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Karl Wette, Liam Dunn, Patrick Clearwater, and Andrew Melatos
Phys. Rev. D 103, 083020 — Published 22 April 2021
DOI: 10.1103/PhysRevD.103.083020
Deep Exploration for Continuous Gravitational Waves at 171–172 Hz in LIGO 2nd Observing Run Data

Karl Wette,1,2,∗ Liam Dunn,3,2 Patrick Clearwater,4,3,2 and Andrew Melatos3,2

1Centre for Gravitational Astrophysics, Australian National University, Canberra ACT 2601, Australia
2ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav), Hawthorn VIC 3122, Australia
3School of Physics, University of Melbourne, Parkville VIC 3010, Australia
4Gravitational Wave Data Centre, Swinburne University of Technology, Hawthorn VIC 3122, Australia

We pursue a novel strategy towards a first detection of continuous gravitational waves from rapidly-rotating deformed neutron stars. Computational power is focused on a narrow region of signal parameter space selected by a strategically-chosen benchmark. We search data from the 2nd observing run of the LIGO Observatory with an optimised analysis run on graphics processing units. While no continuous waves are detected, the search achieves a sensitivity to gravitational wave strain of \( h_0 = 1.01 \times 10^{-25} \) at 90% confidence, 24% to 69% better than past searches of the same parameter space. Constraints on neutron star deformity are within theoretical maxima, thus a detection by this search was not inconceivable.

I. INTRODUCTION

Neutron stars, the dense remnants of exploded stars, are of particular interest in gravitational wave astronomy. Two orbiting neutron stars inevitably collide and merge, generating a characteristic chirp signal in gravitational waves detectable by the LIGO [1] and Virgo [2] observatories. The first such detection, in gravitational waves [3] and electromagnetic radiation [4], has enlightened neutron stars physics, heavy element production in the Universe, and cosmology.

A single rapidly-rotating neutron star may also emit gravitational waves, provided it is non-axisymmetric. The expected continuous wave signal is long-lived, decreases in frequency over time as rotational energy is radiated in gravitational waves, and is modulated by the relative motion between neutron star and detector. The neutron star non-axisymmetry might arise from deformations due to e.g. its magnetic field, accretion of matter from a companion star, or normal oscillation modes; see [5–6] for recent reviews. While theoretical and observational predictions of the non-axisymmetry exist [7–11], typical non-axisymmetries of Galactic neutron stars are unknown [12–13].

Continuous wave signals are expected to be marginally detectable by contemporary detectors; analysis of year-long datasets, at significant computational cost, is likely required for a first detection [11]. It is uncertain what sensitivity is required, and what region of signal parameter space should be explored, in order to maximise detection prospects. Moreover, due to finite computational resources, search sensitivity and parameter-space coverage cannot be maximised simultaneously. This mandates the use of strategies which balance these objectives.

Depth-first strategies, which prioritise sensitivity at the expense of parameter-space coverage, are employed in searches for continuous waves from known pulsars [15–17]. While the signal parameters are known, the targeted pulsars may not radiate detectable continuous waves, or else their gravitational-wave and electromagnetic frequencies may differ [18]. Breadth-first strategies, which prioritise parameter-space coverage at the expense of sensitivity, are used in all-sky surveys for electromagnetically-quiet neutron stars [19–21]. While the expansive parameter space may contain signals, the analysis method may be insufficiently sensitive to detect them. Searches targeting compact remnants of supernovae [22–24], low-mass X-ray binaries [26–29], and the Galactic Centre [30] where some parameters may be unknown, adopt intermediate strategies.

In this paper, we pursue the novel combination of an all-sky survey for continuous waves with a depth-first strategy. The search range of gravitational-wave frequencies is limited to 1 Hz, and a single benchmark is used to select all other search parameters. We apply an optimised analysis method to data from the 2nd observing run (O2) of LIGO [1], and utilise graphics processing units (GPUs) to maximise computational efficiency. While no continuous wave signals are detected, our search is the most sensitive yet performed in the O2 data over the chosen parameter space, improving by 24–69% over previous searches.

