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Diving below the spin-down limit: Constraints on gravitational waves from the energetic young pulsar PSR J0537−6910

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ABSTRACT

We present a search for quasi-monochromatic gravitational-wave signals from the young, energetic X-ray pulsar PSR J0537−6910 using data from the second and third observing runs of LIGO and Virgo. The search is enabled by a contemporaneous timing ephemeris obtained using *NICER* data. The *NICER* ephemeris has also been extended through October 2020 and includes three new glitches. PSR J0537−6910 has the largest spin-down luminosity of any pulsar and exhibits frequent and strong glitches. Analyses of its long-term and inter-glitch braking indices provide intriguing evidence that its spin-down energy budget may include gravitational-wave emission from a time-varying mass quadrupole moment. Its 62 Hz rotation frequency also puts its possible gravitational-wave emission in the most sensitive band of the LIGO/Virgo detectors. Motivated by these considerations, we search for gravitational-wave emission at both once and twice the rotation frequency from PSR J0537−6910. We find no signal, however, and report upper limits. Assuming a rigidly rotating triaxial star, our constraints reach below the gravitational-wave spin-down limit for this star for the first time by more than a factor of two and limit gravitational waves from the $l = m = 2$ mode to account for less than 14% of the spin-down energy budget. The fiducial equatorial ellipticity is constrained to less than about 3×10^{-5}, which is the third best constraint for any young pulsar.

Keywords: gravitational waves — pulsars: general — pulsars: individual (PSR J0537−6910) — stars: neutron

1. INTRODUCTION

The young (1–5 kyr) energetic pulsar PSR J0537−6910 (Wang & Gotthelf 1998; Chen et al. 2006) resides in the Large Magellanic Cloud at a distance of 49.6 kpc (Pietrzyński et al. 2019). Its pulsations are only detectable at X-ray energies, and the pulsar was first observed by Marshall et al. (1998) using the *Rossi X-ray Timing Explorer* (*RXTE*) during searches for pulsations from the remnant of SN1987A. Further observations with *RXTE*, prior to its decommissioning in early 2012, revealed that PSR J0537−6910 often undergoes sudden changes in rotation frequency, i.e., glitches, at a rate of more than three per year, and exhibits interesting inter-glitch behavior (Marshall et al. 2004; Middleditch et al. 2006; Andersson et al. 2018; Antonopoulou et al. 2018; Ferdman et al. 2018). Observations of the pulsar resumed from 2017-2020 using the *Neutron star Interior Composition Explorer* (*NICER*) on board the International Space Station (Gendreau et al. 2012), which revealed more glitches and a continuation of the timing behavior seen with *RXTE* (Ho et al. 2020b).

PSR J0537−6910 is a particularly intriguing potential gravitational-wave source. It is the fastest-spinning known young pulsar (with rotation frequency $f_{\rm rot} = 62$ Hz), which places its gravitational-wave frequency f (e.g., at twice $f_{\rm rot}$; see Section 2.1) in the most sensitive band of ground-based gravitational-wave detectors. PSR J0537−6910 also has the highest spin-down luminosity ($\dot{E} = 4.9 \times 10^{38}$ erg s^{-1}) among the ∼2900 known pulsars in the ATNF Pulsar Catalogue (Manchester et al. 2005). Its spin-down behavior appears to be driven by a process other than pure electromagnetic dipole radiation loss (at constant stellar magnetic field and moment of inertia). Specifically, its (long-term) braking index $n \equiv f_{\rm rot}\ddot{f}_{\rm rot}/\dot{f}^2_{\rm rot} = -1.25 \pm 0.01$, as measured over more than 20 yr (Ho et al. 2020b), indicates an accelerating spin-down rate and significantly deviates from the measured values of most pulsars, $n = 3$, that imply dipole radiation (Shapiro & Teukolsky 1983).

Full author list given at the end of the article.

More importantly, observations of PSR J0537−6910 show the pulsar's (short-term) interglitch braking index $n_{\rm ig}$, as measured during intervals between ~ 50 glitches, has values typically > 10, and approaches an asymptotic value of $\lesssim 7$ at long times after a glitch, i.e., when the effects of a preceding glitch are diminished (see Figure 1; see also Andersson et al. 2018). It is this behavior that provides tantalizing suggestions that PSR J0537−6910 could be losing some of its rotational energy to gravitational-wave emission. In particular, a slightly deformed pulsar can emit gravitational waves that results in $n = 5$, and a r-mode fluid oscillation in a pulsar can emit gravitational waves that results in $n = 7$ (see, e.g., Riles 2017; Andersson et al. 2018; Glampedakis & Gualtieri 2018; Gao et al. 2020).

