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DOI:

[10.3847/1538-4357/ab20cb](https://doi.org/10.3847/1538-4357/ab20cb)

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Document Version

Publisher's PDF, also known as Version of record

Citation for published version (Harvard):

The LIGO Scientific Collaboration & Vecchio, A 2019, 'Searches for gravitational waves from known pulsars at two harmonics in 2015–2017 LIGO data', *The Astrophysical Journal*, vol. 879, no. 1, 10.
<https://doi.org/10.3847/1538-4357/ab20cb>

[Link to publication on Research at Birmingham portal](#)

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Checked for eligibility: 12/07/2019

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Searches for Gravitational Waves from Known Pulsars at Two Harmonics in 2015–2017 LIGO Data

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Received 2019 March 18; revised 2019 May 7; accepted 2019 May 8; published 2019 June 26

Abstract

We present a search for gravitational waves from 222 pulsars with rotation frequencies $\gtrsim 10$ Hz. We use advanced LIGO data from its first and second observing runs spanning 2015–2017, which provides the highest-sensitivity gravitational-wave data so far obtained. In this search we target emission from both the $l = m = 2$ mass quadrupole mode, with a frequency at twice that of the pulsar’s rotation, and the $l = 2, m = 1$ mode, with a frequency at the pulsar rotation frequency. The search finds no evidence for gravitational-wave emission from any pulsar at either frequency. For the $l = m = 2$ mode search, we provide updated upper limits on the gravitational-wave amplitude, mass quadrupole moment, and fiducial ellipticity for 167 pulsars, and the first such limits for a further 55. For 20 young pulsars these results give limits that are below those inferred from the pulsars’ spin-down. For the Crab and Vela pulsars our results constrain gravitational-wave emission to account for less than 0.017% and 0.18% of the spin-down luminosity, respectively. For the recycled millisecond pulsar J0711–6830 our limits are only a factor of 1.3 above the spin-down limit, assuming the canonical value of 10^{38} kg m² for the star’s moment of inertia, and imply a gravitational-wave-derived upper limit on the star’s ellipticity of 1.2×10^{-8} . We also place new limits on the emission amplitude at the rotation frequency of the pulsars.

Key words: gravitational waves – pulsars: general – stars: neutron

Supporting material: machine-readable table

1. Introduction

There have been several previous searches for persistent (or continuous) quasi-monochromatic gravitational waves emitted by a selection of known pulsars using data from the LIGO, Virgo, and GEO600 gravitational-wave detectors (Abbott et al. 2004, 2005, 2017a, 2007, 2008, 2010; Abadie et al. 2011; Aasi et al. 2014). In the majority of these, the signals that have been searched for are those that would be expected from stars with a nonzero $l = m = 2$ mass quadrupole moment Q_{22} and with polarization content consistent with the expectations of general relativity (see, e.g., Zimmermann & Szedenits 1979; Bonazzola & Gourgoulhon 1996; Jaranowski et al. 1998). Such signals would be produced at twice the stellar rotation frequencies, and searches have generally assumed that the rotation frequency derived from electromagnetic observations of the pulsars is phase locked to the star’s rotation and thus the gravitational-wave signal. Some searches have been performed where the assumption of the phase locking to the observed electromagnetic signal has been slightly relaxed, allowing the signal to be potentially offset over a small range of frequencies (~ 10 –100 mHz) and first frequency derivatives (Abbott et al. 2008, 2017b; Aasi et al. 2015b). A search including the prospect of the signal’s polarization content deviating from the purely tensorial modes predicted by general relativity has also been performed in Abbott et al. (2018a). None of these searches have detected a gravitational-wave signal from any of the pulsars that were targeted. Thus, stringent upper limits of the gravitational-wave amplitude, mass quadrupole moment, and ellipticity have been set.

Emission of gravitational waves at a pulsar’s rotation frequency from the $l = 2, m = 1$ harmonic mode, in addition to emission at twice the rotation frequency from the

$l = m = 2$ mode, has long been theorized (Zimmermann & Szedenits 1979; Zimmermann 1980; Jones & Andersson 2002). The fiducial emission mechanism would be from a biaxial or triaxial star undergoing free precession. In the case of a precessing biaxial star, or a precessing triaxial star with a small “wobble angle,” the electromagnetic pulsar emission frequency would be modulated slightly, with the gravitational-wave emission being emitted at frequencies close to once and twice the time-averaged rotation frequency. There is only weak observational evidence for any pulsar showing precession (see the discussions in, e.g., Jones 2012; Durant et al. 2013, and references therein), and free precession would be quickly damped, but as shown in Jones (2010), the existence of a superfluid interior gives rise to the possibility for gravitational-wave emission at the rotation frequency even for a nonprecessing star. A search for emission at both once and twice the rotation frequency for 43 pulsars using data from LIGO’s fifth science run has been performed in Pitkin et al. (2015). That analysis saw no evidence for signals at the rotation frequency and was consistent with the search conducted for signals purely from the $l = m = 2$ mode (Abbott et al. 2010).

The searches implemented in this work are specifically designed for the case where the signal’s phase evolution is very well known over the course of full gravitational-wave detector observing runs. Therefore, here we will only focus on the assumption that emission occurs at precisely once and twice the observed rotation frequency, as given by the model in Jones (2010), so we do not account for the possibility of any of the sources undergoing free precession.

Previous searches, combining the results given in Aasi et al. (2014) and Abbott et al. (2017a), have included a total of 271 pulsars. The most stringent upper limit on gravitational-wave amplitude from the $l = m = 2$ mode was set for PSR J1918–0642 at 1.6×10^{-26} , and the most stringent upper limit on the fiducial ellipticity (see Appendix A, Equations (4)

¹⁹¹ Deceased, 2018 February.¹⁹² Deceased, 2017 November.¹⁹³ Deceased, 2018 July.

and (6)) was set for PSR J0636+5129 at 1.3×10^{-8} (Abbott et al. 2017a). However, for these particular pulsars, both of which are millisecond pulsars (MSPs), the gravitational-wave amplitude limits are above the fiducial spin-down limit (see Appendix A and Equation (9)). In the search described in Abbott et al. (2017a), there were eight pulsars for which their observed gravitational-wave limits were below the fiducial spin-down limits, with the upper limits on emission from the Crab pulsar (PSR J0534+2200) and Vela pulsar (PSR J0835–4510) being factors of more than 20 and 9 below their respective spin-down limits.¹⁹⁴

Concurrently with this work, a search has been performed for 33 pulsars using advanced LIGO data from the second observing run in which the assumption of phase locking between the electromagnetically observed signal and gravitational-wave signal is relaxed by allowing the signal model to vary freely over a narrow band of frequencies and frequency derivatives (Abbott et al. 2019). Even with the slight sensitivity decrease compared to the analysis presented here, due to the wider parameter space, that analysis gives limits that are below the spin-down limit for 13 of the pulsars.

1.1. Signal Model

Using the formalism shown in Jones (2015) and Pitkin et al. (2015), the gravitational-wave waveform from the $l = 2$, $m = 1$ harmonic mode can be written as

$$h_{21}(t) = -\frac{C_{21}}{2}[F_+^D(\alpha, \delta, \psi; t)\sin\iota\cos\iota\cos(\Phi(t) + \Phi_{21}^C) + F_\times^D(\alpha, \delta, \psi; t)\sin\iota\sin(\Phi(t) + \Phi_{21}^C)], \quad (1)$$

and that from the $l = m = 2$ mode can be written as

$$h_{22}(t) = -C_{22}[F_+^D(\alpha, \delta, \psi; t)(1 + \cos^2\iota)\cos(2\Phi(t) + \Phi_{22}^C) + 2F_\times^D(\alpha, \delta, \psi; t)\cos\iota\sin(2\Phi(t) + \Phi_{22}^C)]. \quad (2)$$

Here C_{21} and C_{22} represent the amplitudes of the components, Φ_{21}^C and Φ_{22}^C represent initial phases at a particular epoch, $\Phi(t)$ is the rotational phase of the source, and ι is the inclination of the source’s rotation axis with respect to the line of sight.¹⁹⁵ The detected amplitude is modulated by the detector response functions for the two polarizations of the signal (“+” and “×”), $F_+^D(\alpha, \delta, \psi; t)$ and $F_\times^D(\alpha, \delta, \psi; t)$, which depend on the location and orientation of detector D , the location of the source on the sky, defined by the R.A. α and decl. δ , and the polarization angle of the source ψ .

As shown in Jones (2015), the waveforms given in Equations (1) and (2) describe a generic signal, but the amplitudes (C_{21} and C_{22}) and phases (Φ_{21}^C and Φ_{22}^C) can be related to intrinsic physical parameters describing a variety of source models, e.g., a triaxial star spinning about a principal axis (Abbott et al. 2004), a biaxial precessing star (Jones & Andersson 2002), or a triaxial star not spinning about a principal axis (Jones 2010). In the standard case adopted for previous gravitational-wave searches of a triaxial star spinning about a principal axis, there is only emission at twice the rotation frequency from the $l = m = 2$ mode, so only

Equation (2) is nonzero. In this case the C_{22} amplitude can be simply related to the standard gravitational-wave strain amplitude h_0 via $h_0 = 2C_{22}$.¹⁹⁶ We can simply define the phase Φ_{22}^C as relating to the initial rotational phase ϕ_0 via $\Phi_{22}^C = 2\phi_0$, noting that ϕ_0 actually incorporates the sum of two phase parameters (an initial gravitational-wave phase and another phase offset) that are entirely degenerate and therefore not separately distinguishable (Jones 2015).

Despite Equations (1) and (2) not providing the intrinsic parameters of the source, they do break strong degeneracies between them, which are otherwise impossible to disentangle (see Pitkin et al. 2015, showing this for the case of a triaxial source not rotating about a principal axis).

In this work we adopt two analyses. The first assumes the standard picture of a triaxial star rotating around a principal axis from which we can simply relate the waveform amplitude C_{22} to the gravitational-wave amplitude. In this case we can then compare this to the standard spin-down limit and can calculate each source’s mass quadrupole Q_{22} and fiducial ellipticity upper limits (see Appendix A for definitions of these standard quantities.) The second assumes the model of a triaxial star not spinning about a principal axis, for which there could be emission at both once or twice the rotation frequency. In this case we do not attempt to relate the signal amplitudes to any physical parameter of the source.

1.2. Signal Strength

For the $l = m = 2$ quadrupole mode the strength of the emission is defined by the size of the mass quadrupole moment Q_{22} (see Equations (3) and (5)), which is proportional to the ellipticity of the star and to the star’s moment of inertia, and will therefore depend on the star’s mass and also on the equation of state of neutron star matter (see, e.g., Ushomirsky et al. 2000; Owen 2005; Johnson-McDaniel & Owen 2013). This ellipticity could be provided by some physical distortion of the star’s crust or irregularities in the density profile of the star. For our purposes the mechanism providing the distortion must be sustained over long periods, e.g., the crust must be strong enough for any (submillimeter high) mountain to be maintained (see Owen 2005; Johnson-McDaniel & Owen 2013, for discussions of the maximum sustainable ellipticities for various neutron star equations of state), or there must be a persistent strong internal magnetic field (e.g., Bonazzola &ourgoulhon 1996; Cutler 2002). Johnson-McDaniel & Owen (2013) suggest that, assuming a standard set of neutron star equations of state, maximum fiducial ellipticities of a few $\times 10^{-6}$ could be sustained. Constraints on the neutron star equation of state are now starting to be probed using gravitational-wave observations from the binary neutron star coalescence observed as GW170817 (Abbott et al. 2017c, 2018b). These constraints suggest that softer equations of state are favored over stiffer ones, which would imply smaller maximum crustal quadrupoles. An additional caveat to this is that the maximum crustal deformation is also dependent on the star’s mass, and less massive stars would allow larger deformations (Horowitz 2010; Johnson-McDaniel & Owen 2013), so there is still a wide range of uncertainty. Recent work on the strength of neutron star crusts consisting of

¹⁹⁴ In previous work we have often referred to observed gravitational-wave limits “surpassing,” or “beating,” the spin-down limits, which just means to say that the limits are lower than the equivalent spin-down limits.

¹⁹⁵ For precessing stars the phase evolution $\Phi(t)$ in Equations (1) and (2) will not necessarily be given by the rotational phase, but it can differ by the precession frequency.

¹⁹⁶ To maintain the sign convention between Equation (2) and the equivalent equation in, e.g., Jaranowski et al. (1998), the transform between h_0 and C_{22} should more strictly be $h_0 = -2C_{22}$.

nuclear pasta suggests that these could have larger breaking strains and thus support larger ellipticities (Caplan et al. 2018).

It has recently been suggested by Woan et al. (2018) that the distribution of MSPs in the period–period derivative plane provides some observational evidence that they may all have a limiting minimum ellipticity of $\sim 10^{-9}$. This could be due to some common process that takes place during the recycling accretion stage that spins the pulsar up to millisecond periods. For example, there could be external magnetic field burial (see, e.g., Melatos & Phinney 2001; Payne & Melatos 2004), for which the size of the buried field is roughly the same across all stars, or similar levels of spin-up leading to crust breaking (e.g., Fattoyev et al. 2018). If this is true, it provides a compelling reason to look for emission from these objects.

For the model emitting at both $l = 2, m = 1, 2$ modes, and assuming no precession, the signal amplitudes are related to combinations of moment-of-inertia asymmetries and orientation angles between the crust and core of the star (Jones 2010). These are related in a complex way to the C_{21} and C_{22} amplitudes given in Equations (1) and (2) (see Jones 2015). In general, if the Q_{21} and Q_{22} mass moments are equal, then the gravitational-wave strain from the $l = 2, m = 1$ mode would be roughly four times smaller owing to the fact that it is related to the square of the frequency and that mode is at half the frequency of the $l = m = 2$ mode. However, we do not have good estimates of what the actual relative mass moments might be.

Note that one can in principle also obtain limits on a neutron star’s deformation if one interprets some features of its timing properties as due to free precession. In this case, the limits involve a combination of the differences between the three principal moments of inertia, together with an angular parameter (“wobble angle”) giving the amplitude of the precession. This can be done either for stars that show some periodic structure in their timing properties (see, e.g., Akgün et al. 2006; Ashton et al. 2017) or by assuming that some component of pulsar timing noise is due to precession (Cordes 1993). Note, however, that it is by no means clear whether pulsar timing really does provide evidence for free precession (Jones et al. 2017; Stairs et al. 2019).

1.3. Search Methods

As with the previous searches for gravitational waves from known pulsars described in Aasi et al. (2014) and Abbott et al. (2017a), we make use of three semi-independent search methods. We will not describe these methods in detail here, but we refer the reader to Aasi et al. (2014) for more information. Briefly, the three methods are as follows: a search using narrowband time-domain data to perform Bayesian parameter estimation for the unknown signal parameters, and marginal likelihood evaluation, for each pulsar (Dupuis & Woan 2005; Pitkin et al. 2017); a search using the same narrowband time series, but Fourier-transformed into the frequency domain, to calculate the \mathcal{F} -statistic (Jaranowski et al. 1998) (or equivalent \mathcal{G} -statistic for constrained orientations; Jaranowski & Królak 2010), with a frequentist-based amplitude upper limit estimation procedure (Feldman & Cousins 1998); and a search in the frequency domain that makes use of splitting of any astrophysical signal into five frequency harmonics through the sidereal amplitude modulation given by the detector responses (Astone et al. 2010, 2012). The narrowband time-domain data are produced by

heterodyning the raw detector strain data using the expected signal’s phase evolution (Dupuis & Woan 2005). It is then low-pass-filtered with a knee frequency of 0.25 Hz and down-sampled, via averaging, creating a complex time series with one sample per minute, i.e., a bandwidth of 1/60 Hz centered about the expected signal frequency that is now at 0 Hz. We call these approaches the *Bayesian*, \mathcal{F} -/ \mathcal{G} -statistic, and *5n-vector* methods, respectively. The first of these methods has been applied to all the pulsars in the sample (see Section 2.2), and again following Aasi et al. (2014) and Abbott et al. (2017a), at least two of the above methods have been applied to a selection of 34 high-value targets for which the observed limit is lower than, or closely approaches, the spin-down limit. The results of the *5n-vector* analysis only use data from the LIGO O2 run (see Section 2.1).