II. SEMI-COHERENT ANALYSIS

The gravitational-wave strain of a continuous wave signal is written as four amplitudes \( A_{i} \) multiplying four oscillatory basis functions \( \phi_{i} \). The \( A_{i} \) are functions of the strain amplitude \( h_{0} \), and three angles determining

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1 The Virgo detector joined O2 for only the last \( \sim 9\% \) of the run time. Due to the limited data available, which would not have noticeably improved sensitivity, Virgo O2 data was not used in this search.
the neutron star orientation and the initial signal phase. The basis functions are functions of the phase $\phi(t)$. For an isolated neutron star, $\phi(t)$ is a function of: the sky position, given by its right ascension $\alpha$ and declination $\delta$; and the gravitational-wave frequency $f$, and its first time derivative (or spin-down) $f'$, as observed at the Solar System barycenter at a given reference time. Very young ($\lesssim 1000$ yr old) neutron stars require higher-order frequency derivatives, and those with binary companions require additional orbital parameters. We do not target these sources, as the consequent increase in computational burden is not justified by their expected abundances, which are comparable to isolated neutron stars.

The computational cost of continuous wave searches of large parameter spaces and year-long datasets using fully phase-coherent matched filtering would be prohibitive. We therefore employ a semi-coherent analysis method [33–35]. The data are first partitioned into $N$ segments of time-span $T$. Within each segment, the data are filtered against a bank of signal templates. Each template computes the $F$-statistic $2F$, the fully-coherent matched filter analytically maximised over $A_j$ [32], which represents a signal with parameters $(\alpha', \delta', f', f)$. The template bank is constructed using a parameter-space metric [36, 37] to ensure any signal is recovered within a prescribed maximum loss in signal power (relative to a perfect match), known as the maximum mismatch and given by $\mu_{\text{max}}$. Optimal lattices [38, 39] are used to reduce the overlap between nearby templates, and thereby minimise the template bank and the cost of computing $2F$.

Continuous wave signal templates are then constructed spanning the whole dataset, with parameters $(\alpha, \delta, f, f')$ drawn from a second template bank with maximum mismatch $\mu_{\text{max}}$. For each full-span template, and for each segment, the per-segment template is selected whose frequency evolution $f(t) = d[\phi(t)/2\pi]/dt$ most closely matches the full-span template, as determined by the parameter-space metric [34]. Then, for each full-span template, we compute the detection statistic $2F$: the mean of the $N$ values of $2F$ corresponding to the $N$ best-match per-segment templates. This technique permits better sensitivity than a fully-coherent analysis given limited computational resources [40]. The search setup is determined by the parameters $N$, $T$, $\mu_{\text{max}}$, and $\mu_{\text{max}}$.

### III. PARAMETER SPACE

Table I lists the parameters of the search. They maximise the benchmark

$$h_0^{-2} \times \sigma_h^{-1/4} \times \rho^{1/3}.$$  

In the first factor, $h_0$ is the estimated sensitivity [42, 43] of a semi-coherent search of the LIGO O2 data with the given parameters. The negative exponent denotes that more sensitive searches, where $h_0$ is smaller, are preferred. In the second factor,

$$\sigma_h = \frac{\sqrt{\sigma_{S_H}^2 + \sigma_{S_L}^2}}{S_H + S_L},$$  

where $S_H$ and $S_L$ are the noise power spectral densities, harmonically averaged over a 1-Hz band, of O2 data from the LIGO detectors at Hanford, WA, and Livingston, LA respectively; and $\sigma_{S_H}$ and $\sigma_{S_L}$ are the respective standard deviations of the 1800 power spectral density bins in the same 1-Hz band. The exponent of $\sigma_h$ was chosen empirically to favour 1-Hz bands where the power spectrum has minimal variation over frequency, and does not contain any prominent instrumental artefacts [44]. In the third factor, $\rho$ is the density of observed pulsars [41] within an Earth-centred sphere with radius $d$, the distance out to which the search is sensitive, given by [45]

$$d = h_0^{-1} \sqrt{\frac{5GI_{zz}}{8c^3\tau}},$$  

where $G$ is the gravitational constant, $I_{zz} = 10^{38}$ kg m$^2$ is the principal moment of inertia of a typical neutron star.
star, $c$ is the speed of light, and $\tau = -f/(4\dot{f}_{\text{min}})$ is the characteristic spin-down timescale assuming energy loss only in gravitational waves. As $\rho \propto d^{-3} \propto h_0^3$ in the worst case, the exponents of $h_0$ and $\rho$ in Eq. (1) are chosen so that $h_0^3\rho^{1/3} \propto h_0^{-1}$ and a smaller $h_0$ is preferred.

The use of $\rho$ in Eq. (1) is motivated by the hypothesis that neutron stars which predominately radiate gravitational waves are found in similar regions of the Galaxy, and in overlapping regions of the $f-\dot{f}$ plane (Figure 1) as observed pulsars. We may therefore use the observed density of pulsars as a prior on the possible density of gravitational-wave emitting neutron stars. While it may be only approximately true, this hypothesis is useful in guiding a detection strategy. There is no evidence that gravitational-wave emitting neutron stars only occupy special regions of the Galaxy. Simulations of Galactic neutron stars [12, 13] indicate that, while electromagnetic emission leads to higher spin-down rates and hence lower neutron star rotation frequencies than gravitational radiation, nevertheless the two populations overlap in the $f-\dot{f}$ plane.