In this work, we search for mass quadrupolar gravitational-wave emission from PSR J0537−6910 that follows the same phase as that of the pulsar's rotation. Previously, data from initial LIGO's fifth and sixth science runs (S5 and S6) and Virgo's second and fourth science runs (VSR2 and VSR4), in conjunction with *RXTE* timing measurements, were used to set limits on gravitational-wave emission by PSR J0537−6910 that closely approached the spin-down limit (Abbott et al. 2010; Aasi et al. 2014). Here, we analyze data from the second and third observing runs (O2 and O3) of LIGO and Virgo, tracking the rotation phase with the contemporaneous *NICER* timing ephemeris. In doing so, we also provide an updated ephemeris that includes the latest six months of *NICER* observations of PSR J0537−6910.

Investigations of r-mode gravitational-wave emission ($n = 7$) are not presented here; such searches are more technically challenging and require different methods that search over a range of frequencies (see, e.g., Mytidis et al. 2015, 2019; Abbott et al. 2019b; Fesik & Papa 2020a,b) due to uncertainty in gravitational-wave frequency for a given rotation frequency (Andersson et al. 2014; Idrisy et al. 2015; Caride et al. 2019). Nevertheless, we are able to reach below the spin-down limit of PSR J0537−6910 for the first time, which means that the minimum amplitude we could detect in our analysis is lower than the one obtained by assuming all of the pulsar's rotational energy loss is converted to gravitational waves (see Section 2.1). In other words, we can now obtain physically meaningful constraints.

2. SEARCH METHOD

2.1. *Model of gravitational-wave emission*

The first model considered here allows for gravitational-wave emission at once and twice the spin frequency simultaneously, which has been searched for previously (Pitkin et al. 2015; Abbott et al. 2017, 2019a, 2020), and can result from a triaxial star spinning about an axis that is not its principal axis (Jones 2010, 2015). The amplitudes of each harmonic at once and twice the spin frequency of the star, denoted $h_{21}(t)$ and $h_{22}(t)$, respectively, can be written as

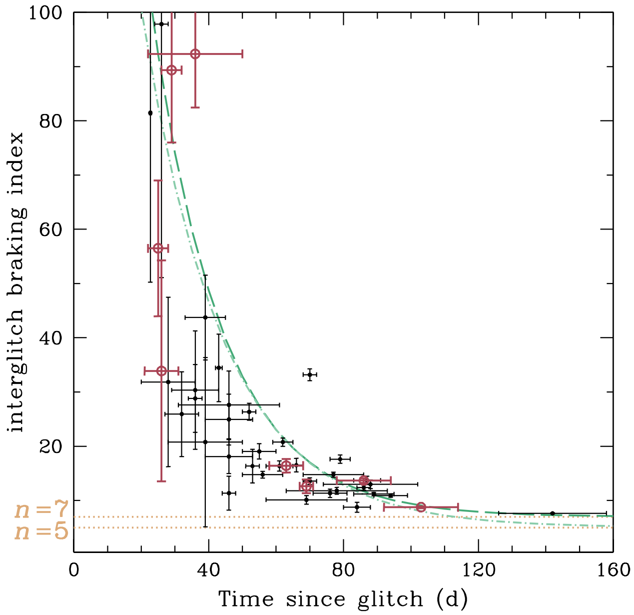

Figure 1. Interglitch braking index $n_{\rm ig}$ calculated from the spin parameters of each segment between glitches as a function of time since the last glitch. Large and small circles denote *NICER* and *RXTE* values, respectively, with the former from Tables 1 and 2 and from Ho et al. (2020b) and latter from Antonopoulou et al. (2018). Errors in $n_{\rm ig}$ are 1σ uncertainty. Orange horizontal dotted lines indicate braking index $n = 5$ and 7, which are expected for pulsar spin-down by gravitational-wave emission due to an ellipticity and r-mode oscillation, respectively. Green dot-dashed and dashed lines indicate exponential decay to $n = 5$ with best-fit time-scale of 24 d and to $n = 7$ with best-fit time-scale of 21 d, respectively.

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

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

Here, C_{21} and C_{22} are dimensionless constant component amplitudes, and Φ_{21}^{C} and Φ_{22}^{C} are phase angles. F_{+}^{D} and $F_{\times}^{D}$ are antenna or beam functions and describe how the two polarization components of the signal are projected onto the detector (see, e.g., Jaranowski et al.

1998). The angles (α, δ) are the right ascension and declination of the source, while the angles (ι, ψ) specify the orientation of the star's spin axis relative to the observer. $\Phi(t)$ is the rotational phase of the source.

