Searching for gravitational waves from known pulsars

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Abstract. We present upper limits on gravitational wave amplitude from, and neutron star ellipticity for, 28 isolated pulsar using data from the second science run of LIGO. We discuss a new way of presenting such ellipticity upper limits that takes account of the uncertainties of the pulsar moment of inertia. We also present a method for searching for known pulsars in binary systems, of which there are about 80 in the sensitive frequency range of LIGO and GEO 600, that includes the system dependent binary time delays in the analysis.

1. Introduction

Over the last few years the LIGO and GEO 600 gravitational wave detectors had three (S1, S2 and S3) and two (S1 and S3) science runs respectively. Data from these runs has been used to set upper limits on gravitational waves from a variety of possible source [1, 2, 3, 4], but here we concentrate on the search for gravitational waves from known pulsars which has been successively extended both in terms of analysis method and number of sources for each run.

S1 (23 August - 9 September 2002) was the *first* major data taking period and a search for gravitational waves from only one pulsar (the fastest millisecond pulsar J1939+2134) was performed [1]. This search used both a time domain and a frequency domain analysis method. For S2 (14 February - 14 April 2003) the number of pulsars being searched for increased to 28 [5], with the criterion that the pulsars were isolated and had spin frequencies within the sensitive region of the instruments i.e. $f > 25\,\mathrm{Hz}$ or gravitational wave frequencies of $f_{\mathrm{GW}} > 50\,\mathrm{Hz}$, assuming emission from a triaxial neutron star [6]. The time domain analysis technique was considered the optimal search for S2 where the source position and frequency parameters were known. The analysis and results from S2, including possible astrophysical interpretations, will be summarised in this paper.

Analysis of the S3 run (31 October 2003 - 9 January 2004) is underway and has the aim of extending the number of pulsars in the search to all those with $f > 25\,\mathrm{Hz}$ (~ 110) including those within binary systems. The additions to the analysis needed to incorporate the binary systems will be discussed in more detail within the paper. We will also discuss how the results on neutron star ellipticity could be interpreted as an exclusion region on a moment of inertia - ellipticity plane.

The main point of note is that these results have been providing the best *direct* upper limits on gravitational wave amplitude and by extension neutron star ellipticity yet produced.

2. S2 summary

2.1. Analysis

S2 data was available for analysis from all three LIGO interferometers. Frequency and positional information for all the isolated pulsars with $f > 25\,\mathrm{Hz}$ can be found on the Australia Telescope National Facility (ATNF) [7] online catalogue. However for some pulsars this information lacked the accuracy required to be sure that the search was coherent over the period of the science run, and additional timing over the epoch of S2 was requested and obtained for 18‡ of these objects [8]. This gave us 28 pulsars with reliable information upon which to reconstruct their phase evolution. Of these 28

‡ The Crab pulsar (J0534+2200) data was taken from the online Jodrell Bank Monthly ephemeris `http://www.jb.man.ac.uk/research/pulsar/crab.html`.

$h_0^{95\%}$	no. of pulsars
$1\times10^{-24} < h_0 < 5\times10^{-24}$	20
$5\times10^{-24} < h_0 < 1\times10^{-23}$	4
$h_0 > 1\times10^{-23}$	4

Table 1. The 95% upper limits on h_0 for the 28 pulsar searched for with the S2 run.

pulsars, 14 are in globular clusters. The list also includes the Crab pulsar (J0534+2200) and the fastest millisecond pulsar J1939+2134 targeted in S1.

The analysis method is described in detail in [1]. In summary we perform a time domain heterodyne of the data with the known phase evolution of the pulsar signal. After heterodyning, any signal in the data would vary only with the beam pattern [6] of the detector and its form would depend on the four unknown parameters of gravitational wave amplitude (h_0) and polarisation angle (ψ), pulsar orientation angle (ι) and the signal's initial phase (ϕ_0). The heterodyned data is then filtered and re-binned from the detector sample rate of 16384 Hz to 1/60 Hz. We then determine the probability distribution functions of the parameter values using a Bayesian inference technique, as shown in [5].

2.2. Hardware injections

During S2 we injected two artificial pulsar signals into the three LIGO interferometers for 12 hours by modulating one mirror of each via the actuation control signal. This was done to perform a validation of the search pipeline from as far up the chain as possible. The injections allowed us to confirm the phase calibration of the detectors, and allowing a joint analysis, combining the data from all the detectors coherently.