All these methods have been adapted to deal with the potential for signals at both once and twice the rotation frequency. For the *Bayesian* method, when searching for such a signal the narrowband time series from both frequencies are included in a coherent manner, with common polarization angles ψ and orientations ι . For the *5n-vector* and \mathcal{F} -/ \mathcal{G} -statistic methods a simpler approach is taken, and signals at the two frequencies are searched for independently. The \mathcal{F} -/ \mathcal{G} -statistic approach for such a signal is described in more detail in Bejger & Królak (2014). As a consequence, given that $C_{21} = 0$ (see Equation (1)) corresponds to the case of a triaxial star rotating around one of its principal axes of inertia, results for the amplitude C_{22} (Equation (2)) from the *5n-vector* method are not given, as they are equivalent to those for the standard amplitude h_0 .

In the case of a pulsar being observed to glitch during the run (see Section 2.2) the methods take different approaches. For the *Bayesian* method it is assumed that any glitch may produce an unknown offset between the electromagnetically observed rotational phase and the gravitational-wave phase. Therefore, an additional phase offset is added to the signal model at the time of the glitch, and this is included as a parameter to be estimated, while the gravitational-wave amplitude and orientation angles of the source (inclination and polarization) are assumed to remain fixed over the glitch. This is consistent with the analysis in Abbott et al. (2010), although it differs from the more recent analyses in Aasi et al. (2014) and Abbott et al. (2017a), in which each interglitch period was treated semi-independently, i.e., independent phases and polarization angles were assumed for each interglitch period, but two-dimensional marginalized posterior distributions on the gravitational-wave amplitude and cosine of the inclination angle from data before a glitch were used as a prior on those parameters when analyzing data after the glitch. For both the \mathcal{F} -/ \mathcal{G} -statistic and *5n-vector* methods, as already done in Aasi et al. (2014) and Abbott et al. (2017a), each interglitch period is analyzed independently, i.e., no parameters are assumed to be coherent over the glitch, and the resulting statistics are incoherently combined.

The prior probability distributions for the unknown signal parameters, as used for the *Bayesian* and *5n-vector* methods, are described in Appendix B.

The *5n-vector* method uses a description of the gravitational-wave signal based on the concept of polarization ellipse. The relation of the amplitude parameter H_0 used by the *5n-vector* method with both the standard strain amplitude h_0 and the C_{21} amplitude given in Equation (1) is described in Appendix E.

2. Data

In this section we briefly detail both the gravitational-wave data that have been used in the searches and the electromagnetic ephemerides for the selection of pulsars that have been included.

2.1. Gravitational-wave Data

The data analyzed in this paper consist of those obtained by the two LIGO detectors (the LIGO Hanford Observatory, commonly abbreviated to LHO or H1, and the LIGO Livingston Observatory, abbreviated to LLO or L1) taken during their first (Abbott et al. 2016) and second observing runs (O1 and O2, respectively) in their advanced detector configurations (Aasi et al. 2015a).¹⁹⁷

Data from O1 between 2015 September 11 (with start times of 01:25:03 UTC and 18:29:03 UTC for LHO and LLO, respectively) and 2016 January 19 at 17:07:59 UTC have been used. The calibration of these data and the frequency-dependent uncertainties on amplitude and phase over the run are described in detail in Cahillane et al. (2017). Over the course of the O1 run the calibration amplitude uncertainty was no larger than 5% and 10%, and the phase uncertainty was no larger than 3° and 4°, for LHO and LLO, respectively, over the frequency range ~10–2000 Hz (these are derived from the 68% confidence levels given in Figure 11 of Cahillane et al. 2017). All data flagged as in “science mode,” i.e., when the detectors were operating in a stable state, and for which the calibration was behaving as expected, have been used. This gave a total of 79 and 66 days of observing time for LHO and LLO, respectively, equivalent to duty factors of 60% and 51%.

Data from O2 between 2016 November 30 at 16:00:00 UTC and 2017 August 25 at 22:00:00 UTC, for both LHO and LLO, have been used. An earlier version of the calibrated data for this observing run, as well as the uncertainty budget associated with it, is again described in Cahillane et al. (2017). However, data with an updated calibration have been produced and used in this analysis, with this having an improved uncertainty budget (Cahillane et al. 2018). Over the course of the O2 run the calibration amplitude uncertainty was no larger than 3% and 8% and the phase uncertainty was no larger than 3° and 4° for LHO and LLO, respectively, over the frequency range of ~10–2000 Hz. The data used in this analysis were post-processed to remove spurious jitter noise that affected detector sensitivity across a broad range of frequencies, particularly for data from LHO, and to remove some instrumental spectral lines (Davis et al. 2019; Driggers et al. 2019).

The Virgo gravitational-wave detector (Acernese et al. 2015) was operating during the last 25 days of O2 (Abbott et al. 2017d); however, due to its higher noise levels as compared to the LIGO detectors and the shorter observing time, Virgo data were not included in this analysis.

2.2. Pulsars

For this analysis we have gathered ephemerides for 222 pulsars based on radio, X-ray, and γ -ray observations. The observations have used the 42 ft telescope and Lovell

telescope at Jodrell Bank (UK), the Mount Pleasant Observatory 26 m telescope (Australia), the Parkes radio telescope (Australia), the Nançay Decimetric Radio Telescope (France), the Molonglo Observatory Synthesis Telescope (Australia), the Arecibo Observatory (Puerto Rico), the Fermi Large Area Telescope, and the Neutron Star Interior Composition Explorer (NICER). As with the search in Abbott et al. (2017a), the criterion for our selection of pulsars was that they have rotation frequencies greater than 10 Hz, so that they are within the frequency band of greatest sensitivity of the LIGO instruments, and for which the calibration is well characterized. There are in fact three pulsars with rotation frequencies just below 10 Hz that we include (PSR J0117+5914, PSR J1826–1256, and PSR J2129+1210A); for two of these the spin-down limit was potentially within reach using our data.

The ephemerides have been created using pulse time-of-arrival observations that mainly overlapped with all, or some fraction of, the O1 and O2 observing periods (see Section 2.1), so the timing solutions should provide coherent phase models over and between the two runs. Of the 222, we have 168 for which the electromagnetic timings fully overlapped with the full O1 and O2 runs. There are 12 pulsars for which there is no overlap between electromagnetic observations and the O2 run. These include two pulsars, J1412+7922 (known as Calvera) and J1849–0001, for which we only have X-ray timing observations from after O2 (Bogdanov et al. 2019).¹⁹⁸ For these we have made the reasonable assumption that timing models are coherent for our analysis and that no timing irregularities, such as glitches, are present.

In all previous searches a total of 271 pulsars had been searched for, with 167 of these being timed for this search. For the other sources ephemerides were not available to us for our current analysis. In particular, we do not have up-to-date ephemerides for many of the pulsars in the globular clusters 47 Tucanae and Terzan 5, or the interesting young X-ray pulsar J0537–6910.

2.2.1. Glitches

During the course of the O2 period, five pulsars exhibited timing glitches. The Vela pulsar (J0835–4510) glitched on 2016 December 12 at 11:36 UTC (Palfreyman 2016; Palfreyman et al. 2018), and the Crab pulsar (J0534+2200) showed a small glitch on 2017 March 27 at around 22:04 UTC (Espinoza et al. 2011).¹⁹⁹ PSR J1028–5819 glitched some time around 2017 May 29, with a best-fit glitch time of 01:36 UTC. PSR J1718–3825 experienced a small glitch around 2017 July 2. PSR J0205+6449 experienced four glitches over the period between the start of O1 and the end of O2, with glitch epochs of 2015 November 19, 2016 July 1, 2016 October 19, and 2017 May 27. Two of these glitches occurred in the period between O1 and O2, and as such any effect of the glitches on discrepancies between the electromagnetic and gravitational-wave phase would not be independently distinguishable, meaning that effectively only three glitches need to be accounted for.

¹⁹⁷ The O1 and O2 data sets are publicly available via the Gravitational Wave Open Science Center at <https://www.gw-openscience.org/O1> and <https://www.gw-openscience.org/O2>, respectively (Vallisneri et al. 2015).

¹⁹⁸ Subsequent to the search performed here, Bogdanov et al. (2019) revised their initial timing model of J1849–0001 so that it now overlaps partially with O2. The revised model is consistent with the initial model used here, and thus the results presented here remain valid.

¹⁹⁹ <http://www.jb.man.ac.uk/pulsar/glitches.html>

2.2.2. Timing Noise

Timing noise is low-frequency noise observed in the residuals of pulsar pulse arrival times after subtracting a low-order Taylor expansion fit (see, e.g., Hobbs et al. 2006a). As shown in Cordes & Helfand (1980), Arzoumanian et al. (1994) timing noise is strongly correlated with pulsar period derivative, so “young,” or canonical, pulsars generally have far higher levels than MSPs. If not accounted for in the timing model, the Crab pulsar’s phase, for example, could deviate by on the order of a cycle over the course of our observations, leading to decoherence of the signal (see Jones 2004; Pitkin & Woan 2007; Ashton et al. 2015). In our gravitational-wave searches we used phase models that incorporate the effects of timing noise when necessary. In some cases this is achieved by using a phase model that includes high-order coefficients in the Taylor expansion (including up to the twelfth frequency derivative in the case of the Crab pulsar) when fitting the electromagnetic pulse arrival times. In others, where expansions in the phase do not perform well, we have used the method of fitting multiple sinusoidal harmonics to the timing noise in the arrival times, as described in Hobbs et al. (2004) and implemented in the FITWAVES algorithm in TEMPO2 (Hobbs et al. 2006b).

2.2.3. Distances and Period Derivatives

When calculating results of the searches in terms of the Q_{22} mass quadrupole, fiducial ellipticity, or spin-down limits (see Appendix A), we require the distances to the pulsars. For the majority of pulsars we use “best-estimate” distances given in the ATNF Pulsar Catalog (Manchester et al. 2005).²⁰⁰ In the majority of cases these are distances based on the observed dispersion measure and calculated using the Galactic electron density distribution model of Yao et al. (2017), although others are based on parallax measurements, or inferred from associations with other objects or flux measurements. The distances used for each pulsar, as well as the reference for the value used, are given in Tables 1 and 2.

The spin-down limits that we compare our results to (see Appendix A) require a value for the first period derivative \dot{P} , or equivalently frequency derivative \dot{f} , of the pulsar. The observed spin-down does not necessarily reflect the intrinsic spin-down of the pulsar, as it can be contaminated by the relative motion of the pulsar with respect to the observer. This is particularly prevalent for MSPs, which have intrinsically small spin-downs that can be strongly affected, particularly if they are in the core of a globular cluster where significant intracluster accelerations can occur, or if they have a large transverse velocity with respect to the solar system and/or are close (the “Shklovskii effect”; Shklovskii 1970.) The spin-down can also be contaminated by the differential motion of the solar system and pulsar due to their orbits around the Galaxy. For the non-globular-cluster pulsars, if their proper motions and distances are well enough measured, then these effects can be corrected for to give the intrinsic period derivative (see, e.g., Damour & Taylor 1991). For pulsars where the intrinsic period derivative is given in the literature we have used those values (see Tables 1 and 2 for the values and associated references). For further non-globular-cluster pulsars for which a transverse velocity and distance are given in

the ATNF Pulsar Catalog, we correct the observed period derivative using the method in Damour & Taylor (1991). In some cases the corrections lead to negative period derivative values, indicating that the true values are actually too small to be confidently constrained. For these cases Table 2 does not give a period derivative value or associated spin-down limit.

As was previously done in Abbott et al. (2017a), for two globular cluster pulsars, J1823–3021A and J1824–2452A, we assume that the observed spin-down is not significantly contaminated by cluster effects following the discussions in Freire et al. (2011) and Johnson et al. (2013), respectively, so these values are used without any correction. For the other globular cluster pulsars, we again take the approach of Aasi et al. (2014) and Abbott et al. (2017a) and create proxy period derivative values by assuming that the stars have characteristic ages of 10^9 yr and braking indices of $n = 5$ (i.e., they are braked purely by gravitational radiation from the $l = m = 2$ mode).²⁰¹

2.2.4. Orientation Constraints

In Ng & Romani (2004, 2008) models are fitted to a selection of X-ray observations of pulsar wind nebulae, which are used to provide the orientations of the nebulae. In previous gravitational-wave searches (Abbott et al. 2008, 2010, 2017a; Aasi et al. 2014) the assumption has been made that the orientation of the wind nebula is consistent with the orientation of its pulsar. In this work we will also follow this assumption and use the fits in Ng & Romani (2008) as prior constraints on orientation (inclination angle ι and polarization angle ψ) for PSR J0205+6449, PSR J0534+2200, PSR J0835–4510, PSR J1952+3252, and PSR J2229+6114. This is discussed in more detail in Appendix B. We refer to results based on these constraints as using restricted priors.

Constraints on the position angle, and therefore gravitational-wave polarization angle, of pulsars are also possible through observations of their electromagnetic polarization (Johnston et al. 2005). None of the pulsars in Johnston et al. (2005) are in our target list, but such constraints may be useful in the future. Constraints on the polarization angle alone are not as useful as those that also provide the inclination of the source (as described above for the pulsar wind nebula observations), which is directly correlated with the gravitational-wave amplitude. However, there are some pulsars for which double pulses are observed (Kramer & Johnston 2008; Keith et al. 2010), suggesting that the rotation axis and magnetic axis are orthogonal, and therefore implying an inclination angle of $\iota \approx \pm 90^\circ$. In terms of upper limits on the gravitational-wave amplitude, the implication of $\iota \approx 90^\circ$ would generally be to lead to a larger limit on h_0 than for an inclination aligned with the line of sight, due to the relatively weaker observed strain for a linearly polarized signal compared to a circularly polarized signal of the same h_0 . Of the pulsars observed in Keith et al. (2010), one (PSR J1828–1101) is in our search, although we have not used the implied constraints in this analysis. In the future these constraints will be considered if appropriate.

²⁰⁰ Version 1.59 of the catalog available at <http://www.atnf.csiro.au/people/pulsar/psrcat/>.

²⁰¹ The braking index n defines the power-law relation between the pulsar’s frequency and frequency derivative via $\dot{f} = -kf^n$, where k is a constant. Purely magnetic dipole braking gives a value of $n = 3$, and purely quadrupole gravitational-wave braking gives $n = 5$. The characteristic age is defined as $\tau = (n - 1)^{-1}(f/\dot{f})$.