The second model is a special case of the first model and is used for gravitational-wave emission at only twice the rotational frequency ($C_{21} = 0$), implying a triaxial star that is spinning about a principal axis, such as its z-axis. In this case, it is simpler to write the gravitational-wave amplitude in terms of the dimensionless value h_0, which requires substituting $C_{22} = -h_0/2$ in equation (2) (Abbott et al. 2019a). The sign change simply maintains consistency with the model from Jaranowski et al. (1998). The cause of such gravitational-wave emission is a deviation from axial symmetry, which can be written in terms of a dimensionless equatorial ellipticity ε, defined in terms of the star's principal moments of inertia (I_{xx}, I_{yy}, I_{zz}):

$$\varepsilon \equiv \frac{|I_{xx} - I_{yy}|}{I_{zz}}. \tag{3}$$

The gravitational-wave amplitude is directly proportional to the ellipticity:

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz}\varepsilon f_{\rm rot}^2}{d}, \tag{4}$$

where d is the star's distance from the Earth. When setting upper limits, we use a fiducial value for the z-component of the moment of inertia, *i.e.*, $I_{zz}^{\rm fid} = 10^{38}\,{\rm kg\,m^2}$. The combination of the ellipticity and fiducial moment of inertia can be cast in terms of the mass quadrupole moment of the $l = m = 2$ mode of the star via $Q_{22} = \sqrt{15/8\pi} I_{zz}\varepsilon$ (Owen 2005). The gravitational-wave amplitude h_0 can be compared to the spin-down limit amplitude $h_0^{\rm sd}$, which is the gravitational-wave amplitude produced assuming that all of the rotational energy lost by the pulsar is converted into gravitational waves:

$$h_0^{\rm sd} = \frac{1}{d}\left(\frac{5GI_{zz}}{2c^3}\frac{|\dot{f}_{\rm rot}|}{f_{\rm rot}}\right)^{1/2}. \tag{5}$$

Our results for the single harmonic case are quoted in terms of $h_0^{\rm sd}$.

NICER observations of PSR J0537−6910 allow for the ephemeris of the pulsar to be determined, which means we know the expected signal frequency and its evolution. With this information, we can perform a targeted search for gravitational waves from this pulsar based on the two signal models discussed, with the phase tracking that of the pulsar rotation.

2.2. *NICER data*

In Ho et al. (2020b), timing analysis is performed on *NICER* data of PSR J0537−6910 from 2017 August 17 to 2020 April 25, with eight glitches detected during this timespan and the last three glitches during O3. Here we present an update and results on timing analysis since the work of Ho et al. (2020b). In particular, data from 2020 May 12 to October 29 is analyzed using the methodology as described in Ho et al. (2020b). Our analysis reveals continuing accelerated spin-down (see Table 1) and three subsequent glitches (see Table 2 and Figure 2), including the smallest glitch of PSR J0537−6910 yet detected using *NICER*. Note that the timing model of segment 8 uses three additional subsequent times-of-arrival (TOAs) beyond those in Table 1 of Ho et al. (2020b) and, as a result, the epoch and other parameters of the model differ; e.g., segment 8 is associated with the data point at 63 d and $n_{\rm ig} = 16$ in Figure 1 compared to 50 d and $n_{\rm ig} = 22$ in Figure 6 of Ho et al. (2020b). Meanwhile, the relatively short timespan of segment 9 means the timing model for this segment is not able to constrain $\ddot{f}_{\rm rot}$. For the most recent glitch 11, its magnitude is large ($\Delta f_{\rm rot} = 33.9\ \mu$Hz), which suggests the time to the next glitch will be long ($\sim 200 \pm 20$ d; Ho et al. 2020b). If the interglitch period is indeed long, then *NICER* measurements could eventually yield $n_{\rm ig} \lesssim 7$ for segment 11, which would lend further support for gravitational-wave emission (see Section 1 and Figure 1).

The gravitational-wave search performed here uses the timing model of Ho et al. (2020b). The differences between the model of Ho et al. (2020b) and the model presented here are well within the former's uncertainties, and thus use of the latter would not yield significantly different results.

2.3. *LIGO and Virgo data*

We use a combination of data from the second and third observing runs of the Advanced LIGO (Aasi et al. 2015) and Virgo (Acernese et al. 2015) gravitational wave detectors. During O2, LIGO Livingston (L1) and LIGO Hanford (H1) took data from 2016 November 30 to 2017 August 25 and had duty factors of ∼ 57% and ∼ 59%, respectively (including commissioning breaks), while Virgo took data from 2017 August 1 to 2017 August 25 with a duty factor of ∼ 85%. As noted in Section 2.2, *NICER* data start on 2017 August 17, and thus one set of searches we undertake uses only about six days of O2 data overlapping with the NICER data in addition to the O3 data (explicitly 5.3, 5.5 and 6.0 d of data for H1, L1 and V1, respectively). Alternatively, we can consider a more optimistic and much

Table 1. Timing model parameters for segments between epochs of new glitches of PSR J0537−6910. Columns from left to right are segment number, timing model epoch, segment start and end dates, number of times-of-arrival, rotation frequency and its first two time derivatives, interglitch braking index, and timing model residual and goodness-of-fit measure. Number in parentheses is 1σ uncertainty in last digit. Segments 1–7 are presented in Ho et al. (2020b).