2.3. Results and astrophysical interpretation

The 95% upper limits on h_0 (i.e. the value of h_0 which, with $h_0 = 0$, bounds 95% of the probability) are summarised in Table. 1. We can recast this upper limit on h_0 as an upper limit on the pulsar's ellipticity, ϵ, calculated via

$$\epsilon = 0.237 \frac{h_0}{10^{-24}} \frac{r}{1\,\mathrm{kpc}} \frac{1\ \mathrm{Hz}^2}{f^2} \frac{10^{38}\,\mathrm{kg\,m}^2}{I_{zz}}, \tag{1}$$

where r is the distance to the pulsar in kpc, f is its spin frequency, and I_{zz} is its principle moment of inertia. The ellipticity limits are summarised in Table. 2 using the canonical value of $10^{38}\,\mathrm{kg\,m}^2$ for the moment of inertia and assuming no error on the measured pulsar's distance. The lowest value of strain upper limits (1.7×10^{-24}) is for pulsar J1910-5959D and that for ellipticity (4.5×10^{-6}) for pulsar J2124-3358. The upper limit for the Crab pulsar is also rather noteworthy as at $h_0 = 4.1\times10^{-23}$ it is only a factor

ellipticity ϵ	no. of pulsars
$1\times10^{-6} < \epsilon < 1\times10^{-5}$	4
$5\times10^{-5} < \epsilon < 1\times10^{-4}$	16
$\epsilon > 1\times10^{-4}$	8

Table 2. The upper limits on ϵ for the 28 pulsar searched for with the S2 run.

of $\sim$ 30 greater than the canonical limit inferred from simple spin-down arguments§. For all other pulsars the upper limits are a few orders of magnitude higher than the canonical limit.

Although the inferred ellipticities are well above those allowed by the majority of conventional neutron star equations of state they are approaching the region of astrophysical interest. Indeed, for the lowest pulsar ellipticities ($\sim 4.5\times10^{-6}$) we are starting to reach the range permitted by at least one exotic theory of neutron star structure [10]. It must should be stressed that these results are the first *direct* upper limits on gravitational wave emission for 26 of the 28 pulsars, with previous upper limits for pulsar J1939+2134 and the Crab pulsar given by [1] and [9] respectively. For the pulsars within globular clusters the spin-down can be masked by local Doppler shifts caused by the cluster dynamics. This makes placing a spin-down based upper limit difficult unless the pulsar motions within the clusters can be independently found. The gravitational wave interferometer upper limits are inherently independent of the cluster dynamics.

3. S3 analysis

We expanded the search in the S3 analysis to include all pulsars with $f > 25$ Hz. These include $\sim$ 70 pulsars within binary (or more complex) systems so it is important to account for the extra Doppler and relativistic time delays due to the pulsar's orbital motion. An advantage over S2 is the availability of GEO 600 data in addition to LIGO data.

3.1. Binary pulsar signal

In the case of an isolated pulsar the signal received at the detector needs to be corrected to the solar system barycentre (SSB) by calculating the Doppler delays and other relativistic effects. This is possible as the pulsar's position is known and we have very good solar system ephemerides. Of course it is simply the reverse procedure to that used to determine the positional and frequency parameters of the pulsar from radio data, so the reconstruction is generally of good quality. The motion of a pulsar in a

§ This limit is imposed by energy conservation and assumes that the rotational kinetic energy is only lost to gravitational waves binary system adds a number of Doppler and relativistic time delays:

$$\Delta T_{\mathrm{bin}} = \Delta_{\mathrm{R}} + \Delta_{\mathrm{E}} + \Delta_{\mathrm{S}} + \Delta_{\mathrm{A}}, \tag{2}$$

where Δ_{R} is the Roemer delay (light travel time), Δ_{E} is the Einstein delay due to special relativistic effects, Δ_{S} is the general relativistic Shapiro delay and Δ_{A} is the abberation delay caused by the pulsar's rotation. These delay changes can be far more pronounced than those from the Earth's motion, with up to a 0.03 Hz frequency shift. The time delays are parameterised by various properties of the binary system e.g. its period, eccentricity, angular velocity, time of periastron, projected semi-major axis and several relativistic parameters depending on the nature of the system. These parameters are found by fitting the radio observations (using the standard TEMPO data reduction package [11]) to various binary models, for an example of this see [12]. The model to which the binary system is fitted will depend on how relativistic it is or which parameters you wish to extract. The 70 binary system pulsars fall mainly into two models: 32 in the low eccentricity (ELL1 model [13]) and 33 in the Blandford-Teukolsky (BT model [12]). Four fall into the highly relativistic Damour-Deruelle (DD [12]) model and a further one into the Blanford-Teukolsky-2-Planet (BT2P) model, although this can be adequately fit using the simpler BT model. With this additional binary information provided the full set of pulsars can be included in the search. So far new timing information for the majority of these pulsars has been provided [8] and the analysis is underway.

3.2. Hardware injections

We injected ten artificial isolated pulsar signals, with a wide range of signal parameters into the LIGO interferometers. One other signal was injected into both GEO 600 and LIGO. The signal strengths ranged from marginally detectable to very strong. These signals have been successfully extracted using the search pipeline. The accuracy to which the paremeter values could be extracted has shown up the small systematic errors in the instrument calibration.

