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Search for Short-Duration Transient Gravitational Waves Emitted by Neutron Star Glitches

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Neutron stars are known to show an accelerated spin-up of their rotational frequency on a short time scale of around 40 s, called a "glitch" in the neutron star. These neutron star glitches can emit short-duration transient gravitational wave signals as *f*-mode oscillations at frequencies between 1.5 and 3 kHz and damping times of less than a few seconds. The observed rate of neutron star glitches are currently limited by their electromagnetic observations. There could be a population of the isolated neutron stars in the galaxy for which there is no electromagnetic observation, but they can produce gravitational wave signals. Here, the sensitivity of the generic all-sky search for short-duration transients towards neutron star glitches during the Advanced LIGO and Virgo's third observing run using the Coherent WaveBurst algorithm is presented. The prospects of detecting signals from such glitching neutron stars for the upcoming fourth and fifth observing runs of Advanced LIGO and Virgo detectors are also described.

1. Introduction

The current ground-based gravitational wave detectors are sensitive to gravitational wave (GW) burst (approximately milliseconds to few seconds) signals. The potential GW burst sources are coalescing compact binaries (CBC), core-collapse supernovae, cosmic strings, pulsar glitches, etc. Not all sources have robust or even known waveform models. The burst signals are targeted by searches with no assumptions regarding the incoming signal direction, polarization, or morphology called unmodeled searches. The third observing run (O3) of the Advanced LIGO and Advanced Virgo detectors extends from April 1, 2019 to March 21, 2020. Here we present the results for the all-sky search for short-duration transients using the unmodeled search method called Coherent WaveBurst (cWB) pipeline during the O3 run[1] and the search sensitivity to GW burst signals emitted by the neutron star (NS) glitches. We also provide the prospects of detecting these signals for the upcoming fourth and fifth observing runs of current generation GW detectors. A dedicated search for continuous gravitational waves from isolated NSs that have glitched during the O3 run is reported in refs. [2, 3].

This article is organized as follows, Section 2 will explain the search method. Section 3 shows the sensitivity to generic morphology and GWs from NS glitches. Finally, Section 4 summarizes the search results during the O3 and prospects of observing the signals during the future observing runs of the Advanced LIGO and Virgo.

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2. Searches

The O3 run was divided into two 6 month segments, O3a (April 1, 2019 to October 1, 2019) and O3b (November 1, 2019 to March 27, 2020). We used the two pipelines, cWB[4,5] and BayesWave algorithm,[6] as the unmodeled search method for short-duration GW transients. The cWB algorithm provides results for the entire frequency range while the BayesWave performs as a follow-up of the loudest cWB candidates event with frequency up to one 1 kHz. cWB does not require prior assumptions on signal morphology. It relies upon the excess coherent power in the network of detectors. The analysis uses multi-resolution Wilson–Daubechies–Meyer wavelet transforms to characterize the signal features.[4] cWB analysis was done in two frequency ranges separately for short-duration signals of up to approximately a few seconds, low-frequency (LF) analysis between 16 and 1024 Hz frequency range, and high-frequency (HF) analysis from 1024 to 4096 Hz.

During the O3 run, the Hanford–Livingston (HL) network has improved sensitivity over the Hanford–Livingston–Virgo (HLV) network. Since we focus on the maximization of detection efficiency, for the O3 LF analysis we consider the HL network rather than the HLV network.[1,7] The Hanford–Virgo (HV) network and the Livingston–Virgo (LV) network were analyzed when data from either of the LIGO detectors were not available. We have used only the HL network for the high-frequency analysis since Virgo has a significant sensitivity imbalance for frequencies higher than 1 kHz (almost a factor 5).[1] For cWB LF analysis, the triggers are divided into three mutually exclusive bins. It is based on background morphologies to isolate loud and frequent background glitches into a small parameter space. Whereas for the HF analysis, division of background triggers into bins is not