Segment	Epoch (MJD)	Start (MJD)	End (MJD)	TOAs	$f_{\rm rot}$ (Hz)	$\dot{f}_{\rm rot}$ (10^{-10} Hz s^{-1})	$\ddot{f}_{\rm rot}$ (10^{-20} Hz s^{-2})	$n_{\rm ig}$	Residual RMS (μs)	χ^2/dof
8	58931	58871.5	58991.2	17	61.908808739(3)	−1.997535(7)	1.06(8)	16(1)	173.7	9.9
9	59020	58995.6	59046.3	11	61.907273376(2)	−1.99699(4)	[1][a]	—	147.8	6.7
10	59074	59050.4	59098.7	10	61.906349948(5)	−1.99762(2)	3.6(8)	56(13)	60.9	1.5
11	59129	59108.7	59150.7	11	61.905434556(6)	−1.99809(3)	2.2(13)	34(20)	72.3	2.1

[a] $\ddot{f}_{\rm rot}$ is fixed at 10^{-20} Hz s^{-2}.

Table 2. Parameters of new glitches of PSR J0537−6910. Columns from left to right are glitch number and epoch, change in rotation phase and changes in rotation frequency and its first two time derivatives at each glitch. Number in parentheses is 1σ uncertainty in last digit. Glitches 1–7 are presented in Ho et al. (2020b).

Glitch	Glitch epoch (MJD)	$\Delta\phi$ (cycle)	$\Delta f_{\rm rot}$ (μHz)	$\Delta\dot{f}_{\rm rot}$ (10^{-13} Hz s^{-1})	$\Delta\ddot{f}_{\rm rot}$ (10^{-20} Hz s^{-2})
8	58868(5)	0.08(12)	24.0(1)	−2.3(6)	−5(1)
9	58993(3)	0.06(12)	0.4(1)	−0.3(8)	—
10	59049(3)	−0.22(2)	8.46(3)	−1.3(5)	—
11	59103(5)	0.42(2)	33.958(7)	−2.0(3)	—

longer time-series of O2 data by taking advantage of the correlation between glitch size and time-to-next-glitch seen for PSR J0537−6910 (Middleditch et al. 2006; Antonopoulou et al. 2018; Ferdman et al. 2018; Ho et al. 2020b). Assuming a (unobserved) glitch occurred on 2017 March 22 with the same size as the largest *NICER* glitch (i.e., glitch 2 with $\Delta f_{\rm rot} = 36\ \mu$Hz), we would expect a subsequent glitch 224 d later (at 68% confidence) on 2017 November 1, which is the earliest estimated date at which glitch 1 occurred (see Figure 2 and Ho et al. 2020b). Thus 2017 March 22 to November 1 is the longest period over which we would expect PSR J0537−6910 to not have undergone a glitch and the *NICER* ephemeris to be valid. O3 lasted from 2019 April 1 to 2020 March 27, with a one-month pause in data collection in October 2019. The three detectors' datasets H1, L1, and V1 had duty factors of ∼ 72%, ∼ 69%, and ∼ 69%, or 259, 248 and 248 d of data, respectively during O3.

In the case of a detection, calibration uncertainties limit our ability to provide robust estimates of the amplitude of the gravitational-wave signal and corresponding ellipticity (Abbott et al. 2017). Even without a detection, these uncertainties affect the estimated instrument sensitivity and inferred upper limits. The uncertainties vary over the course of a run but do not change by large values, so we do not explicitly consider time-dependent calibration uncertainties in our analysis. For further information on O2 calibration techniques, see discussions in Abbott et al. (2019a).

The full raw strain data from the O2 run is publicly available from the Gravitational Wave Open Science Center[1] (Vallisneri et al. 2015; Abbott et al. 2019c). For the LIGO O3 data set, the analysis uses the "C01" calibration. The C01 calibration has estimated maximum amplitude and phase uncertainties of ∼ 7% and ∼ 4 deg, respectively (Sun et al. 2020), which we use as conservative estimates of the true calibration uncertainty near the frequencies analyzed here. For the Virgo O3 data set, we use the "V0" calibration with estimated

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[1] https://www.gw-openscience.org/data