4. Moment of inertia - ellipticity plane

So far we have used the canonical value for the neutron star moment of inertia ($10^{38}\,\mathrm{kg\,m^2}$) when calculating the pulsar ellipticities. This is the moment of inertia of a $1\,\mathrm{M}_\odot$ sphere of uniform density and radius 10 km. The true value can vary by factors of a few under different models for the neutron star equation of state. Equation 1 shows that h_0 can be used to set an upper limit on the neutron star's quadrupole moment, $I_{zz}\epsilon$, that is independent of the actual value of I_{zz}. This value can then be used to form an exclusion region in the $I_{zz} - \epsilon$ plane (see Fig. 1). This plane can provide exclusion regions on both the moment of inertia and ellipticity or can be used to read off an upper limit on ellipticity for a preferred value of I_{zz} such as the canonical value.

Figure 2 shows such an exclusion region for the Crab pulsar upper limit from S2. An exclusion region can also be set using the spin-down based upper limit argument, at

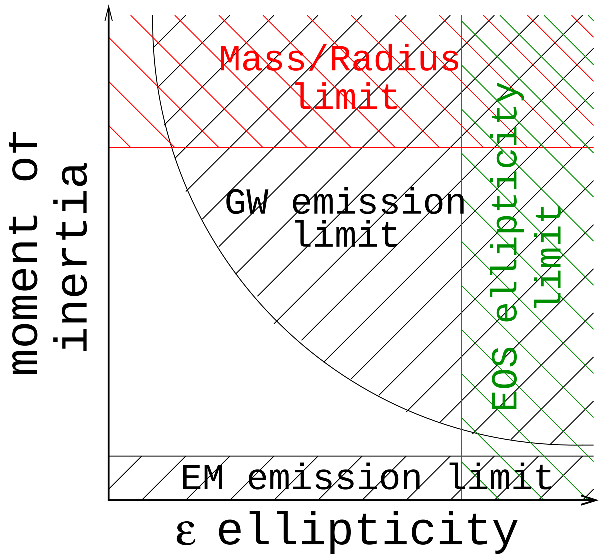

Figure 1. This figure shows is a rough representation of the regions in the moment of inertia I_{zz} - ellipticity ϵ plane for a pulsar that can be excluded via various methods. The electromagnetic emission of a pulsar can set a lower limit on the moment of inertia by equating the EM emission with the rotational energy loss of the pulsar. The various equations-of-state for neutron stars can constrain the mass/radius relation and therefore moment of inertia. Equations-of-state will also put limits on the maximum allowable ellipticity of the neutron star. A limit can be set from upper limits on gravitational wave emission.

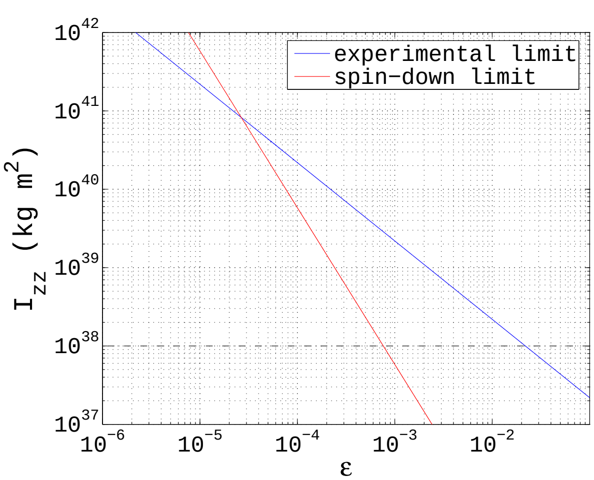

Figure 2. The excluded regions for on the moment of inertia - ellipticity plane for the Crab pulsar as obtained from the S2 h_0 upper limit and the spin-down arguments. These assume a distance to the Crab pulsar of 2 kpc.

$$I_{zz}\epsilon = \frac{5|2\pi\dot{f}|c^5}{32G(2\pi f)^5}\frac{1}{\epsilon}. \tag{3}$$

The point at which the experimental results and the spin-down result cross shows the the point at which the experimental results beats that of spin-down. For the S2 Crab pulsar result it can be seen that the experimental result only beats the spin-down result for unfeasably large values of I_{zz} ($> 8\times10^{40}$kg m^2). The upper limit on the ellipticity for the experimental result and assuming $I_{zz} = 10^{38}$ kg m^2 is $\sim 2\times10^{-2}$.

5. Future work

The analysis of S3 data is presently underway targeting all known pulsars within the band. In addition we will be incorporating other sources of error into the current Bayesian framework, including systematic calibration errors in the value of h_0 and pulsar distance errors into the value of ϵ or the $I_{zz} - \epsilon$ plane exclusion region. The S3 results promise to give a factor of 10 improvement over S2 for some pulsars. In particular, the Crab pulsar result should only be a factor of a few above the spin-down limit.

The next science run of LIGO and GEO 600 (S4) is due to be underway in early 2005 providing more data to analyse. The pipeline used to obtain the results in this paper is at a mature stage and will be applied directly to the S4 data.

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