Table 1
Limits on Gravitational-wave Amplitude, and Other Derived Quantities, for 34 High-value Pulsars from the Three Analysis Methods

Pulsar Name (J2000)	f_{rot} (Hz)	\dot{P}_{rot} (s s^{-1})	Distance (kpc)	h_0^{sd}	Analysis Method	$C_{21}^{95\%}$	$C_{22}^{95\%}$	$h_0^{95\%}$	$Q_{22}^{95\%}$ (kg m^2)	$\varepsilon^{95\%}$	$h_0^{95\%}/h_0^{\text{sd}}$	Statistic ^a $l=2, m=1, 2$	Statistic ^b $l=2, m=2$		
J0030+0451	205.5	1.1×10^{-20} g	0.33 (a)	3.7×10^{-27}	Bayesian	1.7×10^{-26}	5.9×10^{-27}	1.3×10^{-26}	1.8×10^{30}	2.3×10^{-8}	3.4	-3.8	-2.1		
					\mathcal{F} -statistic
					5n-vector	1.3×10^{-26}	...	1.7×10^{-26}	2.3×10^{30}	3.0×10^{-8}	4.5	0.72	0.61		
J0117+5914 ^c	9.9	5.9×10^{-15}	1.7 (b)	1.1×10^{-25}	Bayesian	...	...	3.8×10^{-25}	1.3×10^{35}	1.7×10^{-3}	3.5	-2.4	-1.9
					\mathcal{F} -statistic	
					5n-vector	...	...	2.6×10^{-25}	8.6×10^{34}	1.1×10^{-3}	2.4	...	0.31
J0205+6449 ^c	15.2	1.9×10^{-13}	2.00 (c)	6.9×10^{-25}	Bayesian	$1.8(1.5) \times 10^{-24}$	$2.4(3.6) \times 10^{-26}$	$4.9(7.1) \times 10^{-26}$	$0.8(1.1) \times 10^{33}$	$1.0(1.5) \times 10^{-4}$	0.071(0.1)	-4.8(-4.6)	-2.7(-2.4)		
					\mathcal{F} -statistic	2.2×10^{-24}	4.5×10^{-26}	8.8×10^{-26}	1.4×10^{34}	1.8×10^{-4}	0.13	0.71	0.26		
					5n-vector	...	...	$2.9(4.5) \times 10^{-26}$	$4.6(7.1) \times 10^{33}$	$5.9(9.2) \times 10^{-5}$	0.042(0.065)	...	0.41
J0534+2200 ^c	29.7	4.2×10^{-13}	2.00	1.4×10^{-24}	Bayesian	$7.9(5.8) \times 10^{-26}$	$9.1(7.3) \times 10^{-27}$	$1.9(1.5) \times 10^{-26}$	$7.7(6.0) \times 10^{32}$	$1.0(0.8) \times 10^{-5}$	0.013(0.01)	-5.1(-5.2)	-2.6(-2.7)		
					\mathcal{F} -statistic	$1.6(1.1) \times 10^{-25}$	$1.1(1.1) \times 10^{-26}$	$2.2(1.3) \times 10^{-26}$	$9.1(5.4) \times 10^{32}$	$1.2(0.7) \times 10^{-5}$	0.015(0.0091)	0.32(0.18)	0.65(0.87)		
					5n-vector	$1.7(1.3) \times 10^{-25}$	...	$2.9(2.9) \times 10^{-26}$	$1.2(1.2) \times 10^{33}$	$1.6(1.6) \times 10^{-5}$	0.02(0.02)	0.70	0.45	
J0711-6830 ^c	182.1	1.4×10^{-20}	0.11 (b)	1.2×10^{-26}	Bayesian	2.6×10^{-26}	7.0×10^{-27}	1.5×10^{-26}	9.3×10^{29}	1.2×10^{-8}	1.3	-3.1	-1.9		
					\mathcal{F} -statistic	...	...	...	...	...	...	...	...
					5n-vector	1.2×10^{-26}	...	1.5×10^{-26}	9.1×10^{29}	1.2×10^{-8}	1.3	0.79	0.39		
J0835-4510 ^c	11.2	1.2×10^{-13}	0.29 (j)	3.3×10^{-24}	Bayesian	$1.4(1.1) \times 10^{-23}$	$6.7(6.2) \times 10^{-26}$	$1.4(1.2) \times 10^{-25}$	$5.9(5.2) \times 10^{33}$	$7.6(6.7) \times 10^{-5}$	0.042(0.037)	-4.2(-4.4)	-2.5(-2.8)		
					\mathcal{F} -statistic	$1.3(1.1) \times 10^{-23}$	$1.1(0.9) \times 10^{-25}$	$2.6(2.0) \times 10^{-25}$	$1.1(0.8) \times 10^{34}$	$1.4(1.1) \times 10^{-4}$	0.078(0.06)	0.75(0.75)	0.75(0.75)		
					5n-vector	...	...	$2.3(2.4) \times 10^{-25}$	$9.7(9.9) \times 10^{33}$	$1.3(1.3) \times 10^{-4}$	0.07(0.071)	...	0.41
J0940-5428	11.4	3.3×10^{-14}	0.38 (b)	1.3×10^{-24}	Bayesian	1.6×10^{-23}	7.7×10^{-26}	1.6×10^{-25}	8.7×10^{33}	1.1×10^{-4}	0.13	-3.7	-2.3		
					\mathcal{F} -statistic	...	...	...	...	...	...	...	...
					5n-vector	...	...	1.7×10^{-25}	8.9×10^{33}	1.2×10^{-4}	0.13	...	0.70
J1028-5819	10.9	1.6×10^{-14}	1.42 (b)	2.4×10^{-25}	Bayesian	2.7×10^{-23}	9.1×10^{-26}	2.3×10^{-25}	5.1×10^{34}	6.6×10^{-4}	0.98	-3.5	-2.2		
					\mathcal{F} -statistic	...	...	...	...	...	...	...	...
					5n-vector	...	...	1.9×10^{-25}	4.1×10^{34}	5.3×10^{-4}	0.8	...	0.40
J1105-6107	15.8	1.6×10^{-14}	2.36 (b)	1.7×10^{-25}	Bayesian	1.7×10^{-24}	2.0×10^{-26}	3.9×10^{-26}	6.7×10^{33}	8.7×10^{-5}	0.23	-4.6	-2.8		
					\mathcal{F} -statistic	...	...	...	...	...	...	...	...
					5n-vector	...	...	2.7×10^{-26}	4.6×10^{33}	6.0×10^{-5}	0.16	...	0.93
J1112-6103	15.4	3.1×10^{-14}	4.50 (b)	1.2×10^{-25}	Bayesian	3.4×10^{-24}	2.5×10^{-26}	5.8×10^{-26}	2.0×10^{34}	2.6×10^{-4}	0.47	-4.2	-3.4		
					\mathcal{F} -statistic	...	...	...	...	...	...	...	...
					5n-vector	...	...	3.6×10^{-26}	1.2×10^{34}	1.6×10^{-4}	0.29	...	0.76
J1410-6132	20.0	3.2×10^{-14}	13.51 (b)	4.8×10^{-26}	Bayesian	4.9×10^{-25}	9.4×10^{-27}	2.1×10^{-26}	1.3×10^{34}	1.7×10^{-4}	0.44	-5.7	-3.0		
					\mathcal{F} -statistic	...	...	...	...	...	...	...	...
					5n-vector	5.4×10^{-25}	...	2.6×10^{-26}	1.6×10^{34}	2.1×10^{-4}	0.55	...	0.88		
J1412+7922	16.9	3.3×10^{-15}	2.00 (o)	9.5×10^{-26}	Bayesian	1.8×10^{-24}	3.4×10^{-26}	7.5×10^{-26}	9.6×10^{33}	1.2×10^{-4}	0.78	-4.9	-2.1		
					\mathcal{F} -statistic	2.3×10^{-24}	2.2×10^{-26}	6.2×10^{-26}	7.9×10^{33}	1.0×10^{-4}	0.65	0.24	0.39		
					5n-vector	...	...	3.6×10^{-26}	4.6×10^{33}	6.0×10^{-5}	0.38	...	0.80
J1420-6048	14.8	8.3×10^{-14}	5.63 (b)	1.6×10^{-25}	Bayesian	2.1×10^{-24}	1.9×10^{-26}	4.1×10^{-26}	1.9×10^{34}	2.5×10^{-4}	0.26	-6.2	-2.8		
					\mathcal{F} -statistic	...	...	...	...	...	...	...	...
					5n-vector	...	...	7.6×10^{-26}	3.6×10^{34}	4.7×10^{-4}	0.48	...	0.52
J1509-5850	11.2	9.2×10^{-15}	3.37 (b)	7.7×10^{-26}	Bayesian	1.7×10^{-23}	1.5×10^{-25}	5.4×10^{-25}	2.6×10^{35}	3.4×10^{-3}	7.1	-3.5	-2.0		
					\mathcal{F} -statistic	...	...	...	...	...	...	...	...
					5n-vector	...	...	2.1×10^{-25}	1.0×10^{35}	1.3×10^{-3}	2.7	...	0.72
J1531-5610	11.9	1.4×10^{-14}	2.84 (b)	1.1×10^{-25}	Bayesian	7.9×10^{-24}	5.5×10^{-26}	1.2×10^{-25}	4.4×10^{34}	5.6×10^{-4}	1	-4.2	-2.4		
					\mathcal{F} -statistic	...	...	...	...	...	...	...	...
					5n-vector	...	...	1.4×10^{-25}	5.3×10^{34}	6.8×10^{-4}	1.2	...	0.31

Table 1
(Continued)

Pulsar Name (J2000)	f_{rot} (Hz)	\dot{P}_{rot} (s s ⁻¹)	Distance (kpc)	h_0^{sd}	Analysis Method	$C_{21}^{95\%}$	$C_{22}^{95\%}$	$h_0^{95\%}$	$Q_{22}^{95\%}$ (kg m ²)	$\epsilon^{95\%}$	$h_0^{95\%}/h_0^{\text{sd}}$	Statistic ^a $l=2, m=1, 2$	Statistic ^b $l=2, m=2$
J1718–3825	13.4	1.3×10^{-14}	3.49 (b)	9.7×10^{-26}	Bayesian	3.2×10^{-24}	4.2×10^{-26}	8.7×10^{-26}	3.1×10^{34}	4.0×10^{-4}	0.9	-5.6	-2.4
					\mathcal{F} -statistic	...	...	...	...	...	...	...
					5n-vector	...	...	6.5×10^{-26}	2.3×10^{34}	3.0×10^{-4}	0.67	0.67	
J1809–1917	12.1	2.6×10^{-14}	3.27 (b)	1.4×10^{-25}	Bayesian	6.6×10^{-24}	4.9×10^{-26}	9.8×10^{-26}	4.0×10^{34}	5.2×10^{-4}	0.72	-4.4	-2.5
					\mathcal{F} -statistic	6.2×10^{-24}	6.2×10^{-26}	7.3×10^{-26}	3.0×10^{34}	3.9×10^{-4}	0.53	0.76	0.76
					5n-vector	...	...	1.1×10^{-25}	4.3×10^{34}	5.6×10^{-4}	0.77	0.19	
J1813–1246	20.8	1.8×10^{-14}	2.50 (z)	1.9×10^{-25}	Bayesian	3.9×10^{-25}	2.2×10^{-26}	4.7×10^{-26}	5.0×10^{33}	6.4×10^{-5}	0.24	-4.2	-2.2
					\mathcal{F} -statistic	3.8×10^{-25}	1.0×10^{-26}	3.3×10^{-26}	3.5×10^{33}	4.5×10^{-5}	0.17	0.08	0.73
					5n-vector	1.0×10^{-24}	...	4.5×10^{-26}	4.7×10^{33}	6.1×10^{-5}	0.23	0.22	
J1826–1256	9.1	1.2×10^{-13}	1.39 (cc)	6.1×10^{-25}	Bayesian	...	...	6.2×10^{-25}	1.9×10^{35}	2.5×10^{-3}	1	-2.0	-2.1
					\mathcal{F} -statistic	...	...	...	...	...	...	...
					5n-vector	...	...	4.7×10^{-25}	1.5×10^{35}	1.9×10^{-3}	0.77	...	
J1828–1101	13.9	1.5×10^{-14}	4.77 (b)	7.7×10^{-26}	Bayesian	7.5×10^{-24}	4.6×10^{-26}	7.2×10^{-26}	3.3×10^{34}	4.2×10^{-4}	0.94	-4.6	-2.5
					\mathcal{F} -statistic	...	...	...	...	...	...	...
					5n-vector	...	...	5.5×10^{-26}	2.5×10^{34}	3.2×10^{-4}	0.71	0.13	
J1831–0952	14.9	8.3×10^{-15}	3.68 (b)	7.7×10^{-26}	Bayesian	3.2×10^{-24}	3.1×10^{-26}	6.9×10^{-26}	2.1×10^{34}	2.7×10^{-4}	0.9	-5.0	-2.4
					\mathcal{F} -statistic	...	...	...	...	...	...	...
					5n-vector	...	...	4.3×10^{-26}	1.3×10^{34}	1.7×10^{-4}	0.56	0.75	
J1833–0827 ^c	11.7	9.2×10^{-15}	4.50 (m)	5.9×10^{-26}	Bayesian	1.9×10^{-23}	8.8×10^{-26}	3.3×10^{-25}	2.0×10^{35}	2.6×10^{-3}	5.6	-3.3	-1.9
					\mathcal{F} -statistic	...	...	...	...	...	...	...
					5n-vector	...	...	1.4×10^{-25}	8.3×10^{34}	1.1×10^{-3}	2.3	0.94	
J1837–0604	10.4	4.5×10^{-14}	4.77 (b)	1.2×10^{-25}	Bayesian	4.0×10^{-23}	1.1×10^{-25}	2.4×10^{-25}	1.9×10^{35}	2.5×10^{-3}	2	-3.7	-2.3
					\mathcal{F} -statistic	...	...	...	...	...	...	...
					5n-vector	...	...	1.6×10^{-25}	1.3×10^{35}	1.6×10^{-3}	1.4	0.38	
J1849–0001	26.0	1.4×10^{-14}	7.00 (dd)	7.0×10^{-26}	Bayesian	7.1×10^{-25}	7.9×10^{-27}	1.9×10^{-26}	3.7×10^{33}	4.7×10^{-5}	0.28	-3.4	-2.6
					\mathcal{F} -statistic	6.8×10^{-25}	9.1×10^{-27}	2.8×10^{-26}	5.3×10^{33}	6.9×10^{-5}	0.4	0.04	0.75
					5n-vector	6.8×10^{-26}	...	2.0×10^{-26}	3.8×10^{33}	4.9×10^{-5}	0.29	0.23	0.49
J1856+0245	12.4	6.2×10^{-14}	6.32 (b)	1.1×10^{-25}	Bayesian	7.2×10^{-24}	7.3×10^{-26}	1.5×10^{-25}	1.1×10^{35}	1.4×10^{-3}	1.3	-3.8	-2.1
					\mathcal{F} -statistic	...	...	...	...	...	...	...
					5n-vector	...	...	1.6×10^{-25}	1.2×10^{35}	1.6×10^{-3}	1.5	0.36	
J1913+1011	27.8	3.4×10^{-15}	4.61 (b)	5.4×10^{-26}	Bayesian	1.6×10^{-25}	1.8×10^{-26}	3.7×10^{-26}	4.0×10^{33}	5.2×10^{-5}	0.7	-4.1	-2.2
					\mathcal{F} -statistic	...	...	...	...	...	...	...
					5n-vector	1.7×10^{-25}	...	2.1×10^{-26}	2.3×10^{33}	3.0×10^{-5}	0.39	0.56	0.90
J1925+1720	13.2	1.0×10^{-14}	5.06 (b)	5.9×10^{-26}	Bayesian	3.3×10^{-24}	5.5×10^{-26}	1.1×10^{-25}	5.8×10^{34}	7.5×10^{-4}	1.9	-5.6	-2.4
					\mathcal{F} -statistic	...	...	...	...	...	...	...
					5n-vector	...	...	1.1×10^{-25}	5.8×10^{34}	7.5×10^{-4}	1.9	0.44	
J1928+1746	14.5	1.3×10^{-14}	4.34 (b)	8.1×10^{-26}	Bayesian	2.4×10^{-24}	5.5×10^{-26}	1.2×10^{-25}	4.3×10^{34}	5.6×10^{-4}	1.4	-5.2	-2.6
					\mathcal{F} -statistic	2.2×10^{-24}	3.9×10^{-26}	1.3×10^{-25}	4.9×10^{34}	6.3×10^{-4}	1.6	0.61	0.61
					5n-vector	...	...	8.6×10^{-26}	3.2×10^{34}	4.2×10^{-4}	1.1	0.59	
J1935+2025	12.5	6.1×10^{-14}	4.60 (b)	1.5×10^{-25}	Bayesian	7.3×10^{-24}	5.2×10^{-26}	1.1×10^{-25}	6.2×10^{34}	8.0×10^{-4}	0.75	-4.4	-2.4
					\mathcal{F} -statistic	5.0×10^{-24}	5.5×10^{-26}	1.3×10^{-25}	7.0×10^{34}	9.1×10^{-4}	0.85	0.71	0.71
					5n-vector	...	...	1.4×10^{-25}	7.6×10^{34}	9.8×10^{-4}	0.92	0.37	
J1952+3252 ^c	25.3	5.8×10^{-15}	3.00 (m)	1.0×10^{-25}	Bayesian	$2.8(2.9) \times 10^{-25}$	$8.7(9.0) \times 10^{-27}$	$1.9(1.8) \times 10^{-26}$	$1.7(1.5) \times 10^{33}$	$2.1(2.0) \times 10^{-5}$	0.19(0.17)	-3.4(-3.5)	-2.7(-2.6)
					\mathcal{F} -statistic	...	...	...	...	...	...	...
					5n-vector	$2.0(2.0) \times 10^{-25}$	...	$2.4(2.5) \times 10^{-26}$	$2.1(2.1) \times 10^{33}$	$2.7(2.7) \times 10^{-5}$	0.24(0.24)	0.06	0.70