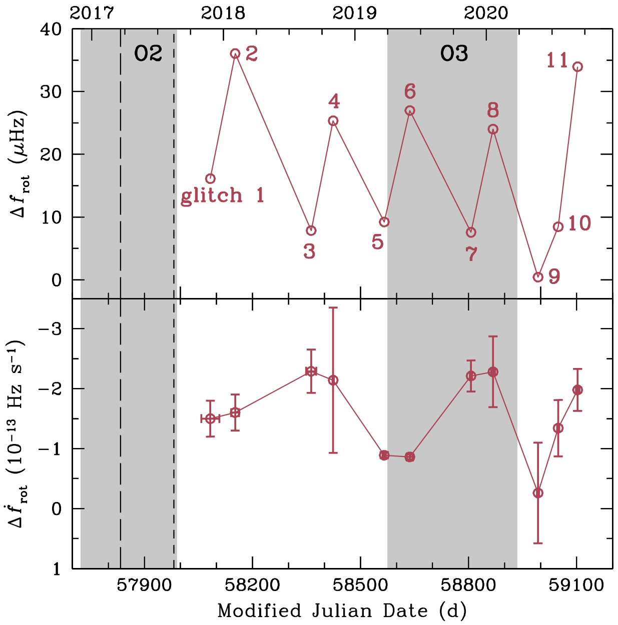

Figure 2. Glitch $\Delta f_{\rm rot}$ (top) and $\Delta \dot{f}_{\rm rot}$ (bottom) as functions of time. Glitch numbers and values from Table 2 and Ho et al. (2020b). Errors in $\Delta \dot{f}_{\rm rot}$ are 1σ uncertainty, while errors in $\Delta f_{\rm rot}$ are not shown because they are generally smaller than the symbols. Shaded regions denote second observing run (O2) and third observing run (O3) of LIGO/Virgo. Vertical long and short-dashed lines indicate two possible start dates of O2 data used in the present work (see Section 2.3).

maximum amplitude and phase uncertainties of 5% and 2 deg, respectively.

2.4. *Search pipeline*

The time-domain Bayesian method performs a coherent analysis of the interferometers' data, meaning that we analyze the entire data set with an effective single Fourier Transform, thereby preserving the phase information. First, the raw strain data are heterodyned (Dupuis & Woan 2005) using the expected signal phase evolution, known precisely from the electromagnetic timing ephemeris. Then a low-pass filter with a knee frequency of 0.25 Hz is applied, and the data are downsampled so that the sampling time is one minute, compared to 60 microseconds originally. This heterodyning is performed for an expected signal whose frequency is at once or twice the rotational frequency of the pulsar. The heterodyned data is the input to a nested sampling algorithm that is a part of the LALInference package (Veitch & Vecchio 2010; Veitch et al. 2015), which infers the unknown signal parameters depending on the model of gravitational-wave emission.

PSR J0537−6910 glitched three times over the course of the gravitational-wave observations (see Figure 2). For each glitch, we assume an unknown phase offset between the electromagnetic and gravitational-wave phase. The individual phase offsets of multiple glitches that occurred between O2 and O3 cannot be disentangled, so only one phase offset is included for these glitches. This means that we introduce four additional phase parameters when performing parameter estimation.

We also make use of restricted and unrestricted priors when performing the analysis. In the first case, we use estimates of the orientation of the pulsar relative to the Earth based on a model fit of the observed pulsar wind nebulae torus (Ng & Romani 2008), which imply narrow priors in our analysis on the polarization and inclination angles. Therefore, we use a Gaussian prior on ψ of 2.2864 ± 0.0384 rad and a bimodal Gaussian prior on ι with modes at 1.522 ± 0.016 and 1.620 ± 0.016 rad (see Jones 2015, for reasons behind the bimodality). This range of ι would suggest the pulsar's rotation axis is almost perpendicular to the line-of-sight, which would in turn lead to a linearly polarized gravitational-wave signal dominated by the '+' polarization component. The second case assumes a uniform isotropic prior on the axis direction, which therefore does not rely on assumptions about the pulsar's orientation matching that of the wind nebula or uncertainties in the above modeling of the not-well-resolved X-ray observations. The initial signal phase and glitch phase offsets all use uniform priors over their full ranges. For the single harmonic search, we parameterize the signals using the mass quadrupole Q_{22} and distance. As a conservative approach, we use an unphysical flat prior on Q_{22} with a lower bound at zero and an upper bound of $5{\times}10^{37}$ kg m^2, which is well above the largest upper limits found in Abbott et al. (2019a). For the distance, we use a Gaussian prior with mean of 49.59 kpc and standard deviation of 0.55 kpc based on the value given in Pietrzyński et al. (2019), combining the statistical and systematic errors in quadrature. For the dual harmonic search, which uses the amplitudes C_{21} and C_{22} rather than the physical parameters of Q_{22} and d, we use flat priors that are bounded between zero and 1×10^{-22}, which is again well above the limit implied in Abbott et al. (2019a). To analyze multiple detectors' data sets simultaneously, we combine the product of the Student's t-likelihoods calculated for each detector (Dupuis & Woan 2005).

The outputs of the analysis are posterior distributions of the parameters of interest, which are $h_0/Q_{22}/\varepsilon$ for the single harmonic search, C_{21} and C_{22} for the dual harmonic search, and the angles $\cos\iota$ and ψ for both choices of priors. In Section 3, we present results on the amplitude parameters marginalized over the rest of the parameter space. We also provide odds ratios between two hypotheses: the data contain a coherent signal in the detectors, or incoherent signals or noise in the different detectors. These values are used to assess the presence of a signal in the data and, for a given prior choice, can be thought of as a "detection statistic".