Assuming gravitational-wave emission at twice the neutron star rotation frequency, the number of pulsars in Figure 1 with frequencies $166.5$–$176.5$ Hz, bracketing the search frequency range (Table I), is $0.2$ per Hz. The expected number of Galactic neutron stars ($\gtrsim 10^8$; [16]) is, however, much larger than the number of observed pulsars ($\sim 3 \times 10^3$; [11]). An optimistic estimate (ignoring e.g. selection effects) of the number of neutron stars within the search frequency range is therefore $\sim 7 \times 10^3$. More pessimistic estimates, which account for the distance out to which the search is sensitive, are outlined in the Discussion.

Millisecond pulsars [7] with $f \gtrsim 100$ Hz, are hypothesised to have spun up by accretion of matter from a companion star; the same emission mechanism could also have built a non-axisymmetric neutron star [27]. A plausible explanation for the maximum observed millisecond pulsar spin frequency is that spin-up due to accretion is balanced by spin-down due to gravitational waves [47]. If true, this suggests that at frequencies where one finds millisecond pulsars which are still undergoing accretion, one might also expect millisecond pulsars where accretion has ceased and which may be spinning down dominantly though gravitational waves.

Parameters are chosen to maximise Eq. (1) through a Monte Carlo process. Trial values are drawn according to three sampling modes. In the first mode (chosen for 70% of trials), parameters are sampled from large initial ranges: $f_{\text{min}}$ from 25 to 500 Hz, set by the limited sensitivity of LIGO O2 data at low frequencies, and by the quadratic scaling of computational cost with frequency; $\dot{f}_{\text{min}}$ from the ranges shown in Figure 1 at a given $f_{\text{min}}$: $N$

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2 We note that, as shown in Figure 1, the setup of the search did not consider the most rapidly-spinning millisecond pulsars with $f > 500$ Hz, due to computational restrictions.

IV. IMPLEMENTATION

LIGO O2 data, starting at UTC 2016 November 30 17:31:57 (GPS 1164562334), are partitioned into 10 segments, followed by a gap where no usable data are present, followed by a further 6 segments, ending at UTC 2017 August 25 21:59:34 (GPS 1187733592); all segments and gaps are of time-span $T$. The data are further divided into 12626 blocks [48] of 1800 s duration, and then Fourier transformed.

Computational efficiency was optimised using GPUs. For this search, times to compute the $F$-statistic [39] and the semi-coherent $2F$ are reduced by factors of $\sim 240$ and $\sim 4.2$ respectively, relative to non-GPU processors. Computation of $2F$ dominates the total analysis time. The analysis ran for $\sim 5800$ days on the OzSTAR supercomputer using NVIDIA P100 type GPUs; a total of $4.3 \times 10^{16}$ templates were analysed.

V. CANDIDATES

Figure 2 plots the detection statistic $2F$ of the top $10^5$ candidates as a function of sky position. Clear outliers are visible with maximum $2F \approx 14.7$, at $\alpha$ separated by $\sim 12.1^h$, and at $\delta \sim -66.1^\circ$. The presence of outliers of similar strength at opposing points suggests an instrumental artefact. Figure 3 plots, as a function of frequency, the single-detector $2F$ of the top $10^5$ candidates and the noise power spectrum of the Hanford and Livingston detectors individually, and the multi-detector $2F$ [51] and harmonically-averaged noise power spectrum of both detectors. A feature at $f \approx 171.4276$ Hz appears
The largest found $2\hat{F} = 11.1$, after removal of the outlier, is indicated in Figure 4 and is consistent with the expected distribution $P(2\hat{F})$. We conclude that no continuous wave signals are detected.
VI. SENSITIVITY

Table II lists the estimated sensitivity $h_0 = 1.01 \times 10^{-25}$ achieved by the search. This is a statistical statement at 90% confidence: were a large number of continuous wave signals present within the parameter space, with the given $h_0$ and other amplitude parameters chosen at random, we would have detected 90% of them. This statement is validated by performing 500 searches of small regions of the parameter space, each containing a simulated signal as described above, and confirming the expected 90% detection rate. For comparison with previous searches, we have also estimated the sensitivity at 95% confidence, which gives $h_0 = 1.07 \times 10^{-25}$.