Table 1
(Continued)

Pulsar Name (J2000)	f_{rot} (Hz)	\dot{P}_{rot} (s s^{-1})	Distance (kpc)	h_0^{sd}	Analysis Method	$C_{21}^{95\%}$	$C_{22}^{95\%}$	$h_0^{95\%}$	$Q_{22}^{95\%}$ (kg m^2)	$\varepsilon^{95\%}$	$h_0^{95\%}/h_0^{\text{sd}}$	Statistic ^a $l=2, m=1, 2$	Statistic ^b $l=2, m=2$	
J2043+2740	10.4	1.3×10^{-15}	1.48 (b)	6.3×10^{-26}	Bayesian	2.6×10^{-23}	7.3×10^{-26}	1.6×10^{-25}	4.1×10^{34}	5.3×10^{-4}	2.6	-4.2	-2.5	
					\mathcal{F} -statistic	2.1×10^{-23}	6.4×10^{-26}	2.8×10^{-25}	7.0×10^{34}	9.1×10^{-4}	4.5	0.79	0.79	
					5n-vector	...	...	1.9×10^{-25}	4.7×10^{34}	6.1×10^{-4}	3	...	0.17
J2124-3358	202.8	$9.0 \times 10^{-21}\text{g}$	0.38 (g)	2.9×10^{-27}	Bayesian	1.4×10^{-26}	6.3×10^{-27}	1.3×10^{-26}	2.2×10^{30}	2.9×10^{-8}	4.6	-3.8	-2.2	
					\mathcal{F} -statistic
					5n-vector	2.6×10^{-26}	...	1.3×10^{-26}	2.2×10^{30}	2.8×10^{-8}	4.5	0.58	0.58	
J2229+6114	19.4	7.8×10^{-14}	3.00 (hh)	3.3×10^{-25}	Bayesian	$3.9(3.7) \times 10^{-25}$	$1.2(0.8) \times 10^{-26}$	$2.5(1.6) \times 10^{-26}$	$3.7(2.3) \times 10^{33}$	$4.8(3.0) \times 10^{-5}$	0.077(0.048)	-5.0(-5.1)	-2.8(-2.9)	
					\mathcal{F} -statistic	5.6×10^{-25}	2.9×10^{-26}	2.1×10^{-26}	3.1×10^{33}	4.0×10^{-5}	0.063	0.55	0.43	
					5n-vector	...	...	$2.5(1.9) \times 10^{-26}$	$3.7(2.8) \times 10^{33}$	$4.8(3.6) \times 10^{-5}$	0.077(0.057)	...	0.99
J2302+4442 ^c	192.6	1.4×10^{-20}	0.86 (b)	1.5×10^{-27}	Bayesian	1.5×10^{-26}	6.5×10^{-27}	1.4×10^{-26}	5.7×10^{30}	7.4×10^{-8}	8.9	-3.9	-2.0	
					\mathcal{F} -statistic	2.5×10^{-26}	5.6×10^{-27}	1.1×10^{-26}	4.7×10^{30}	6.0×10^{-8}	7.2	0.49	0.49	
					5n-vector	...	...	...	...	...	...	...	...

Notes. For references and other notes see Table 2. Values in parentheses are those produced using the restricted orientation priors described in Section 2.2.4.

^a For the *Bayesian* method this column shows the base-10 logarithm of the Bayesian odds, \mathcal{O} , comparing a coherent signal model at both the $l = 2, m = 1, 2$ modes to incoherent signal models. For the \mathcal{F} -/ \mathcal{G} -statistic method this column shows the false-alarm probability for a signal just at the $l = 2, m = 1$ mode, assuming that the $2\mathcal{F}$ value has a χ^2 distribution with 4 degrees of freedom and the $2\mathcal{G}$ value has a χ^2 distribution with 2 degrees of freedom. For the *5n-vector* method this column shows the p -value for a search for a signal at just the $l = 2, m = 1$ mode, where the null hypothesis being tested is that the data are consistent with pure Gaussian noise.

^b This is the same as in footnote a, but for all the methods the assumed signal model is from the $l = m = 2$ mode.

^c The observed \dot{P} has been corrected to account for the relative motion between the pulsar and observer.

(This table is available in its entirety in machine-readable form.)

Table 2
(Continued)

Pulsar Name (J2000)	f_{rot} (Hz)	\dot{P}_{rot} (s s ⁻¹)	Distance (kpc)	h_0^{sd}	$C_{21}^{95\%}$	$C_{22}^{95\%}$	$h_0^{95\%}$	$Q_{22}^{95\%}$ (kg m ²)	$\varepsilon^{95\%}$	$h_0^{95\%}/h_0^{\text{sd}}$	$\mathcal{O}_{m=1,2}^{l=2}$	$\mathcal{O}_{m=2}^{l=2}$
J1914+0659	54.0	3.1×10^{-20}	8.47 (b)	1.2×10^{-28}	2.7×10^{-26}	4.3×10^{-27}	9.1×10^{-27}	4.8×10^{32}	6.2×10^{-6}	74	-4.7	-2.2
J1915+1606 ^a	16.9	8.6×10^{-18}	5.25 (b)	1.9×10^{-27}	1.2×10^{-24}	1.6×10^{-26}	3.1×10^{-26}	1.0×10^{34}	1.4×10^{-4}	17	-5.8	-2.7
J1918-0642 ^a	130.8	2.4×10^{-20}	1.10 (a)	1.3×10^{-27}	1.9×10^{-26}	7.0×10^{-27}	1.5×10^{-26}	1.7×10^{31}	2.2×10^{-7}	11	-3.6	-1.7
J1921+0137	400.6	1.9×10^{-20}	5.06 (b)	4.4×10^{-28}	4.1×10^{-26}	9.1×10^{-27}	1.7×10^{-26}	1.0×10^{31}	1.3×10^{-7}	40	-2.9	-2.1
J1923+2515 ^a	264.0	7.0×10^{-21}	1.20 (b)	9.1×10^{-28}	1.9×10^{-26}	5.7×10^{-27}	1.3×10^{-26}	4.0×10^{30}	5.1×10^{-8}	14	-4.0	-2.2
J1932+17	23.9	4.1×10^{-19}	2.07 (b)	1.2×10^{-27}	2.1×10^{-25}	2.0×10^{-26}	4.0×10^{-26}	2.6×10^{33}	3.4×10^{-5}	32	-4.0	-2.0
J1939+2134	641.9	1.1×10^{-19} (g)	3.27 (g)	2.0×10^{-27}	2.7×10^{-26}	2.3×10^{-26}	4.6×10^{-26}	6.6×10^{30}	8.6×10^{-8}	23	-3.3	-1.4
J1943+2210	196.7	8.8×10^{-21}	6.78 (b)	1.6×10^{-28}	1.8×10^{-26}	6.3×10^{-27}	1.4×10^{-26}	4.3×10^{31}	5.6×10^{-7}	86	-3.8	-2.0
J1944+0907 ^a	192.9	3.8×10^{-21}	1.22 (b)	5.7×10^{-28}	2.2×10^{-26}	1.2×10^{-26}	2.2×10^{-26}	1.3×10^{31}	1.7×10^{-7}	38	-2.7	-1.3
J1946+3417 ^b	315.4	...	6.97 (b)	...	2.0×10^{-26}	6.4×10^{-27}	1.4×10^{-26}	1.8×10^{31}	2.3×10^{-7}	...	-4.0	-2.1
J1946-5403	368.9	2.7×10^{-21}	1.15 (b)	7.0×10^{-28}	1.9×10^{-26}	7.8×10^{-27}	1.7×10^{-26}	2.6×10^{30}	3.4×10^{-8}	24	-4.0	-2.1
J1950+2414	232.3	1.9×10^{-20}	7.27 (b)	2.3×10^{-28}	1.6×10^{-26}	9.7×10^{-27}	1.9×10^{-26}	4.8×10^{31}	6.2×10^{-7}	83	-3.5	-1.6
J1955+2527 ^a	205.2	1.1×10^{-20}	8.18 (b)	1.5×10^{-28}	1.7×10^{-26}	8.1×10^{-27}	1.7×10^{-26}	5.9×10^{31}	7.6×10^{-7}	110	-3.5	-1.8
J1955+2908 ^a	163.0	3.1×10^{-20}	6.30 (b)	2.9×10^{-28}	2.1×10^{-26}	5.9×10^{-27}	1.3×10^{-26}	5.7×10^{31}	7.4×10^{-7}	46	-3.7	-2.1
J1959+2048 ^a	622.1	1.1×10^{-20}	1.73 (b)	1.2×10^{-27}	2.8×10^{-26}	1.2×10^{-26}	2.5×10^{-26}	2.1×10^{30}	2.7×10^{-8}	21	-4.1	-2.2
J2007+2722	40.8	9.6×10^{-19}	7.10 (b)	7.1×10^{-28}	5.7×10^{-26}	1.2×10^{-26}	2.2×10^{-26}	1.7×10^{33}	2.2×10^{-5}	30	-3.7	-1.5
J2010-1323 ^a	191.5	4.0×10^{-21}	1.16 (b)	6.1×10^{-28}	3.0×10^{-26}	9.1×10^{-27}	2.1×10^{-26}	1.2×10^{31}	1.6×10^{-7}	34	-2.9	-1.7
J2017+0603 ^a	345.3	8.0×10^{-21}	1.40 (b)	9.6×10^{-28}	2.4×10^{-26}	1.3×10^{-26}	2.7×10^{-26}	5.8×10^{30}	7.5×10^{-8}	28	-4.0	-1.6
J2017-1614	432.1	2.4×10^{-21}	1.44 (b)	5.7×10^{-28}	1.7×10^{-26}	1.4×10^{-26}	3.0×10^{-26}	4.2×10^{30}	5.4×10^{-8}	52	-3.7	-1.7
J2019+2425 ^a	254.2	1.6×10^{-21}	1.16 (b)	4.4×10^{-28}	2.8×10^{-26}	1.4×10^{-26}	3.3×10^{-26}	1.1×10^{31}	1.4×10^{-7}	75	-3.3	-1.7
J2033+1734 ^a	168.1	8.4×10^{-21}	1.74 (b)	5.5×10^{-28}	1.4×10^{-26}	7.8×10^{-27}	1.6×10^{-26}	1.8×10^{31}	2.3×10^{-7}	28	-3.9	-2.0
J2042+0246	220.6	1.4×10^{-20}	0.64 (b)	2.2×10^{-27}	2.1×10^{-26}	6.9×10^{-27}	1.4×10^{-26}	3.3×10^{30}	4.2×10^{-8}	6.1	-3.6	-2.0
J2043+1711 ^a	420.2	4.1×10^{-21}	1.60 (a)	6.6×10^{-28}	2.6×10^{-26}	1.1×10^{-26}	2.2×10^{-26}	3.7×10^{30}	4.8×10^{-8}	34	-3.9	-2.1
J2045+3633 ^a	31.6	6.0×10^{-19}	5.63 (b)	6.2×10^{-28}	5.3×10^{-26}	9.9×10^{-27}	2.1×10^{-26}	2.1×10^{33}	2.8×10^{-5}	33	-4.8	-2.3
J2047+1053	233.3	2.1×10^{-20}	2.79 (b)	6.4×10^{-28}	3.4×10^{-26}	6.1×10^{-27}	1.3×10^{-26}	1.3×10^{31}	1.6×10^{-7}	21	-3.1	-2.1
J2051-0827 ^a	221.8	1.2×10^{-20}	1.47 (b)	9.0×10^{-28}	1.9×10^{-26}	8.4×10^{-27}	1.7×10^{-26}	9.4×10^{30}	1.2×10^{-7}	19	-3.6	-1.8
J2052+1218	503.7	6.7×10^{-21}	3.92 (b)	3.8×10^{-28}	2.0×10^{-26}	9.6×10^{-27}	2.1×10^{-26}	6.0×10^{30}	7.7×10^{-8}	56	-4.1	-2.3
J2053+4650 ^a	79.5	1.7×10^{-19}	3.81 (b)	7.8×10^{-28}	1.9×10^{-26}	5.4×10^{-27}	1.1×10^{-26}	1.3×10^{32}	1.6×10^{-6}	15	-4.1	-1.9
J2129+1210A ^c	9.0	8.8×10^{-19}	10.00 (ff)	2.3×10^{-28}	...	...	7.2×10^{-25}	1.6×10^{36}	2.1×10^{-2}	3200	-2.5	-1.9
J2129+1210B ^c	17.8	4.4×10^{-19}	10.00 (ff)	2.3×10^{-28}	8.9×10^{-25}	1.4×10^{-26}	2.9×10^{-26}	1.7×10^{34}	2.2×10^{-4}	130	-4.9	-2.9
J2129+1210C ^c	32.8	2.4×10^{-19}	10.00 (ff)	2.3×10^{-28}	7.2×10^{-26}	8.5×10^{-27}	1.7×10^{-26}	2.9×10^{33}	3.7×10^{-5}	75	-4.8	-2.4
J2129+1210D ^c	208.2	3.8×10^{-20}	10.00 (ff)	2.3×10^{-28}	1.7×10^{-26}	8.5×10^{-27}	1.8×10^{-26}	7.5×10^{31}	9.7×10^{-7}	78	-3.6	-1.9
J2129+1210E ^c	215.0	3.7×10^{-20}	10.00 (ff)	2.3×10^{-28}	1.9×10^{-26}	7.2×10^{-27}	1.5×10^{-26}	5.9×10^{31}	7.6×10^{-7}	66	-3.8	-2.0
J2145-0750	62.3	2.9×10^{-20} (g)	0.65 (g)	1.7×10^{-27}	2.7×10^{-26}	6.9×10^{-27}	1.4×10^{-26}	4.4×10^{31}	5.7×10^{-7}	8.7	-4.1	-1.8
J2205+60	414.0	2.0×10^{-20}	3.53 (b)	6.5×10^{-28}	1.8×10^{-26}	1.1×10^{-26}	2.4×10^{-26}	8.9×10^{30}	1.2×10^{-7}	36	-4.0	-1.9
J2214+3000 ^a	320.6	1.3×10^{-20}	0.60 (a)	2.7×10^{-27}	2.0×10^{-26}	1.3×10^{-26}	2.6×10^{-26}	2.8×10^{30}	3.6×10^{-8}	9.5	-3.5	-1.7
J2222-0137	30.5	4.1×10^{-21} (gg)	0.27 (gg)	1.1×10^{-27}	8.6×10^{-26}	1.1×10^{-26}	2.2×10^{-26}	1.1×10^{32}	1.5×10^{-6}	20	-4.7	-2.3
J2229+2643 ^a	335.8	1.4×10^{-21}	1.80 (b)	3.1×10^{-28}	3.2×10^{-26}	1.1×10^{-26}	2.3×10^{-26}	6.6×10^{30}	8.5×10^{-8}	72	-3.2	-1.8
J2234+0611 ^a	279.6	3.6×10^{-21}	1.50 (a)	5.4×10^{-28}	2.0×10^{-26}	8.9×10^{-27}	1.8×10^{-26}	6.4×10^{30}	8.3×10^{-8}	34	-3.7	-1.9
J2234+0944 ^a	275.7	1.3×10^{-20}	0.80 (a)	1.9×10^{-27}	1.7×10^{-26}	7.7×10^{-27}	1.6×10^{-26}	3.1×10^{30}	4.0×10^{-8}	8.2	-3.9	-2.0
J2235+1506 ^a	16.7	9.2×10^{-20}	1.54 (b)	6.5×10^{-28}	1.5×10^{-24}	3.3×10^{-26}	6.2×10^{-26}	6.2×10^{33}	8.0×10^{-5}	95	-3.4	-1.9
J2241-5236	457.3	6.6×10^{-21}	0.96 (b)	1.5×10^{-27}	2.5×10^{-26}	8.8×10^{-27}	2.0×10^{-26}	1.6×10^{30}	2.1×10^{-8}	13	-4.1	-2.2

