for GWs from a possible Neutron Star (NS) remnant of SN1987A using a Garching 30 m interferometer (100 hrs of data from 1989; searching around 2 and 4 kHz): $h_0 < 9 \times 10^{-21}$;
- 1986–1995: Tokyo group Crab pulsar search using a 74 kg torsion-type antenna (cooled at 4.2 K) Owa et al. [13, 14], Suzuki [15] using a cooled (4.2 K) 1200 kg antenna: $h_0 < 2 \times 10^{-22}$ ($\sim 140 \times$ spin-down limit);
- 2008: CLIO search for GWs from Vela [16]: $h_0 < 5.3 \times 10^{-20}$ at 99.4 % CL;
- 2010: Tokyo prototype low-frequency mag-lev torsional bar antenna search for slowest pulsar (PSR J2144-3933 at $\nu_{\mathrm{rot}} \sim 0.1$ Hz) [17]: $h_0 < 8.4 \times 10^{-10}$ (Bayesian 95 % UL with 10 % calibration errors);
- Various narrow-band all-sky, and galactic centre, blind searches have been performed using EXPLORER and AURIGA bar detectors [18, 19, 35]; for a review see [36]) $h_0 < 2 \times 10^{-22}$ ($\sim 140 \times$ spin-down limit).

We will divide our paper as follows: Section 2 offers a basic introduction to GW emission from pulsars, then results from past and present research are given in Section 3. Future work is outlined in Section 4, conclusions and open questions are dealt with in Section 5.

2. Basics of GW emission by pulsars

GW emission is a non-axisimmetric process, since GWs are emitted through a quadrupolar mechanism. Possible processes for this kind of asymmetry, involving neutron stars, are: a rotating tri-axial ellipsoid (i.e. an NS with a bump), precessing NS (wobbling angle), oscillating NS, and accreting NS in an inspiralling binary system.

We will focus on the first three items, since they give rise to continuous GW emission, while accreting NS gives rise to a chirping GW emission in the very last stage of life of the system.

GW amplitude can be decomposed into two polarizations: "+" and "×", according to the effect they have on a circle of free falling masses orthogonal to the propagation direction. The functional form is described by [21]

$$\begin{aligned} h_+ = &\quad h_0 \tfrac{1+\cos^2\iota}{2} \cos 2\Omega \left(t - \tfrac{d}{c}\right) \\ h_\times = &\quad h_0 \cos\iota \sin 2\Omega \left(t - \tfrac{d}{c}\right) \end{aligned} \tag{1}$$

being $\Omega = 2\pi\nu$ the rotational angular velocity and

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz}\nu^2}{d} \epsilon \tag{2}$$

where ι is the angle between the rotation plane and the observer, I_{zz} is the momentum of inertia of NS with respect to the rotation axis, d is the distance from the observation point, and $\epsilon = (I_{xx} - I_{yy})/(I_{zz})$ is quadrupole ellipticity. From a large set of Equations of State (EoS), describing NS matter at supra-nuclear densities one gets: $I_{zz} = (1{\div}3)\times 10^{38}\,\mathrm{kg\,m^2}$ depending on the EoS and on the rotation velocity. So the scale parameter of GW amplitude can be expressed in more physical units as

$$\begin{aligned} h_0 = 4 \times 10^{-25} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I}{10^{38}\,\mathrm{kg\,m^2}}\right) \\ \left(\frac{100\,\mathrm{pc}}{d}\right) \left(\frac{\nu}{100\,\mathrm{Hz}}\right)^2 . \end{aligned} \tag{3}$$

GWs can also be emitted by an axisimmetric rotating star, when the symmetry and the rotation axes are misaligned by "wobble" angle α.

The maximum sustainable quadrupole deformation ϵ for an NS depends on the physics of the crust and the EoS of matter at super-nuclear density. We can set a limit in ϵ by looking at the maximum strain sustainable by the crust without breaking. Modeling of crustal strains indicates that [21]

$$\epsilon < k \frac{u_{\mathrm{break}}}{Br_{\mathrm{Lim}}}$$

where u_{break} is the crustal limit strain, and k and Br_{Lim} depend on the star model. From molecular dynamics simulations, one obtains: $k = 2 \times 10^{-5}$ and $u_{\mathrm{break}} \simeq Br_{\mathrm{Lim}} = 0.1$. This means that a NS breaks for deformations larger than 20 cm.