3. RESULTS

Results from our searches do not show evidence for gravitational-wave emission from PSR J0537−6910 via the two models that we assume. For the single harmonic model, the Bayesian odds of the data containing a coherent signal between detectors versus incoherent signals or noise in the different detectors (see equation A6 of Abbott et al. 2017) favor the latter case by $\sim 20\,000$ and $\sim 31\,000$ for the unrestricted and restricted priors, respectively. For the dual harmonic model, the case of an incoherent signal or noise in the detectors is favored by $\lesssim 2\times10^8$ for both prior choices.

An amplitude spectral density obtained after the heterodyne correction is displayed in Figure 3 for each of the three detectors. If a loud continuous gravitational-wave signal was present, we would expect to see a narrow line feature in the spectrum. The amplitude spectral densities also give an estimation of the sensitivity of the search.

Given the lack of evidence for a signal from either the single or dual harmonic models, we expect the odds between these models to favor the simpler single harmonic model. Indeed, we find that the single harmonic model is strongly favored by factors of ~ 5700 and ~ 9200 for the restricted and unrestricted orientation cases, respectively. However, it is worth noting that the odds between models will depend on our choice of the uniform prior range on the amplitude parameters.

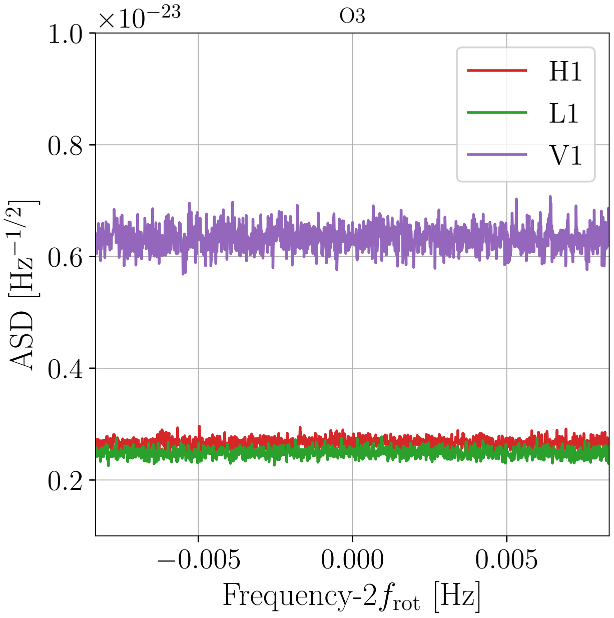

Figure 3. Two-sided amplitude spectral density (ASD) after heterodyning, low pass filtering, and downsampling the raw strain data for the $l = m = 2$ gravitational-wave mode. Different color lines indicate the Hanford (H1), Livingston (L1), and Virgo (V1) detectors.

Though no gravitational waves are detected, we can still determine upper limits on possible gravitational-wave emission from PSR J0537−6910. Here, we use 95% credible upper bounds on the amplitude parameters based on their marginalized probability distributions.[2] The dimensionless gravitational-wave amplitude h_0 and coefficients C_{21} and C_{22} are constrained for the single and dual harmonic searches, respectively. For the single harmonic search, h_0 can be mapped to a limit on the maximum ellipticity ε using equation (4). In Table 3, we show the different constraints for both searches using all O3 data and the last ~ 6 days of O2 data (see Section 2.3). In addition to the detector calibration uncertainties discussed in Section 2.3, we estimate that the statistical uncertainty on the upper limits due to the use of a finite number of posterior samples is on the order of 1%.

Table 3. 95% upper limits on gravitational-wave strain, ellipticity, and other quantities based on unrestricted (UR) and restricted (R) choices for priors on polarization and inclination angles. Results here come from analyzing all O3 data and the last 6 days of O2 data.

Prior	$h_0^{95\%}$ (10^{-26})	$\varepsilon^{95\%}$ (10^{-5})	$h_0^{95\%}/h_0^{\rm sd}$	$C_{21}^{95\%}$ (10^{-26})	$C_{22}^{95\%}$ (10^{-27})
UR	1.1	3.4	0.37	2.2	5.6
R	1.0	3.1	0.33	1.8	5.0

Figure 4 shows the marginalized posterior probability distributions on the pulsar ellipticity and h_0 for the single harmonic search with unrestricted and restricted source orientation priors. The posteriors show significant support at ellipticities of zero, indicating no evidence of a signal at current sensitivities. We therefore

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[2] Simulations on independent and identically distributed noise realizations show that the different noise instantiations can produce upper limits that vary by $\sim 20\%$ at a 1σ confidence level. However, the Bayesian credible limits we present are valid for our particular dataset.

show 95% credible upper limits on the ellipticity for both prior choices along with the fiducial spin-down limit.