Table 2
(Continued)

Pulsar Name (J2000)	f_{rot} (Hz)	\dot{P}_{rot} (s s ⁻¹)	Distance (kpc)	h_0^{sd}	$C_{21}^{95\%}$	$C_{22}^{95\%}$	$h_0^{95\%}$	$Q_{22}^{95\%}$ (kg m ²)	$\varepsilon^{95\%}$	$h_0^{95\%}/h_0^{\text{sd}}$	$\mathcal{O}_{m=1,2}^{l=2}$	$\mathcal{O}_{m=2}^{l=2}$
J2256–1024	435.8	1.1×10^{-20}	1.33 (b)	1.3×10^{-27}	2.6×10^{-26}	1.2×10^{-26}	2.3×10^{-26}	2.9×10^{30}	3.8×10^{-8}	17	–3.7	–2.1
J2310–0555	382.8	5.0×10^{-21}	1.55 (b)	7.2×10^{-28}	1.9×10^{-26}	9.7×10^{-27}	2.0×10^{-26}	3.9×10^{30}	5.0×10^{-8}	28	–4.0	–2.1
J2317+1439	290.3	3.5×10^{-21} (g)	1.01 (g)	8.0×10^{-28}	1.5×10^{-26}	1.2×10^{-26}	2.6×10^{-26}	5.6×10^{30}	7.2×10^{-8}	32	–3.6	–1.6
J2322+2057	208.0	4.4×10^{-22} (ii)	0.23 (ii)	1.1×10^{-27}	2.1×10^{-26}	6.2×10^{-27}	1.3×10^{-26}	1.3×10^{30}	1.6×10^{-8}	12	–3.7	–2.0
J2339–0533 ^a	346.7	6.9×10^{-21}	1.10 (jj)	1.1×10^{-27}	2.2×10^{-26}	8.1×10^{-27}	1.8×10^{-26}	2.9×10^{30}	3.8×10^{-8}	15	–4.9	–2.4

Notes. The information in Table 2 is available in the machine readable version of Table 1.

^a The observed \dot{P} has been corrected to account for the relative motion between the pulsar and observer.

^b The corrected pulsar \dot{P} value is negative, so no value is given and no spin-down limit has been calculated.

^c This is a globular cluster pulsar for which a proxy period derivative has been derived assuming a characteristic age of 10^9 yr and a braking index of $n = 5$.

References. The following is a list of references for pulsar distances and intrinsic period derivatives, and they should be consulted for information on the associated uncertainties on these quantities: (a) Arzoumanian et al. (2018), (b) Yao et al. (2017), (c) Kothes (2013), (d) Verbiest & Lorimer (2014), (e) Antoniadis et al. (2013), (f) Reardon et al. (2016), (g) Desvignes et al. (2016), (h) Bassa et al. (2016), (i) Deller et al. (2009), (j) Dodson et al. (2003), (k) Mingarelli, private communication, (l) Abbott et al. (2017a), (m) Verbiest et al. (2012), (n) Boyles et al. (2013), (o) Halpern et al. (2013), (p) Fonseca et al. (2014), (q) Braga et al. (2015), (r) Vigeland et al. (2018), (s) Mingarelli et al. (2018), (t) Freire et al. (2012), (u) Espinoza et al. (2013), (v) Ortolani et al. (2007), (w) Ferdman et al. (2014), (x) Harris (1996), (y) Valenti et al. (2010), (z) Marelli et al. (2014), (aa) Valenti et al. (2007), (bb) Rees & Cudworth (1991), (cc) Wang (2011), (dd) Gotthelf et al. (2011), (ee) Gratton et al. (2003), (ff) McNamara et al. (2004), (gg) Deller et al. (2013), (hh) Halpern et al. (2001), (ii) Spiewak et al. (2018), (jj) Romani & Shaw (2011), (kk) Ng et al. (2014).

3. Results

For each pulsar the results presented here are from analyses coherently combining the data from both the LIGO detectors. As described below, we see no strong evidence for a gravitational-wave signal from any pulsar, so we therefore cast our results in terms of upper limits on the gravitational-wave amplitude. These limits are subject to the uncertainties from the detector calibration as described in Section 2.1, as well as statistical uncertainties that are dependent on the particular analysis method used. For the *Bayesian* analysis, statistical uncertainties on the 95% credible upper limits are on the order of 1% (see Figure 12 of Pitkin et al. 2017). For the *5n-vector* method the statistical uncertainty on the upper limits is of the order of 1%–5%, depending on the pulsar.

For all pulsars, we present the results of our analyses in terms of several quantities. For the searches including data at both once and twice the rotation frequency and searching for a signal from both the $l = 2, m = 1, 2$ modes we present the inferred limits on the C_{21} and C_{22} amplitude parameters given in Equations (1) and (2). For the searches looking only for emission from the $l = m = 2$ mode we present limits on the signal’s gravitational-wave strain h_0 . For the *Bayesian search* these limits are 95% credible upper bounds derived from the posterior probability distributions. For the *5n-vector* pipeline the upper limits are obtained with a hybrid frequentist/*Bayesian* approach, described in Appendix D, consisting in evaluating the posterior probability distribution of the signal amplitude H_0 , conditioned to the measured value of a detection statistic, and converting it to a 95% credible upper limit on h_0 or C_{21} (see Section 1.3, Appendix E, and Aasi et al. 2014, for more details.) Upper limits have been computed assuming both flat and, when information from electromagnetic observation is available, restricted priors on the polarization parameters, as detailed in Section 2.2.4 and Appendix B.

For the purely $l = m = 2$ mode search, we are able to convert these limits into equivalent limits on several derived quantities. In cases where we have an estimate for the pulsar distance (see Section 2.2 and Tables 1 and 2) h_0 can be converted directly into a limit on the Q_{22} mass quadrupole (see Equation (5)). Under the assumption of a fiducial principal moment of inertia of $I_{zz}^{\text{fid}} = 10^{38} \text{ kg m}^2$ this can also place a limit on the fiducial ellipticity ε . When we also have a reliable estimate of the intrinsic period derivative, the spin-down limit h_0^{sd} can be calculated (see Equation (9)) and the ratio of the observed limits on h_0 to this value, $h_0^{95\%}/h_0^{\text{sd}}$, is shown (the square of this value gives the ratio of the limit on the gravitational-wave luminosity to the spin-down luminosity of the pulsar).

For the *Bayesian* method, an odds value giving a ratio of probabilities is also calculated (the base-10 logarithm of which we denote as \mathcal{O} , which is equivalent to $\log_{10} \mathcal{O}_{S/1}$ from Abbott et al. 2017a), where the numerator is the probability of the data being consistent with a coherent signal model in both detectors and the denominator is the probability of an incoherent signal present in both detectors or Gaussian noise being present in both detectors (see Appendix A.3 in Abbott et al. 2017a or Section 2.6 of Pitkin et al. 2017 for more details). These odds can be used to assess when the coherent signal model is favored by the data. The values of \mathcal{O} for each pulsar are shown in Tables 1 (where it is the value given in the “Statistic” column for the *Bayesian search*) and 2, but in all cases the values are

negative, indicating no pulsars for which the coherent signal model is favored. Also, examination of the posterior probability distributions for the amplitude parameters shows that none are significantly disjoint from the probability of the amplitude being zero.

In the *5n-vector* search the significance of each analysis is expressed through a p -value, which is a measure of how compatible the data are with pure noise. It is obtained by empirically computing the noise-only distribution of the detection statistic, over an off-source region, and comparing it to the value of the detection statistic found in the actual analysis. Conventionally, a threshold of $p < 0.01$ on the p -value is used to identify potentially interesting candidates: pulsars for which the analysis provides a p -value smaller than the threshold would deserve a deeper study (see also Aasi et al. 2014; Abbott et al. 2017a). The computed p -values are reported in Table 1. For all the analyzed pulsars they are well above $p = 0.01$, suggesting that the data are fully compatible with noise.

For the \mathcal{F} -/ \mathcal{G} -statistic method false-alarm probabilities of obtaining the observed statistic values are calculated. They are derived assuming that for the \mathcal{F} -statistic the $2\mathcal{F}$ value has a χ^2 distribution with 4 degrees of freedom (Jaranowski et al. 1998) and for the \mathcal{G} -statistic the $2\mathcal{G}$ value has a χ^2 distribution with 2 degrees of freedom (Jaranowski & Królak 2010). The false-alarm probabilities reported in Table 1 are all close to unity and show no strong indication that the statistics deviate from their expected distributions.

The results for the 34 high-value targets are shown in Table 1, and the results for all the other pulsars are shown in Table 2. The 95% credible upper limits on C_{21} and C_{22} for all 222 pulsars from the *Bayesian* analysis are shown as a function of the gravitational-wave emission frequency in Figure 1. Also shown are estimates of the expected sensitivity of the search given representative noise amplitude spectral densities from the O1 and O2 observing runs (see Appendix C for descriptions of how these were produced). The 95% credible upper limits on h_0 for all 222 pulsars from the search purely for emission from the $l = m = 2$ mode are shown in Figure 2. Figure 2 also shows spin-down limits on the emission as triangles, and in the cases where our observed upper limits are below these the result is highlighted with a circular marker and is linked to its associated spin-down limit with a vertical line.

Figure 3 shows a histogram of the spin-down ratio $h_0^{95\%}/h_0^{\text{sd}}$ from the *Bayesian* analysis for the $l = m = 2$ mode search, for pulsars where it was possible to calculate a spin-down limit. This shows 20 pulsars for which $h_0^{95\%} < h_0^{\text{sd}}$ and 53 for which the results are between 1 and 10 times greater than h_0^{sd} . If we just look at MSPs, then 41 are within a factor of 10 of the spin-down limit.²⁰² The spin-down limits and the Q_{22} and ε values assume a particular distance, intrinsic period derivative, and fiducial moment of inertia of 10^{38} kg m^2 , but there can be considerable uncertainties on these values. For example, distances calculated using the Galactic electron density model of Yao et al. (2017) have a 1σ relative error of $\sim 40\%$, with some parts of the sky having several 100% relative errors. The true moment of inertia depends on the pulsar’s mass and equation of state and could be within a range of roughly

²⁰² Based on our sample of pulsars with rotation frequencies greater than 10 Hz, there is a clear distinction between the MSP and young (or normal) population based on a cut in \dot{P} of $10^{-17} \text{ s s}^{-1}$, i.e., we assume that any pulsar with a \dot{P} smaller than this is an MSP.

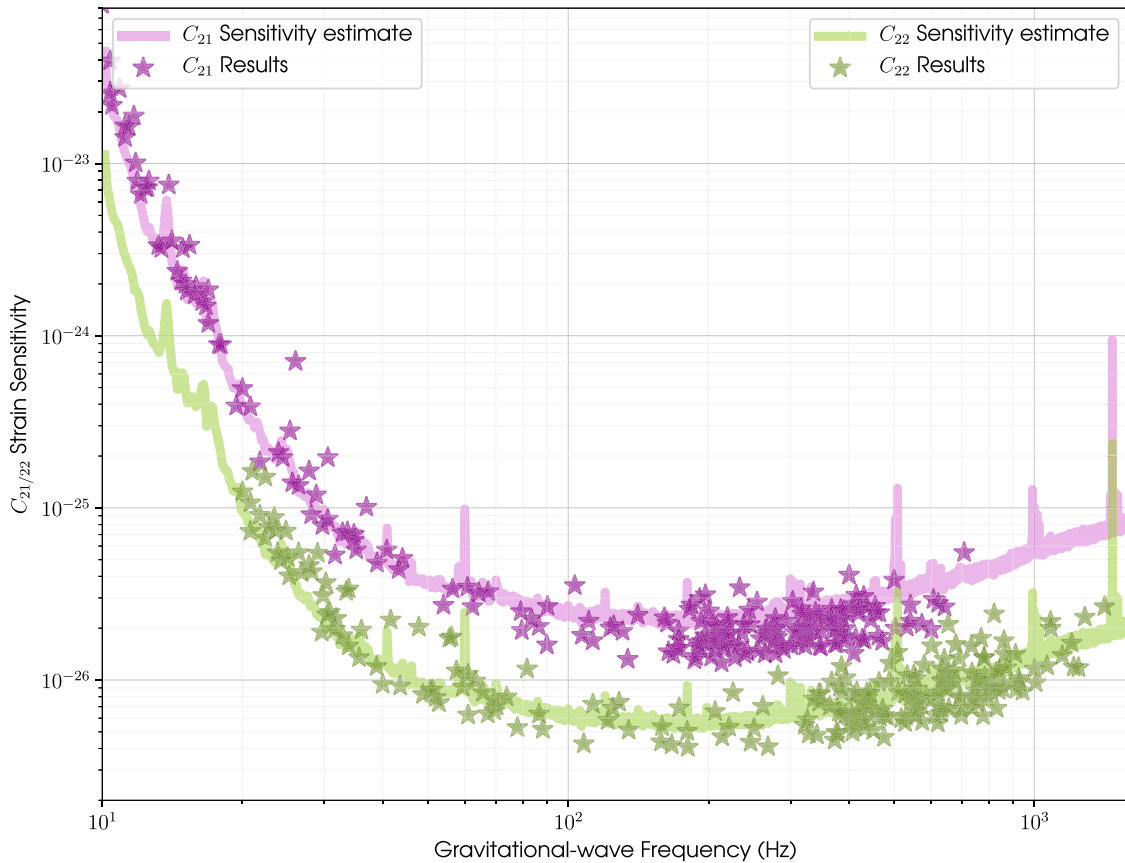


Figure 1. Upper limits on C_{21} and C_{22} for 222 pulsars. The stars show the observed 95% credible upper limits on observed amplitudes for each pulsar. The solid lines show an estimate of the expected sensitivity of the searches.