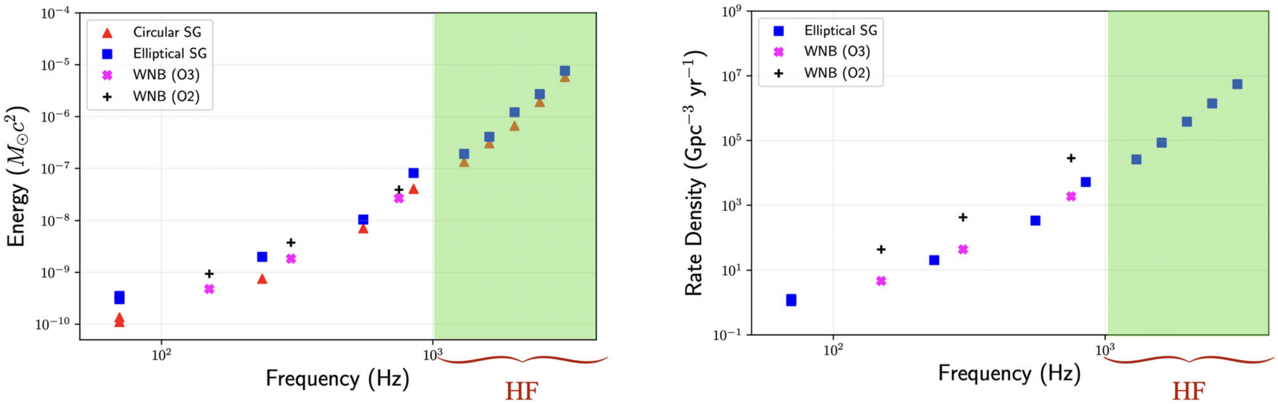

Figure 1. (Left) The GW emitted energy corresponds to a 50% detection efficiency at an iFAR ≥ 100 years for a source at 10 kpc during the O3 run. The waveform morphologies like circularly (an optimally oriented source) and elliptically (uniform distribution in the cosine of the inclination angle) polarized SG and WNB are considered. (Right) Upper limits for the GW rate density at 90% confidence intervals assuming $1M_\odot c^2$ of GW energy has been emitted from the source during the O3 run. The results are compared to the second observing run (O2) for the WNB waveforms. The shaded region is the high-frequency search range. Figure 1 reproduced with permission.[12] Copyright 2021, Phys. Rev. D.

required. The detailed description of binning is mentioned in refs. [1, 7].

Short GW burst searches are sensitive to CBC sources, the GW signals from CBC observed during the O3 run are reported in catalog papers [8] and [9]. The LF analysis results found no new candidates apart from the known CBC with high statistical significance during the all-sky short-duration transients search. In this work, we focused on the HF region where the search does not find any significant events and the loudest event is well within the expected noise. HF part of the parameter space is cleaner in the duration of background (lower glitch rates) when compared to the LF, however there exist (non-)stationary lines in power spectral density of O3 run.[1,10,11] The first part of the O3 run (until May 16, 2019) was affected by glitches at a very high frequency (> 3.4 kHz). Hence, the triggers with central frequency > 3.4 kHz were excised from the analysis before May 16, 2019.

3. Sensitivity

In order to place the search results in an astrophysical context, it is necessary to measure the detection efficiency of generic signal morphologies. The search sensitivity to the generic signal morphologies is described by a set of ad hoc waveforms sine-Gaussian wavelets (SG), Gaussian pulse (GA), and band-limited white-noise bursts (WNB). The ad hoc waveforms are injected over a range of amplitudes in the network of detectors in terms of the root-mean-squared strain amplitude (h_{rss}). Detection efficiency is expressed as the amount of energy emitted in GW for a detection, assuming source at a distance of $r_0 = 10$ kpc and isotropically radiating at a central frequency of f_0. Assuming the signal to be circularly polarized and narrowband, the amount of energy radiated is

$$E_{\rm GW}^{\rm iso} = \frac{\pi^2 c^3}{G} r_0^2 f_0^2 h_{\rm rss}^2 \tag{1}$$

While for the elliptically polarized waveforms, the energy is given as $E_{\rm GW}^{\rm rot} = (2/5) \times E_{\rm GW}^{\rm iso}$. The $h_{\rm rss}$ value at which 50% of the signals are detected with an inverse false alarm rate (iFAR) ≥ 100 years is used to find the amount of energy radiated by the source. The results are shown in **Figure 1** (left) since the search does not find any GW transient sources other than CBC signals. The upper limit of the rate per unit volume of non-CBC GW burst sources at 90% confidence, assuming $1M_\odot c^2$ of GW energy emitted is shown in Figure 1 (right). The energy can be scaled to any emission energy by the relation rate density $\propto E_{\rm GW}^{-3/2}$. The high-frequency search was interpreted in terms of neutron star f-modes, which may be excited by pulsar glitches.

3.1. Sensitivity to Neutron Star Glitches

The two main proposed mechanisms for pulsar glitches are starquakes and superfluid crust interactions.[13] NS glitches are a well-known and observed phenomenon in EM astronomy.[14] We detect only a sub-set of NSs in our galaxy and the population of NSs nearby us can be much more than what we observe in the EM spectrum. NS glitches can be a potential source of short-duration GW bursts during the spin-up phase. The pulsar glitch may excite various oscillations damped by GW emission in the form of a decaying sinusoid. The f-mode oscillations in particular are thought to be primary emitters of GW.[15–18] Assuming that the bulk of GW emission associated with oscillatory motion is generated by mass quadrupole (spherical harmonic index $l = 2$) f-mode oscillations, if all the available energy is absorbed into the excitation of the fundamental mode of oscillation[15] the energy generated during the glitch is given as

$$E_{\rm glitch} = 4\pi^2 I \nu_s \Delta\nu_s \tag{2}$$

where $I \approx 10^{38}{\rm kgm}^2$ is the NS moment of inertia, ν_s is the spin frequency, and $\Delta\nu_s$ is the increase in the spin frequency. The signal is modeled as a damped sinusoid, with frequency $\nu_{\rm gw}$ induced at time $t = 0$ and damps on a timescale $\tau_{\rm gw}$. Calculations of the frequency and damping time of the fundamental quadrupole mode for various models of the equation of state (EoS) indicate that the frequency lies in the range $1 \le \nu_{\rm gw} \le 3$ kHz and the damping time lies in the range $0.05 \le \tau_{\rm gw} \le 0.5$ s.[19] Hence GWs