According to various models for solid quark stars, we can have $Br_{\mathrm{Lim}} = 10^{-2}$ and $k = 6\times10^{-4} {\div} 6\times10^{-3}$. For strong initial magnetic fields (10^{16} G), the star can emit intense GWs, due to the deformation induced by the magnetic field.

In brief, we have many estimates for the ellipticity, but few certainties. Something can be gathered by looking at the data from GW experiments. How can LIGO and Virgo and astronomical data be useful for constraining the EoS of NS using the upper limits on ϵ and the momentum of inertia I? Let us start from what we know from astrophysical observations and gravitational observatory data.

In our galaxy we can estimate a number of NS of about 10^8, 2000 of which are radio pulsars. Distance d and rotation frequency ν can be evaluated from radio and optical observations (GW emission has a frequency given by 2ν). If the variation of the rotational period is such that $\dot\nu < 0$, there is a mechanism that makes the pulsar lose its energy. It can be: electromagnetic (EM) dipole radiation, particle acceleration and GW emission. Since $\dot\nu = k\nu^n$, one can derive the breaking index n from the rotational frequency and its derivatives,

$$n = \frac{\nu\ddot\nu}{\dot\nu^2}.$$

It has been evaluated that for pure magnetic dipole radiation, the breaking index is $n = 3$, while for pure GW radiation $n = 5$.

For the few objects that have been observed with sufficient accuracy to determine the breaking index, there is $n < 3$, thus some other mechanism or a combination must be invoked (see [20] for an interesting phenomnological analysis of the problem).

Now let us try to derive some upper limit on GW emission. We start with the strong hypothesis that all the energy is lost by GW emission. Thus the *spindown* GW amplitude is given by

$$h_{\mathrm{SD}} \sim \left(\frac{5}{2} \frac{G I_{zz} |\dot\nu|}{c^3 d^2 \nu}\right)^{1/2}$$

or, expressed in a more convenient set of units,

$$\begin{aligned} h_{\mathrm{SD}} \sim 2.5 \times^{-25} \left(\frac{I_{zz}}{10^{38}\,\mathrm{kg\,m^2}}\right) \left(\frac{|\dot\nu|}{10^{-11}\,\mathrm{Hz\,s^{-1}}}\right) \\ \left(\frac{100\,\mathrm{Hz}}{\nu}\right) \left(\frac{1\,\mathrm{kpc}}{d}\right) \end{aligned}$$

from which we can get an upper limit for I_{zz} combining EM and GW observations.

3. GW FROM PULSARS, AND RESULTS FROM THE PAST UNTIL NOW

In recent years, since ground-based GW interferometric detectors have come into operation, several studies have been carried out to detect GW signals from continuous sources, both by single interferometers and by coherent searches using two or more detectors, but as of June 2012, the results of these searches have only involved the upper limits on the rate and breaking strain threshold.

The search for periodic sources (or Continuous Waves – CW), benefits from long integration times and coincident analysis between different detectors. This was the first to be started in Scientific Run 1 (S1) of the LIGO detector, using time and frequency domain

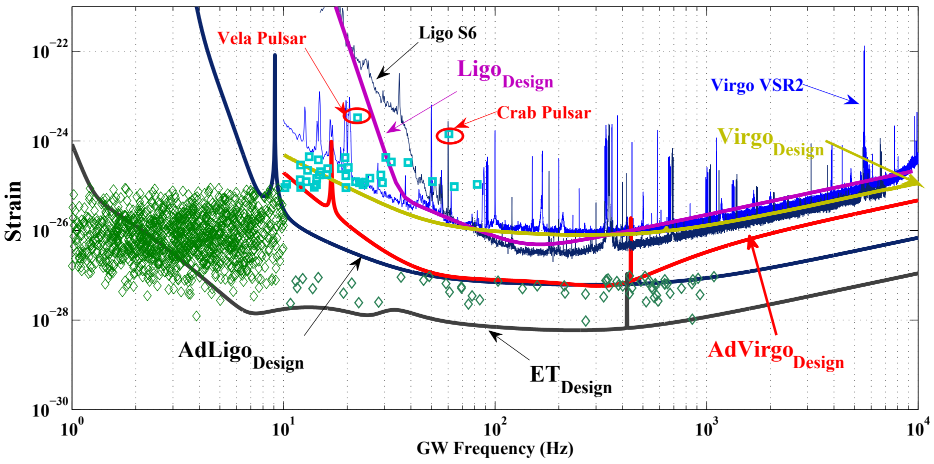

Figure 1. The figure shows the upper bounds on GW amplitude from known pulsars, assuming 100 % conversion of spindown energy into GWs. An integration time of one year is assumed. The (green) diamonds represent a pulsar with a spindown outside the detection band for both AdV and Advanced LIGO; the (cyan) squares are in the potential detection band for at least one of the advanced detectors. The red circles represent Crab and Vela pulsars.