$(1-3) \times 10^{38} \text{ kg m}^2$ (see, e.g., Figures 4 and 7 of Worley et al. 2008 and Figures 6 and 7 of Bejger 2013). We do not incorporate these uncertainties into the results we present here, but they should be kept in mind when interpreting the limits.²⁰³ In the case of pulsar distances the references provided in Tables 1 and 2 should be consulted to provide an estimate of the associated uncertainty. These uncertainties dominate the few percent uncertainties arising from the calibration of the gravitational-wave detectors described in Section 2.1.

The $h_0^{95\%}$ results from the *Bayesian* analysis, recast as limits on Q_{22} and the fiducial ellipticity and assuming the distances given in Tables 1 and 2, are shown in Figure 4. The much lower limits on ε inferred for the MSPs easily follow from the frequency scaling seen in Equation (6).

3.1. Results Highlights

For decades, two of the most intriguing targets in searches for gravitational waves from pulsars have been the Crab and Vela pulsars (J0534+2200 and J0835–4510, respectively), due to their large spin-down luminosities. For these two pulsars, assuming emission from the $l = m = 2$ mode and with the phase precisely locked to the observed rotational phase, the limits observed using the initial LIGO and Virgo detectors in Abbott et al. (2008) and Abadie et al. (2011), respectively,

were lower than the equivalent spin-down limits. Using data from the O1 run, the observed limits were also below the spin-down limit for these two pulsars in searches where the strict phase locking of the observed rotational phase and gravitational-wave phase was relaxed (Abbott et al. 2017b).²⁰⁴

For the Crab pulsar, this analysis finds an observed 95% limit of $h_0^{95\%} = 1.9 \times 10^{-26}$ for the *Bayesian* analysis (with consistent values of 2.2×10^{-26} and 2.9×10^{-26} for the *F-statistic* and *5n-vector* analyses, respectively). This is 0.013 times the spin-down ratio, or, equivalently, it means that less than 0.017% of the available spin-down luminosity is emitted via gravitational waves (see Equation (7)). These limits are also well below less naive spin-down limits that can be calculated by taking into account the power radiated electromagnetically or through particle acceleration (Ostriker & Gunn 1969; Palomba 2000). As shown in Table 1, slightly tighter constraints are possible if one assumes that the orientation of the pulsar matches that derived from the observed orientation of its pulsar wind nebula (see Section 2.2.4). The above h_0 upper limit corresponds to limits on Q_{22} of $7.7 \times 10^{32} \text{ kg m}^2$ and an equivalent fiducial ellipticity of 1.0×10^{-5} . This mass quadrupole is almost in the range of maximum allowable quadrupoles for standard neutron star equations of state (see discussion in Section 1.2 and Johnson-McDaniel & Owen 2013).

²⁰³ From Equations (4), (5), and (9) it can be seen that fractional uncertainties on distance will scale directly into the uncertainties on ε , Q_{22} , and h_0^{sd} . Increasing the value of I_{zz}^{fid} will proportionally decrease the inferred ε value and increase the inferred spin-down limit by a factor given by the square root of the fractional increase compared to the canonical moment of inertia.

²⁰⁴ In the similar narrowband searches for the Crab pulsar in Abbott et al. (2008) and Aasi et al. (2015b) the limits were also below the spin-down limit, under the assumption that the orientation was restricted to that derived from the pulsar wind nebula (see Section 2.2.4).

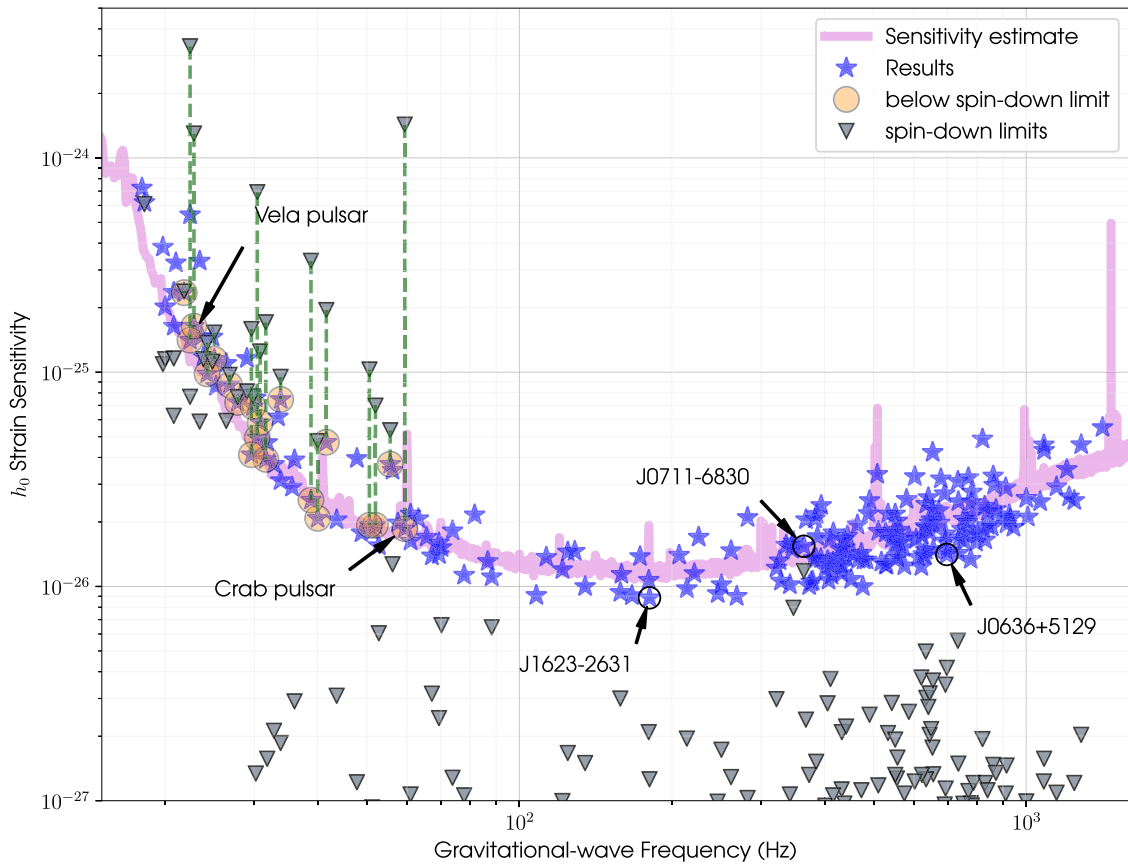


Figure 2. Upper limits on h_0 for 222 pulsars. The stars show the observed 95% credible upper limits on observed amplitude for each pulsar. The solid line shows an estimate of the expected sensitivity of the search. Triangles show the limits on gravitational-wave amplitude derived from each pulsar’s observed spin-down.

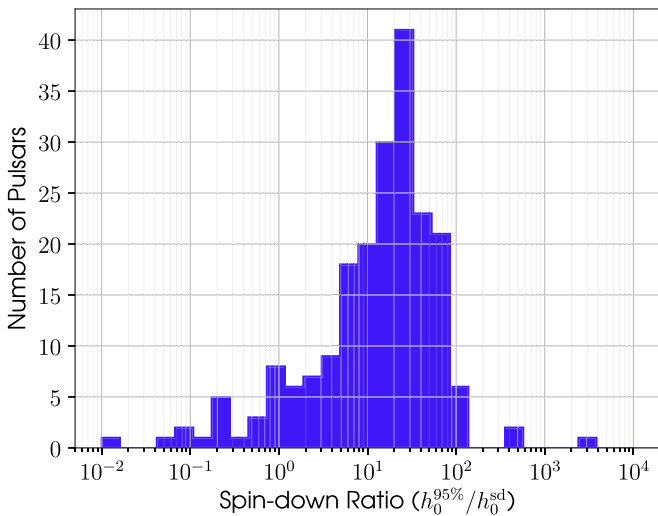


Figure 3. Histogram of ratios of upper limits on h_0 compared to the spin-down limit.

Similarly, for the Vela pulsar, this analysis finds an observed 95% limit of $h_0^{95\%} = 1.4 \times 10^{-25}$ for the *Bayesian* analysis (with broadly consistent values of 2.6×10^{-25} and 2.3×10^{-25} for the *F-statistic* and *5n-vector* analyses, respectively). This is 0.042 times the spin-down ratio, or, equivalently, it means that less than 0.18% of the available spin-down luminosity is emitted via gravitational waves. The above h_0 upper limit corresponds to limits on Q_{22} of $5.9 \times 10^{33} \text{ kg m}^2$ and an equivalent fiducial ellipticity of 7.6×10^{-5} .

Of all the pulsars in the analysis, the one with the smallest upper limit on h_0 is PSR J1623–2631 (with a rotational frequency of 90.3 Hz and distance of 1.8 kpc), with $h_0^{95\%} = 8.9 \times 10^{-27}$. The pulsar with the smallest limit on the Q_{22} mass quadrupole is PSR J0636+5129 (with a rotational frequency of 348.6 Hz and distance of 0.21 kpc), with $Q_{22}^{95\%}$ of 4.5×10^{29} and an equivalent fiducial ellipticity limit of 5.8×10^{-9} . These limits are only a factor of 3.4 above the pulsar’s spin-down limit. Of the MSPs in our search (which, as above, we take as any pulsar with $\dot{P} < 10^{-17} \text{ s s}^{-1}$), the one for which our limit is closest to the spin-down limit is J0711–6830 (with a rotational frequency of 182.1 Hz and a distance of 0.11 kpc). It is within a factor of 1.3 of the spin-down limit, with an observed upper limit of $h_0^{95\%} = 1.5 \times 10^{-26}$ and derived limits on Q_{22} and ellipticity of $9.3 \times 10^{29} \text{ kg m}^2$ and 1.2×10^{-8} , respectively.²⁰⁵ The upper bound on possible neutron star moments of inertia is roughly $3 \times 10^{38} \text{ kg m}^2$, for which the fiducial spin-down limit could be increased by a factor of $\sqrt{3} \approx 1.7$, which would be greater than our upper limit.

²⁰⁵ It is interesting to note that in Abbott et al. (2017a) PSR J0437–4715 was the MSP with an observed upper limit closest to its spin-down limit, being only a factor of 1.4 above that value, while J0711–6830 had a limit that was a factor of ~ 20 above its spin-down limit. For J0437–4715, despite now having an improved upper limit on the gravitational-wave amplitude, the correction of the observed period derivative to the intrinsic period derivative has lowered the spin-down limit by roughly a factor of two. For J0711–6830 the distance estimated using the YMW16 Galactic electron density model (Yao et al. 2017) is about a factor of 9 closer than that estimated with the previously used NE2001 model (Cordes & Lazio 2002).

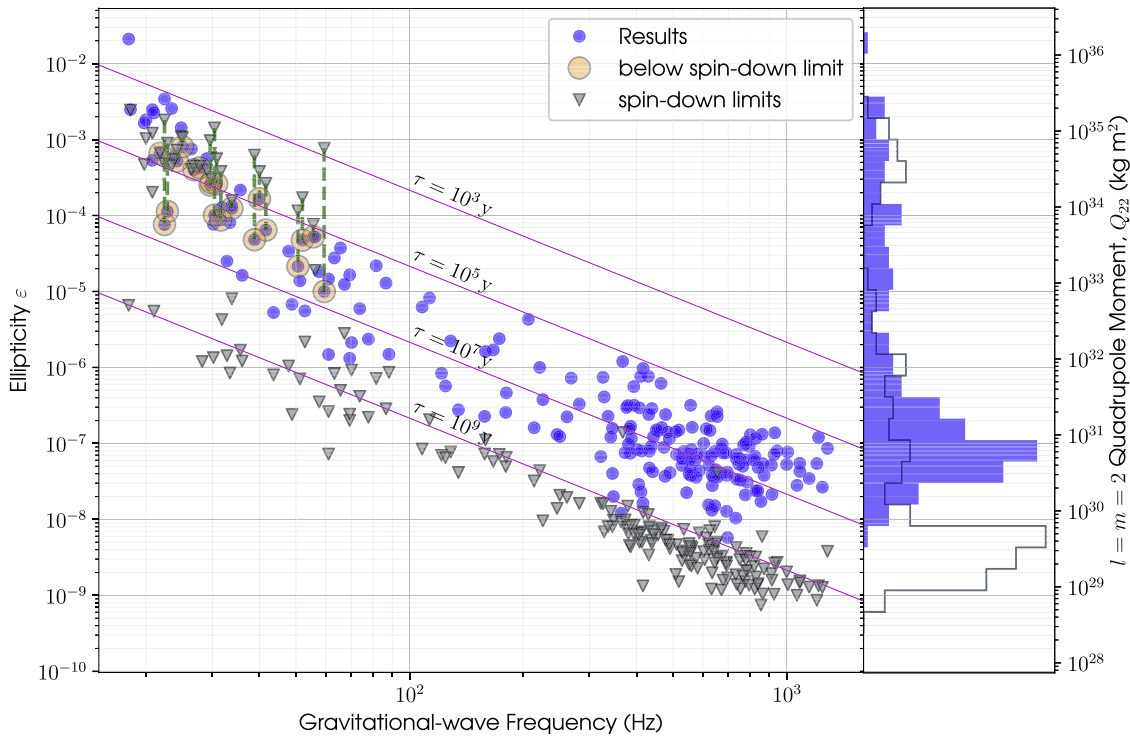


Figure 4. Upper limits on mass quadrupole Q_{22} and fiducial ellipticity ϵ for 222 pulsars. The filled circles show the limits as derived from the observed upper limits on the gravitational-wave amplitude h_0 assuming the canonical moment of inertia and distances given in Tables 1 and 2. Triangles show the limits derived from each pulsar’s observed spin-down. The diagonal lines show contours of equal characteristic age τ assuming that braking is entirely through gravitational-wave emission. The distributions of these limits are also shown in histogram form to the right of the figure, with the filled and unfilled histograms showing our observed limits and the spin-down limits, respectively.

Similarly to Abbott et al. (2017a), our most stringent limits on ellipticity for MSPs still imply limits on the internal toroidal magnetic field strength of $\lesssim 10^9$ T (or 10^{13} G) (applying Equation (2.4) of Cutler 2002, and assuming a superconducting core). The method in Mastrano & Melatos (2012) could also be applied to these results to constrain the ratio of the poloidal magnetic field energy to the total field energy.

For the searches that include the $l = 2$, $m = 1$ mode, the smallest upper limit on the C_{21} amplitude is for PSR J1744–7619 (with a rotational frequency of 213.3 Hz), at $C_{21}^{95\%} = 1.3 \times 10^{-26}$. As C_{21} and C_{22} are not very strongly correlated, the upper limits on C_{22} are generally consistent with $C_{22}^{95\%} \approx h_0^{95\%}/2$.

4. Discussion

In this paper we have used data from the first two observation runs of Advanced LIGO (O1 and O2) to update the upper limits on the gravitational-wave amplitude h_0 for emission from the $l = m = 2$ mass quadrupole for 167 pulsars. This compares to 271 results presented previously in Aasi et al. (2014) (using data from the initial runs of the LIGO [Abbott et al. 2009] and Virgo [Accadia et al. 2012] detectors, S1–6 and VSR1–4) and Abbott et al. (2017a) (using data from the first observing run, O1, of the advanced LIGO detectors; Aasi et al. 2015a; Abbott et al. 2016). New upper limits on h_0 have been set for a further 55 pulsars. Other than the results in Pitkin et al. (2015), we have also presented the first comprehensive set of results for searches that also include the possibility of emission from the $l = 2$, $m = 1$ mode at the pulsar’s rotation frequency. These are expressed as upper limits on two amplitude parameters C_{21} and C_{22} defined in Jones (2015). We find no

strong evidence for gravitational-wave emission from any pulsar in the searches purely for the $l = m = 2$ mode, or both the $l = 2$, $m = 1, 2$ modes.