VII. DISCUSSION

Table II lists the sensitivity $h_0$ achieved by previous searches for continuous waves; they covered parameter spaces including, and significantly larger than, the parameter space of this search. Our search improves in sensitivity by 24–69% over previous searches, and is the most sensitive exploration of this parameter space yet performed.

While optimisation techniques are used to select the most sensitive continuous wave search, when the parameter space is specified a priori [40, 56–58], optimisation of the parameter space and search setup simultaneously is uncommon [59]. Our approach realises a simple astrophysically-motivated benchmark [Eq. (1)] as optimised choices for both parameter space and search setup. It makes explicit the prior assumptions used to construct the parameter space, which then permits those assumptions to be refined by improved understanding of neutron star physics and Galactic neutron star populations.

The minimum spin-down $f_{\text{min}}$ (Table II) is smaller than used in the previous searches listed in Table II. While [40] also focus on small spin-downs, our choice of $f_{\text{min}}$ was not made a priori, but arose as a consequence of Eq. (1). The chosen $f_{\text{min}}$ and Eq. (1) imply that the search is sensitive to gravitationally-radiating neutron stars within a distance $d = 320 \text{ pc}$. Of the 289 pulsars indicated in Figure II only 10 are within this distance. Nevertheless, only a small fraction ($\sim 3 \times 10^3/10^5$) of Galactic neutron stars are observed as pulsars, and therefore one might naïvely expect $\sim 3 \times 10^5$ electromagnetically-quiet neutron stars within this distance. A more pessimistic count may be derived starting from the modelled volume density of neutron stars in the solar neighbourhood [46] of $\sim 1–5 \times 10^{-4}\text{ pc}^{-3}$; this suggests only $\sim 3 \times 10^3–2 \times 10^5$ neutron stars within a volume with radius $d = 320 \text{ pc}$. Taken together with the estimated number of pulsars within the searched frequency band as a fraction of the number of observed pulsars ($\sim 0.2/3 \times 10^3$), the number of neutron stars within the searched band and sensitive volume might be $\sim 20$ in the naive estimate, or $\sim 0.2–13$ in the pessimistic estimate. Given the many assumptions and simplicity of the above calculations, at best this suggests substantial uncertainty in the number of electromagnetically-quiet neutron stars this search is sensitive to.

Neutron star non-axisymmetry is characterised by the equatorial ellipticity $\epsilon$. The minimum $\epsilon$ to which this search is sensitive at 90% confidence and $d = 320 \text{ pc}$ is

$$\epsilon = \frac{c^4 h_0 d}{4\pi^2 G f_0 f^2} = 1.04 \times 10^{-6},$$

is within conservative maximum values attainable by theoretical models [4]. A detection of continuous waves by this search was certainly possible, therefore, based on current knowledge of neutron star physics.

The sensitivity achieved by this search confirms the advantages of a depth-first strategy for all-sky continuous wave surveys. Such a strategy, in concert with complimentary breadth-first surveys of wide parameter spaces, should continue to be pursued. There is ample scope to refine the benchmark of Eq. (1), perhaps by including a more informed distribution of Galactic neutron stars spinning down through electromagnetic and gravitational waves. An insightful choice of benchmark could be pivotal to a first detection of continuous gravitational waves.

ACKNOWLEDGMENTS

We thank Hannah Middleton for helpful comments on the manuscript. This research was supported by the Australian Research Council Centre of Excellence for Gravitational Wave Discovery (OzGrav) through project number CE170100004. It used data, software and/or web tools obtained from the Gravitational Wave Open Science Center (https://www.gw-openscience.org/), a service of LIGO Laboratory, the LIGO Scientific Collaboration and the Virgo Collaboration. LIGO Laboratory and Advanced LIGO are funded by the United States National Science Foundation (NSF) 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. Virgo is funded, through the European Gravitational Observatory (EGO), by the French Centre National de Recherche Scientifique (CNRS), the Italian Istituto Nazionale della Fisica Nucleare (INFN) and the Dutch Nikhef, with contributions by institutions from Belgium, Germany, Greece, Hungary, Ireland, Japan, Monaco, Poland, Portugal, Spain. It used the software packages LALSuite [63], Octave [64], OctApps [65], Python [66], NumPy [67], Matplotlib [68], and SciPy [69]. The search was performed on the OzSTAR national facility at Swinburne University of Technology. The OzSTAR program receives funding in part from the Astronomy
National Collaborative Research Infrastructure Strategy (NCRIS) allocation provided by the Australian Government. Document number LIGO-P2000536.

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