analyses [22] on a single pulsar of known frequency. In S2–S5, it evolved into a broadband search [23, 24], using various techniques, e.g. the Hough transforms, the short Fourier transforms and excess power. Recently, the S5/VSR1 (VSR1 is the first Virgo Scientific Run) search on pulsars of known period and spindown using ephemerides given by radio-telescopes and X-ray satellites [25], has set lower limits on GW radiation from targets, on the assumption that it is locked to EM emission. A further analysis was performed on joint data from S6 and the VSR2 run and results interesting for physics were obtained from the upper limit in GW emission from the Crab pulsar [25] and the Vela pulsar (Abadie et al. 2011) as shown by the red circles in Fig. 1.

Figure 1 shows that the great majority of known pulsars (green diamonds) are below the present sensitivity curves of the LIGO and Virgo GW antennas, and only a few of them (shown in cyan) fall in the range of sensitivity of either Advanced LIGO or Advanced Virgo or in the range of the Einstein Telescope [32]. The upper limits obtained by the analysis of the sources that can be studied by the present interferometers, provide interesting astrophysical information, since they give non-trivial constraints on the structure and the evolution of NS. Two highlight results have come from pulsars GW data analysis [26, Abadie et al. 2011]: for the Crab pulsar the $h_{\mathrm{SD}} \simeq 1.4 \times 10^{-24}$ limit was beaten, finding $h_0 < 2.4 \times 10^{-25}$ i.e. $\approx h_{\mathrm{SD}}/6$. This implies that less than 2 % of the rotational energy is lost in GW and also constrains the ellipticity to $\epsilon < 1.3 \times 10^{-4}$. For the Vela pulsar the $h_{\mathrm{SD}} \simeq 3.29 \times 10^{-24}$ limit was beaten, by finding $h_0 < 2.4 \times 10^{-24}$ implying that less than 35 % of the rotational energy is lost in GW and constraining the ellipticity to $\epsilon < 1.1 \times 10^{-3}$. These results also impose stringent limits on the EoS of an NS [21].

4. The near future: the new proposals

The ground-based GW detector network has been running with improved sensitivity (the Virgo VSR3 run in 2010 July and the S6b Ligo run), major upgrades, e.g. Advanced LIGO [27] and Advanced Virgo [28], are aimed at achieving one order of magnitude better sensitivity than the current instruments (Fig. 1 blue and red curves). These detectors come into operation in 2014 or 2015, and, unless something in GR theory is wrong, we can foresee regular detections of binary inspirals with very good prospects of detecting various other signals. The proposals for other large interferometric detectors, LCGT in Japan [29] (approval received in June 2010) and AIGO in Australia [30], will significantly improve the capabilities of the current detector network. We will have good chances of detecting low-frequency signals with pulsar timing arrays on about the same time scale (Hobbs et al. 2010), while space-based detectors such as LISA/NGO [33], aimed to detect GW in the range $10^{-4} \div 10^{-1}$ Hz and Decigo [34], are anticipated years later to open up the intermediate frequency band. Third generation conceptual designs for the Einstein Telescope (ET) (Fig .1) [32] will be at future opportunity for GW detection since this telescope should attain greater sensitivity by a factor of 100 more in sensitivity than first generation Virgo and LIGO interferometers.

5. Conclusions and open questions

In this paper we have given an overview of the past and present status of Gravitational Wave (GW) research associated with pulsars. Many questions remain open, e.g.: What are the upper limits for pulsars: When there will be a direct detection? What fraction of pulsars energy is emitted in the form of gravitational waves? Can we have direct inferences on pulsar parameters from gravitational waves to constrain the EoS of an NS? What will be the model of NS or quark stars?

With interferometric GW antennas (LIGO, GEO600, Tama, Virgo), we have as yet only succeeded in setting interesting upper limits, but the cherished belief is that the first direct detection will be possible with the new generation of interferometers, and as a result answers may be found to some open questions.

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