Further analyses of this data set are possible. For example, we have not presented any updated results regarding potential emission from nontensorial polarization modes as performed in Abbott et al. (2018a). In addition to this, the results from all pulsars could be combined in a way, such as that described in Pitkin et al. (2018), to constrain the underlying pulsar ellipticity distribution and determine whether the ensemble of all pulsars provides evidence for any gravitational-wave signal.

With the MSPs PSR J0636+5129 and PSR J0711–6830 within a factor of ~ 3 of their respective spin-down limits, the imminent third observing run of the advanced LIGO and Virgo detectors (O3) could allow us to obtain limits below the spin-down limit for an MSP for the first time. This offers the intriguing possibility for signal detection from these extremely smooth objects, with spin-down-derived ellipticities of a few $\times 10^{-9}$. The O3 sensitivity could also bring the limits for the Crab pulsar into the range of mass quadrupoles allowed by reasonably standard neutron star equations of state.

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO, as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors

gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS), and the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies, as well as by the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación, the Vicepresidència i Conselleria d’Innovació Recerca i Turisme and the Conselleria d’Educació i Universitat del Govern de les Illes Balears, the Conselleria d’Educació Investigació Cultura i Esport de la Generalitat Valenciana, the National Science Centre of Poland, the Swiss National Science Foundation (SNSF), the Russian Foundation for Basic Research, the Russian Science Foundation, the European Commission, the European Regional Development Funds (ERDF), the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the National Research, Development and Innovation Office Hungary (NKFI), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the Natural Science and Engineering Research Council Canada, the Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, Innovations, and Communications, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Leverhulme Trust, the Research Corporation, the Ministry of Science and Technology (MOST), Taiwan, and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, MPS, INFN, CNRS, and the State of Niedersachsen/Germany for provision of computational resources.

The Nançay Radio Observatory is operated by the Paris Observatory, associated with the French CNRS. We acknowledge financial support from the “Programme National Gravitation, Références, Astronomie, Métrologie (PNGRAM) and “Programme National Hautes Énergies (PNHE) of CNRS/INSU, France. Work at the Naval Research Laboratory is supported by NASA. We gratefully acknowledge the continuing contributions of the NICER science team in providing up-to-date spin ephemerides for X-ray-bright pulsars of interest to the LVC. NICER is a 0.2–12 keV X-ray telescope operating on the International Space Station. The NICER mission and portions of the NICER science team activities are funded by NASA.

This work has been assigned LIGO document number LIGO-P1800344.

Facilities: Arecibo, *Fermi*, LIGO, Lovell, Molonglo Observatory, MtPO:26 m, NICER, NRT, Parkes.

Software: Much of the analysis described in the paper was performed using the publicly available LALSUITE library (LIGO Scientific Collaboration 2018). Production of many of the pulsar timing ephemerides used in this analysis was performed with TEMPO²⁰⁶ and TEMPO2 (Hobbs et al. 2006b). Figures in this publication have been produced using Matplotlib (Hunter 2007).

²⁰⁶ <http://tempo.sourceforge.net/>

Appendix A Definitions

Here we will define some of the standard useful quantities reported and used in our results (many of these are defined in Aasi et al. 2014). The standard definition for the gravitational-wave amplitude from the $l = m = 2$ mass quadrupole for a nonprecessing triaxial star rotating about a principal axis is

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz}^{\text{fid}} \varepsilon f_{\text{rot}}^2}{d} \approx 4.23 \times 10^{-26} \left(\frac{1 \text{ kpc}}{d} \right) \times \left(\frac{I_{zz}^{\text{fid}}}{10^{38} \text{ kg m}^2} \right) \left(\frac{\varepsilon}{10^{-6}} \right) \left(\frac{f_{\text{rot}}}{100 \text{ Hz}} \right)^2, \quad (3)$$

where d is the pulsar distance, I_{zz}^{fid} is the fiducial component of the moment-of-inertia tensor ellipsoid about the rotation axis, f_{rot} is the pulsar’s rotation frequency, and ε is the star’s fiducial ellipticity (see, e.g., Johnson-McDaniel 2013) defined as

$$\varepsilon = \frac{|I_{xx} - I_{yy}|}{I_{zz}^{\text{fid}}}, \quad (4)$$

where I_{xx} and I_{yy} are the true moments of inertia about the principal axes other than the rotation axis.

The gravitational-wave amplitude is related to the $l = m = 2$ mass quadrupole Q_{22} via

$$Q_{22} \equiv I_{zz}^{\text{fid}} \varepsilon \sqrt{\frac{15}{8\pi}} = h_0 \left(\frac{c^4 d}{16\pi^2 G f_{\text{rot}}^2} \right) \sqrt{\frac{15}{8\pi}} \approx 1.83 \times 10^{32} \left(\frac{h_0}{10^{-25}} \right) \left(\frac{d}{1 \text{ kpc}} \right) \left(\frac{100 \text{ Hz}}{f_{\text{rot}}} \right)^2 \text{ kg m}^2, \quad (5)$$

where we use the definition of the mass quadrupole used in Owen (2005) and defined in Ushomirsky et al. (2000). Alternatively, we can use h_0 to calculate the fiducial ellipticity, defined as

$$\varepsilon = \frac{h_0}{I_{zz}^{\text{fid}}} \left(\frac{c^4 d}{16\pi^2 G f_{\text{rot}}^2} \right) \approx 2.36 \times 10^{-6} \left(\frac{h_0}{10^{-25}} \right) \times \left(\frac{d}{1 \text{ kpc}} \right) \left(\frac{100 \text{ Hz}}{f_{\text{rot}}} \right)^2 \left(\frac{10^{38} \text{ kg m}^2}{I_{zz}^{\text{fid}}} \right). \quad (6)$$

If emission of gravitational radiation via the $l = m = 2$ mass quadrupole is considered to be the sole energy loss mechanism for a pulsar, then by equating the gravitational-wave luminosity (see, e.g., Equation (4) of Aasi et al. 2014)

$$\dot{E}_{\text{gw}} = \frac{8\pi^2 c^3}{5G} f_{\text{rot}}^2 h_0^2 d^2 \approx 6.07 \times 10^{29} \times \left(\frac{f_{\text{rot}}}{100 \text{ Hz}} \right)^2 \left(\frac{h_0}{10^{-25}} \right)^2 \left(\frac{d}{1 \text{ kpc}} \right)^2 \text{ W}, \quad (7)$$

with the loss of kinetic energy inferred from the the first frequency derivative \dot{f}_{rot} of the pulsar

$$\dot{E}_{\text{KE}} = 4\pi^2 I_{zz}^{\text{fid}} f_{\text{rot}} |\dot{f}_{\text{rot}}| \approx 3.95 \times 10^{30} \times \left(\frac{I_{zz}^{\text{fid}}}{10^{38} \text{ kg m}^2} \right) \left(\frac{f_{\text{rot}}}{100 \text{ Hz}} \right) \left(\frac{|\dot{f}_{\text{rot}}|}{10^{-11} \text{ Hz s}^{-1}} \right) \text{ W}, \quad (8)$$

one can define the spin-down limit on h_0 , where

$$h_0^{\text{sd}} = \frac{1}{d} \left(\frac{5 G I_{zz}^{\text{fid}} |\dot{f}_{\text{rot}}|}{2 c^3 f_{\text{rot}}} \right)^{1/2} \approx 2.55 \times 10^{-25} \left(\frac{1 \text{ kpc}}{d} \right) \times \left(\frac{I_{zz}^{\text{fid}}}{10^{38} \text{ kg m}^2} \right)^{1/2} \left(\frac{100 \text{ Hz}}{f_{\text{rot}}} \right)^{1/2} \left(\frac{|\dot{f}_{\text{rot}}|}{10^{-11} \text{ Hz s}^{-1}} \right)^{1/2}. \quad (9)$$

By equating Equations (3) and (9), we can rearrange and get spin-down limits on Q_{22} as

$$Q_{22}^{\text{sd}} = \left(\frac{75}{4096 \pi^5} \frac{I_{zz}^{\text{fid}} c^5 \dot{f}_{\text{rot}}}{G f_{\text{rot}}^5} \right)^{1/2} \approx 4.66 \times 10^{32} \times \left(\frac{I_{zz}^{\text{fid}}}{10^{38} \text{ kg m}^2} \right)^{1/2} \left(\frac{100 \text{ Hz}}{f_{\text{rot}}} \right)^{5/2} \left(\frac{|\dot{f}_{\text{rot}}|}{10^{-11} \text{ Hz s}^{-1}} \right)^{1/2} \text{ kg m}^2 \quad (10)$$

and on ε as

$$\varepsilon^{\text{sd}} = \left(\frac{5}{512 \pi^4} \frac{c^5 \dot{f}_{\text{rot}}}{I_{zz}^{\text{fid}} G f_{\text{rot}}^5} \right)^{1/2} \approx 6.03 \times 10^{-6} \times \left(\frac{10^{38} \text{ kg m}^2}{I_{zz}^{\text{fid}}} \right)^{1/2} \left(\frac{100 \text{ Hz}}{f_{\text{rot}}} \right)^{5/2} \left(\frac{|\dot{f}_{\text{rot}}|}{10^{-11} \text{ Hz s}^{-1}} \right)^{1/2}, \quad (11)$$

where it is interesting to note that these are independent of the distance to the pulsar.

For a triaxial source not rotating about a principal axis, and emitting via both the $l = 2, m = 1$ and the $l = m = 2$ quadrupole modes, the relations between the waveform amplitudes and phases given in Equations (1) and (2) and the source moment-of-inertia tensor components and Euler orientation angle θ are described in Section 3.1 of Jones (2015). We will not repeat the relationships here, but note that how to convert between the two definitions is described in detail in the Appendix of Pitkin et al. (2015).

Appendix B Priors

In this appendix we will detail the prior probability distributions used on parameters by the *Bayesian* and *5n-vector* analysis methods. The use of these priors for the *Bayesian* search is discussed in Pitkin et al. (2017), and the motivation behind some of the prior limits used is discussed in Jones (2015) and Pitkin et al. (2015). For the *5n-vector* pipeline, priors are set on signal initial phase ϕ_0 and polarization parameters $\psi, \cos \iota$ in the computation of upper limits.

For the gravitational-wave-specific orientation parameters for searches purely from the $l = m = 2$ mode, the following priors have been used.²⁰⁷ The initial rotational phase of the pulsar at a given epoch ϕ_0 , the polarization angle ψ , and the cosine of the inclination angle $\cos \iota$ have uniform priors²⁰⁸

given by

$$\begin{aligned} \phi_0 &\sim \mathcal{U}(0, \pi), \\ \psi &\sim \mathcal{U}(0, \pi/2), \\ \cos \iota &\sim \mathcal{U}(-1, 1). \end{aligned}$$

For the *Bayesian* search, the prior on the gravitational-wave amplitude h_0 is based on observed upper limits, or sensitivity estimates, from previous LIGO and Virgo runs. The form of the prior is given by a Fermi–Dirac-type probability distribution (see, e.g., that used in Middleton et al. 2016) as described in Pitkin et al. (2017), which has a flat region followed by an exponential decay region but is nonzero for all positive values. It is defined as

$$p(x|\sigma, \mu, I) = \begin{cases} \frac{1}{\sigma \ln(1 + e^{\mu/\sigma})} (e^{(x-\mu)/\sigma} + 1)^{-1} & \text{if } x \geq 0, \\ 0 & \text{otherwise,} \end{cases} \quad (12)$$

where μ gives the value at which the distribution decays to 50% of its maximum value and σ controls the width of the band over which the bulk of the decay happens. The band around μ over which the probability density falls from 97.5% to 2.5% of its peak value is given by $\mu \pm 7.33\mu/2r$, where $r = \mu/\sigma$. In our case we specify that this fall-off happens over a range that is 40% of the value of μ , so that $r = 7.33/(2 \times 0.4) = 9.1625$. The value of μ is set by finding the value that produces a specific bound within which 95% of the probability is constrained (bounded by zero at the lower end) given the previous value of r . The specific bound is that based on the sensitivity for each pulsar (i.e., the 95% upper limits on h_0 ; see Appendix C) that would have been expected if using data from the sixth LIGO science run and fourth Virgo science run, scaled up by a factor of 25 to be conservative and make sure that the likelihood is well within the flat part of the prior distribution, while disfavoring arbitrarily large values.²⁰⁹

For the searches that include both the $l = 2, m = 1, 2$ modes the phase and orientation angle priors have been given by

$$\begin{aligned} \Phi_{21}^C &\sim \mathcal{U}(0, 2\pi), \\ \Phi_{22}^C &\sim \mathcal{U}(0, 2\pi), \\ \psi &\sim \mathcal{U}(0, \pi/2), \\ \cos \iota &\sim \mathcal{U}(-1, 1). \end{aligned}$$

As discussed above, in the *Bayesian* method the priors on the amplitude parameters C_{21} and C_{22} have used Fermi–Dirac probability distributions for which the parameters have been set in the same way as done for h_0 . However, in this case the sensitivity estimate used for h_0 is assumed to be valid for C_{21} and C_{22} , while in reality there are factors of a few differences. These differences are allowable given the scaling factor used and the sensitivity improvements over S6.

In our searches we make use of the pulsar rotational phase parameters (frequency, frequency derivatives, sky location, proper motion, and Keplerian and relativistic binary system

²⁰⁷ In the notation used here \sim stands for “has the probability distribution of,” and $\mathcal{U}(a, b)$ is a continuous uniform distribution with a constant probability $1/(b-a)$ for $x \in [a, b]$.

²⁰⁸ The polarization angle ψ and orientation angle ι have a joint prior that is uniform over a sphere, with degeneracies when thinking purely in terms of the gravitational-wave waveforms described in Jones (2015), but these can be reparameterized to independent uniform priors if in terms of $\cos \iota$.

²⁰⁹ A discussion about a choice between a uniform prior and a uniform in logarithm prior for the amplitude parameter is given in Appendix B of Isi et al. (2017).

orbital parameters if relevant) derived from electromagnetic observation of pulse times of arrival. These parameters are obtained by fitting the phase model to the times of arrival using software such as TEMPO2 Hobbs et al. (2006b) to produce ephemeris files, and these fits include uncertainty estimates. In most cases, and where it is computationally feasible, for any combination of parameters in the ephemeris files that have been refit (i.e., a new estimate has been performed using data that matched the requirements of our search, such as being concurrent with the LIGO observing runs) we include a multivariate Gaussian prior in our analysis, for which the diagonal of the covariance matrix is derived from the uncertainties in the ephemeris file and taking them to be one standard deviation values. In the prior covariance matrix we assume no correlations between parameters except in two pairs of cases for pulsars in binary systems; for very low eccentricity systems ($e < 0.001$) with refitted uncertainties on both the time and angle of periastron, or with refitted values on the period and time derivative of the angle of periastron, the covariance matrix is set such as to make these pairs fully correlated.

As described in Abbott et al. (2010, 2017a) and Aasi et al. (2014), there are some pulsars for which we can place tighter constraints on their orientation. In particular, the inclination angle and gravitational-wave polarization angle can be assumed to be measured by modeling X-ray observations of their surrounding pulsar wind nebulae (Ng & Romani 2004, 2008). In this analysis, for PSR J0205+6449, PSR J0534+2200, PSR J0835–4510, PSR J1952+3252, and PSR J2229+6114, in addition to a search using the above priors, we also perform parameter estimation using the restricted priors given in Table 3 of Abbott et al. (2017a), based on values taken from Ng & Romani (2008). In these cases the priors are on the inclination angle ι rather than its cosine. The prior probability distribution on ψ is a unimodal Gaussian, but that on ι is given by the sum of a pair of Gaussian distributions with different means, which is required to account for the fact that rotation directions of the stars are unknown (Jones 2015).