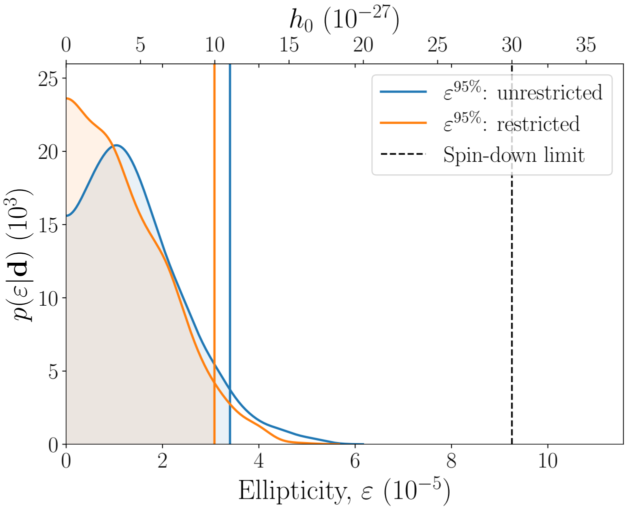

Figure 4. Posterior probability distribution for ellipticity and h_0 for the analyses with unrestricted and restricted priors on the pulsar orientation. The 95% credible upper limits are shown as vertical colored lines, while the spin-down limit is given by the vertical dashed black line.

Figure 5 shows a similar posterior distribution on the dimensionless amplitudes C_{21} and C_{22} for the dual harmonic model. For this model, no evidence of gravitational waves is found, so an upper limit at 95% is indicated in both panels of this figure. The model given by equation (1) implies that the value of C_{21} becomes completely unconstrained when $\sin\iota = 0$. For the unrestricted orientation prior result shown in the left panel of Figure 5, this leads to a long high amplitude tail in the C_{21} posterior distribution. In Figures 4 and 5, we see that the amplitude posteriors can peak away from zero. This behavior was unsurprising and can occur even for pure Gaussian noise. Even with these peaks, the posteriors are still entirely consistent with zero ellipticity. For example, for the unrestricted posterior distribution shown in Figure 4, a value of zero ellipticity is within the minimum 66% credible interval around the mode.

In contrast to emission in the single harmonic case, an energy-based limit on gravitational-wave emission is rather complex in the dual harmonic case. The relevant constraint is that the observed spin-down energy is equal to the sum of the luminosities at the two harmonics. These two emissions have different beam patterns: the emission at the rotation frequency is strongest along the rotational equator ($\iota = \pi/2$ direction), where the polarization is linear, while emission at twice the rotation frequency is strongest along the axis of rotation ($\iota = 0$), where the polarization is circular. Therefore, the spin-down limit on the maximum amplitudes of the two harmonics depends on both the relative size of the intrinsic strength of the two components and the orientation of the spin axis relative to the observer. To provide some insight, if we compare the sky-averaged emission strength at only the rotation frequency to emission at only twice the rotation frequency, the spin-down limit would allow the amplitude of the radiation at the rotation frequency to be approximately twice as strong as that at twice the rotation frequency (see Section 3 of Jones 2010, for more details).

The results presented above use all O3 data in combination with about six days of O2 data, when *NICER* was operating and monitoring PSR J0537−6910. We also conducted searches using only O3 data or using O3 data plus O2 data from 2017 March 22 to the end of O2. The latter analysis assumes no glitches occurred during the additional time and represents the estimated maximum time that can be safely included without a contemporaneous timing model (see Section 2.3). For only O3 data, we obtain h_0 and ε limits that are worse by $\sim 7\%$ for the unrestricted prior and unchanged for the restricted prior, compared to those from those shown in Table 3. For O3 data plus the extra O2 data, we obtain amplitude limits that are improved by $\lesssim 20\%$ compared to those shown in Table 3.

4. CONCLUSIONS

Using data from LIGO/Virgo's second and third observing runs, we searched for mass quadrupolar-sourced gravitational waves from the young, dynamic PSR J0537−6910 at once or twice the pulsar's rotational frequency of 62 Hz. For the first time, we reached below the gravitational-wave spin-down limit for PSR J0537−6910 and showed that gravitational-wave emission for a pure $l = m = 2$ mode accounts for less than 14% of the pulsar's spin-down energy budget. We placed the third most stringent constraint on the ellipticity ($\varepsilon < 3 \times 10^{-5}$) of any young pulsar (behind only the Crab pulsar and B1951+32/J1952+3252; Abbott et al. 2019a, 2020). While this limit is much higher than those of old recycled millisecond pulsars (for which $\varepsilon < 10^{-8}$; Abbott et al. 2020), young pulsars such as PSR J0537−6910 and the Crab pulsar are important because they have much stronger magnetic fields (and are hotter) and thus might have greater ellipticities. The ellipticity constraint of PSR J0537−6910 is also above or near estimates of the maximum ellipticity that can be sustained by an elastically deformed neutron star crust (Johnson-McDaniel & Owen 2013; Caplan et al. 2018; Gittins et al. 2021).