Appendix C Sensitivity Estimates

Here we will describe the expected sensitivity of the Bayesian analysis in searches for signals purely from the $l = m = 2$ mode, and for coherent searches for signals at both the $l = 2, m = 1, 2$ modes. We define the expected sensitivity based on the observation time (T_{obs}) weighted noise power spectral density $S_n(f)$ as a function of frequency f , such that for a single detector

$$\langle h(f) \rangle = D \sqrt{\frac{S_n(f)}{T_{\text{obs}}}}, \quad (13)$$

where in our case $\langle h(f) \rangle$ is the expected 95% credible upper limit on amplitude and D is an empirically derived scaling factor (similar to the sensitivity depth defined in Behnke et al. 2015). When combining data from multiple detectors and observing runs, for which the power spectral densities will be different, we take the harmonic mean of the time-weighted power spectral densities. For example, for a set of different noise power spectral densities $S_{n_i}(f)$ associated with observation times T_{obs_i} we would have

$$\langle h(f) \rangle = D \left(\sum_{i=1}^N \left[\frac{S_{n_i}(f)}{T_{\text{obs}_i}} \right]^{-1} \right)^{-1/2}. \quad (14)$$

For a search for emission from the $l = m = 2$ mode, where the limit is on the gravitational-wave amplitude h_0 (see Equation (3)), it was shown in Dupuis & Woan (2005) that $D \approx 10.8 \pm 0.2$, based on the simulations containing purely Gaussian noise with variance drawn from a known power spectral density, marginalized over orientations and averaged over the sky. If we instead take the median rather than the mean over a similar set of simulations, to suppress any outlier values, we find $D \approx 10.4$ (see left panel of Figure 5), which is used here in producing the sensitivity curve in Figure 2.

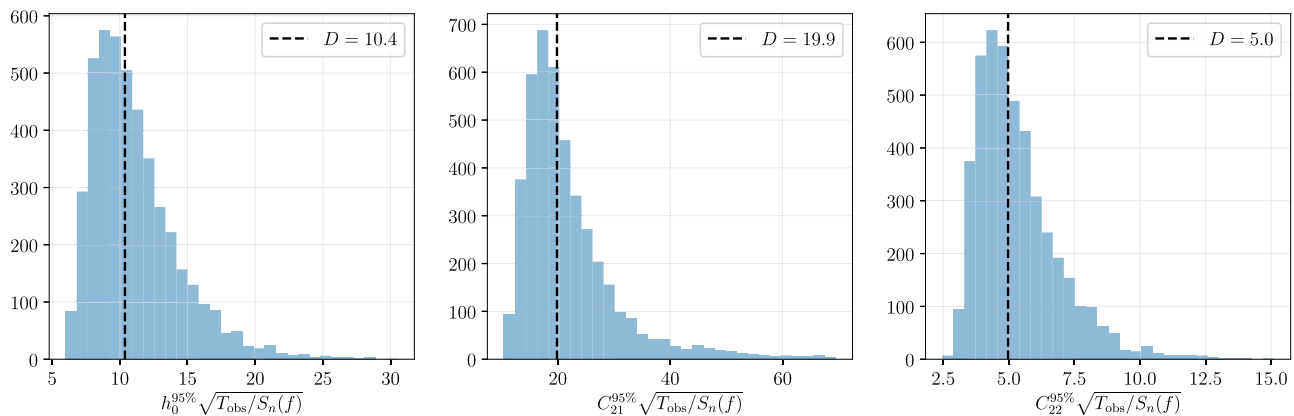


Figure 5. Distributions of 95% credible upper limits on h_0 (left), C_{21} (middle), and C_{22} (right) scaled by the observation times and noise power spectral density for a set of simulations consisting of Gaussian noise. To average over effects of different antenna patterns in performing parameter estimation, each simulation assumes a random source sky location for a uniform distribution over the sky.

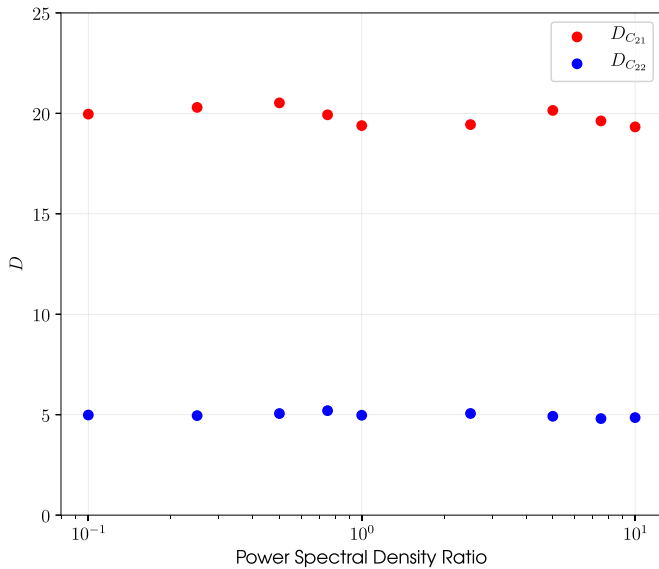


Figure 6. D scale factor for the C_{21} and C_{22} upper limits as a function of the power spectral density ratio between the data at equivalents of the rotation frequency and twice the rotation frequency.

To estimate the sensitivity to the C_{21} and C_{22} amplitude parameters for an $l = 2$, $m = 1, 2$ mode search, we have performed similar simulations to those described above. A search including both modes is not completely independent for each mode, as there are common orientation parameters. Hence, we also wanted to investigate whether the sensitivity at either amplitude is affected by the noise level at the other amplitude. We generated simulations consisting of independent Gaussian noise in two data streams: one equivalent to the data at the rotation frequency and another equivalent to the data at twice the rotation frequency. For the data stream at twice the rotation frequency the noise was always drawn from a Gaussian distribution with the same variance defined by a power spectral density of $10^{-48} \text{ Hz}^{-1/2}$. For the data stream at the rotation frequency we created multiple sets of 500 instantiations where the noise was drawn from a Gaussian distribution with a variance defined by a power spectral density of $10^{-48} x \text{ Hz}^{-1/2}$, where for each set of 500 x was a different factor between 0.1 and 10. The D scale factor from Equation (13) for both the C_{21} and C_{22} amplitude upper limit for each set of 500 simulations and as a function of x is shown in Figure 6. It can be seen that there is no obvious correlation between the power spectral density ratio x and the value of D , which suggests that the upper limits on the two amplitudes are actually largely independent.

We see from Figures 5 and 6 that the value of D used to estimate the sensitivity for C_{21} is 19.9, and the value of D used to estimate the sensitivity for C_{22} is 5.0. These values have been used when producing the sensitivity curves in Figure 1.

Appendix D Mixed Bayesian/Frequentist Upper Limit Computation for the $5n$ -vector Method

Given a measured value S^* of a detection statistic \mathcal{S} , the frequentist upper limit at a given confidence level α is defined as that value of signal amplitude h_{ul} such that a signal with amplitude $h_0 > h_{\text{ul}}$ produces a value of the detection statistic bigger than S^* in a fraction α of a large number of repeated experiments: $P(S > S^* | h_0 > h_{\text{ul}}) = \alpha$. Typically, the upper limit is computed using Neyman’s rule for the construction of confidence intervals (Neyman 1937). This classical frequentist upper limit has the following well-known and unpleasant feature: if the value of the detection statistic S^* falls in the first $1-\alpha$ quantile of its noise-only distribution, the resulting upper limit is exactly zero. This behavior, although legitimate in the frequentist framework, poses a problem, for instance, when upper limits obtained in the analysis of data sets with different sensitivity are compared. It may happen that, due to a noise fluctuation, the upper limit set for the more noisy data is below that computed for the less noisy one. This kind of problem may happen also for Bayesian upper limits, but it is exacerbated in the classical frequentist case.

The unwanted features of the classical Neyman’s construction have been overcome in the Feldman–Cousins unified approach, where, using the freedom inherent in Neyman’s construction, a method to obtain a unified set of classical confidence intervals for computing both upper limits and two-sided confidence intervals has been obtained (Feldman & Cousins 1998). The Feldman–Cousins approach sometimes is difficult to implement and, similarly to Neyman’s approach, does not allow accounting for nonuniform prior distributions for nuisance parameters.

We have developed an alternative method for setting upper limits on signal amplitude that keeps the advantages of the frequentist approach, like the ease of implementation and computational speed, while avoiding its problems. The basic idea is that of computing the posterior distribution of the signal amplitude conditioned to the measured value of the detection statistic. The main steps of the procedure can be summarized as follows.

We consider a set of possible signal amplitudes H_0 . For each amplitude we generate several signals with polarization parameters distributed according to given prior distributions, and for each signal we compute the corresponding value of the detection statistic. Hence, the probability distribution of the detection statistic, for the different signal amplitudes, can be built; see Figure 7.

For each distribution we determine the value corresponding to the measured detection statistic $p(S^* | H_0)$. By multiplying each value by the prior probability density of the signal amplitude, $p(H_0)$, and normalizing, we obtain the posterior probability distribution for the signal amplitude: $p(H_0 | S^*) \propto p(S^* | H_0) p(H_0)$; see Figure 8.

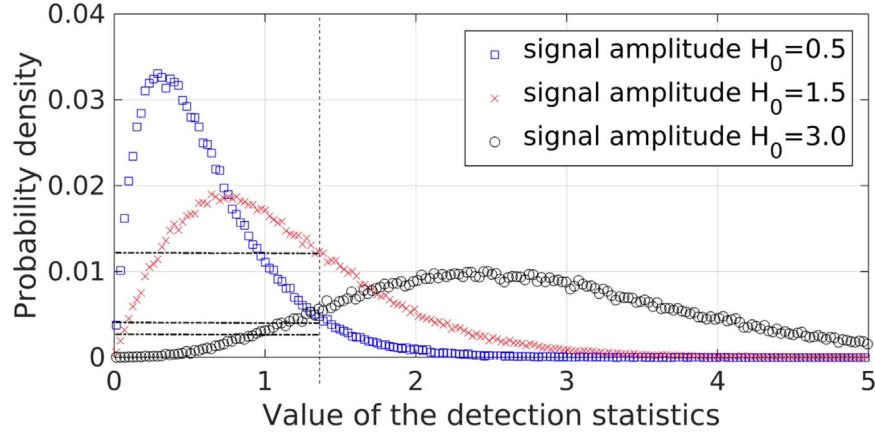


Figure 7. Probability distributions of the detection statistic \mathcal{S} after having injected into Gaussian noise with $\sigma = 1$ signals with three different amplitudes. Given the measured value of the detection statistic \mathcal{S}^* (shown by the vertical dashed line), the corresponding values of probability density for the various signal amplitudes are determined (shown by the horizontal dot-dashed lines).

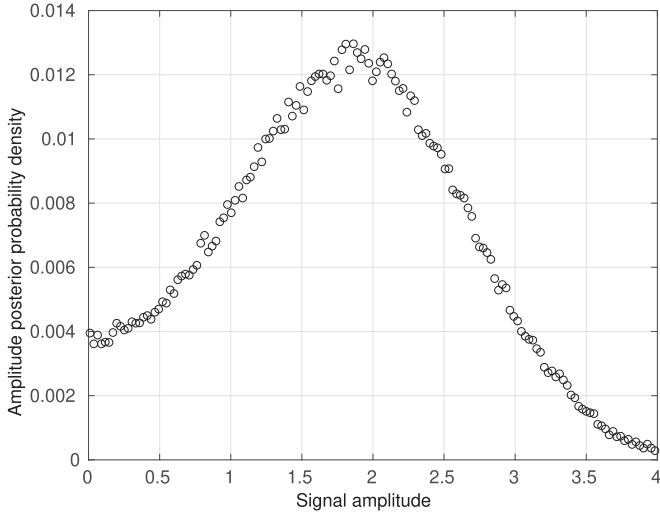


Figure 8. Posterior probability distribution of the signal amplitude for the given measured value \mathcal{S}^* of the detection statistic.

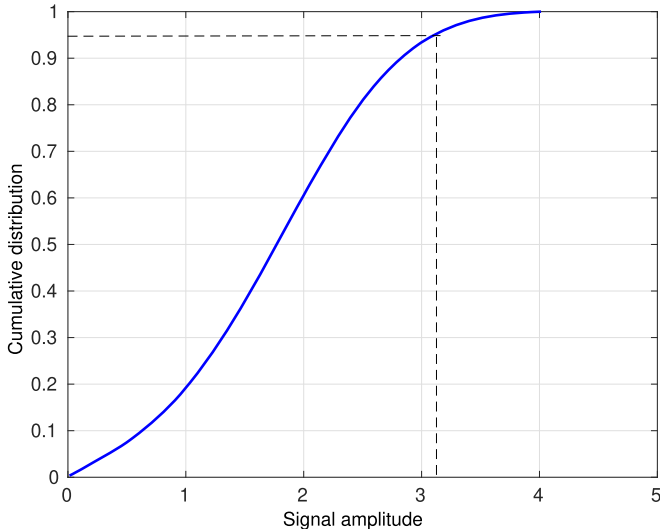


Figure 9. Cumulative posterior probability distribution of the signal amplitude. The amplitude value corresponding to 95% of the cumulative is the wanted credible upper limit.

We then calculate the cumulative probability distribution and obtain the amplitude value corresponding to a given probability, e.g., 0.95; see Figure 9. This is the 95% credible upper limit.

Appendix E

Amplitude Conversion Factors for the $5n$ -vector Method

The $5n$ -vector method uses a nonstandard formalism to describe the gravitational-wave signal, based on the concept of polarization ellipse (Astone et al. 2010; Abadie et al. 2011; Aasi et al. 2014). In this formalism the signal strain is given by the real part of

$$h(t) = H_0(H_+e^+ + H_\times e^\times)e^{i(\omega_0(t)t + \Phi_0)}, \quad (15)$$

where $\omega_0(t)$ is the signal angular frequency, $e^{+/\times}$ are the two basis polarization tensors, Φ_0 is the signal phase at the time $t = 0$, and the two complex amplitudes H_+ , H_\times are given by

$$H_+ = \frac{\cos 2\psi - \eta \sin 2\psi}{\sqrt{1 + \eta^2}}, \quad H_\times = \frac{\sin 2\psi + \eta \cos 2\psi}{\sqrt{1 + \eta^2}}, \quad (16)$$

in which $\eta \in [-1, 1]$ is the ratio of the polarization ellipse semiminor to semimajor axis and the polarization angle ψ defines, as usual, the direction of the major axis with respect to the celestial parallel of the source (measured counterclockwise). The signal described by Equation (15) is general, i.e., does not assume any specific emission mechanism by a spinning neutron star. Assuming a triaxial star spinning about a principal axis of inertia, the overall amplitude H_0 is related to the standard h_0 by

$$h_0 = \frac{2H_0}{\sqrt{1 + 6\cos^2 \iota + \cos^4 \iota}}. \quad (17)$$

For the emission at the star's rotational frequency of the $l = 2$, $m = 1$ harmonic mode (see Equation (1)), the relation between H_0 and the amplitude C_{21} is given by

$$C_{21} = \frac{2H_0}{\sqrt{1 - \cos^4 \iota}}. \quad (18)$$

As discussed in, e.g., Aasi et al. (2014), upper limits are computed on H_0 and then converted to h_0 or C_{21} using Equations (17) and (18), where the functions of ι are replaced by their mean value: $h_0^{95\%} \simeq 1.37H_0^{95\%}$ and $C_{21}^{95\%} \simeq 1.31H_0^{95\%}$.

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