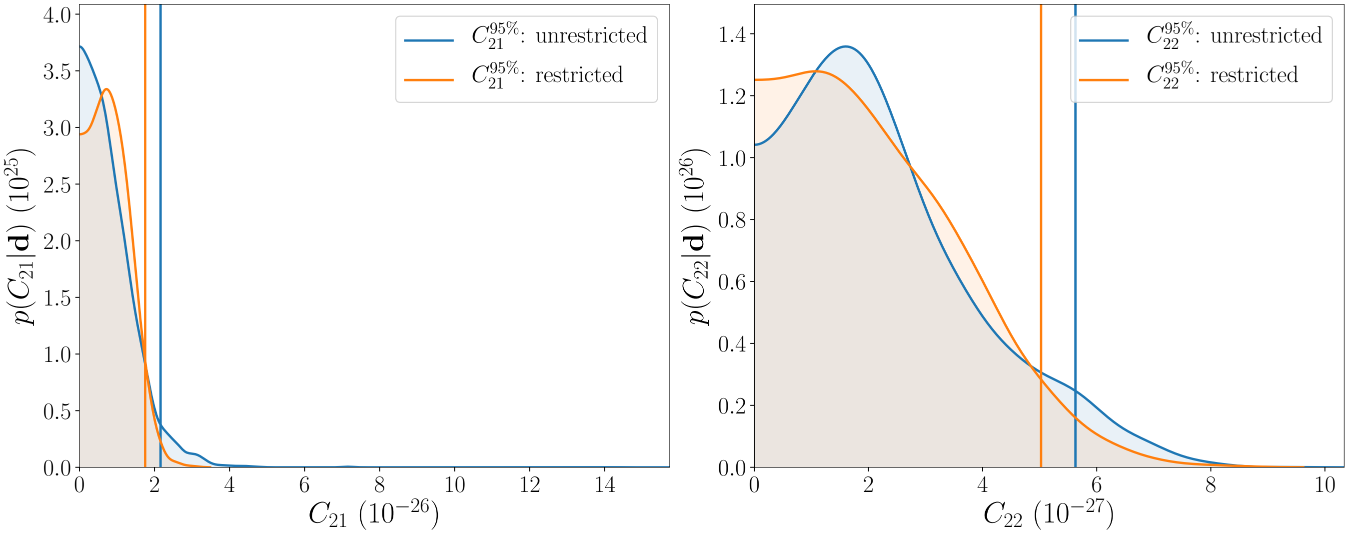

Figure 5. Posterior probability distributions for the amplitudes C_{21} and C_{22} with unrestricted and restricted priors on the pulsar orientation. The 95% credible upper limits are shown as vertical colored lines.

PSR J0537−6910 is a frequently glitching pulsar and potential source of continuous gravitational waves. The X-ray data from *NICER* gives us the necessary tools to account for the phase evolution of a gravitational-wave signal over time, which allows us to perform a fully coherent and sensitive search for such a signal. While our multi-messenger analysis focuses on gravitational waves from a time-varying mass quadrupole ($n = 5$), another search could be performed for gravitational waves from a r-mode fluid oscillation ($n = 7$) using wider-band techniques (e.g., Fesik & Papa 2020a,b, using O2 data). The strain sensitivity achieved in our analysis (1×10^{-26}) is also comparable to the $(2-3) \times 10^{-26}$ estimated in Andersson et al. (2018) for r-mode emission from PSR J0537−6910.

Finally, from the observed correlation between glitch size and time-to-next-glitch for PSR J0537−6910 (Middleditch et al. 2006; Antonopoulou et al. 2018; Ferdman et al. 2018; Ho et al. 2020b), we can hope to measure in the future low braking indices (7 or even lower) after the largest glitches. As noted above, braking indices of 5 and 7 are predicted by gravitational wave-emitting mechanisms. The observed evolution of $n_{\rm ig}$ to lower values than those shown in Figure 1, which may occur after the effects of glitches on the pulsar's spin-down behavior have decayed, may indicate that gravitational waves are continuously emitted between glitches. On the other hand, glitches may trigger detectable transient gravitational waves (Prix et al. 2011; Ho et al. 2020a; Yim & Jones 2020), and gravitational-wave searches at glitch epochs of other pulsars have been conducted (Keitel et al. 2019). It is therefore vital to continue to monitor the spin evolution of PSR J0537−6910, not only to obtain the timing ephemeris and measure braking indices, but also to know when this pulsar undergoes a glitch. Since the spin period of PSR J0537−6910 is only detectable at X-ray energies, *NICER* is the only effective means to perform the necessary observations. Fortunately *NICER* is anticipated to operate until at least late 2022, overlapping with the fourth observing run of LIGO/Virgo and KAGRA (Aso et al. 2013), which is likely to begin in 2022 and continue into 2023.

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