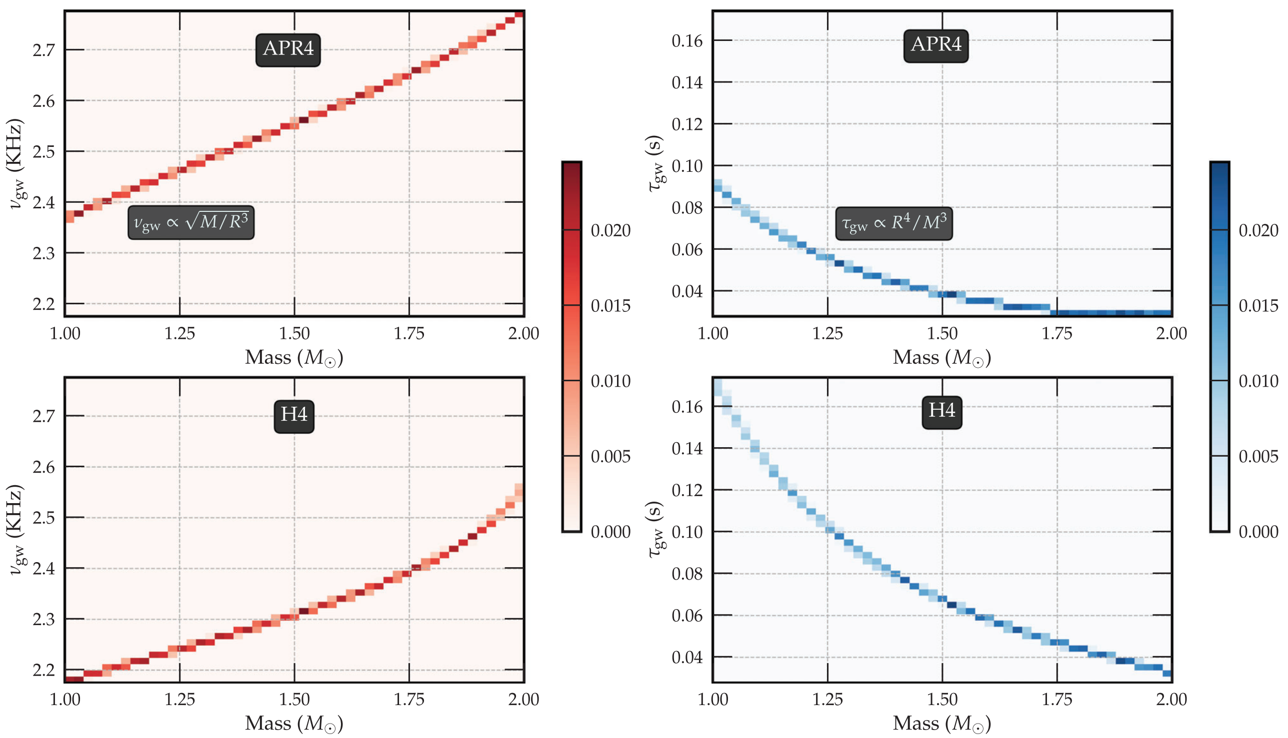

Figure 2. Distribution of GW frequency (left) and damping time (right) as a function of NS mass and EoS for APR4 and H4. Here we compare the relation for two EoS, APR4 (soft) and H4 (hard).

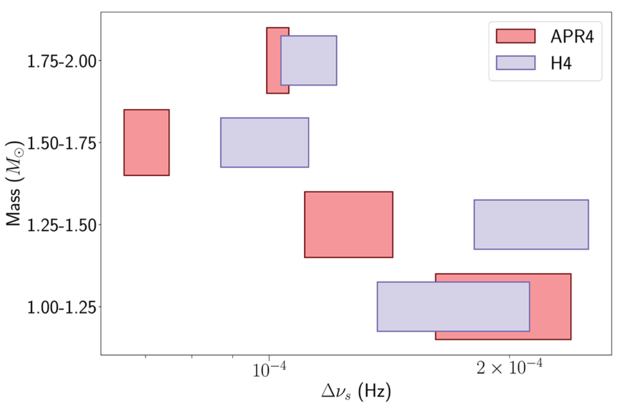

Figure 3. Sensitivity to neutron star glitches is shown in terms of detectable glitch size by considering the Vela pulsar as a reference in the distance and spin frequency for soft (APR4) and hard (H4) EoS, assuming an optimally oriented source distributed uniform in all-sky direction. For each EoS, the boxes show the search sensitivity of the glitch size for 50% detection efficiency at iFAR ≥ 100 years, and the spread of the box shows the variation within the mass bin. Figure 3 reproduced with permission.[1] Copyright 2021, Phys. Rev. D.

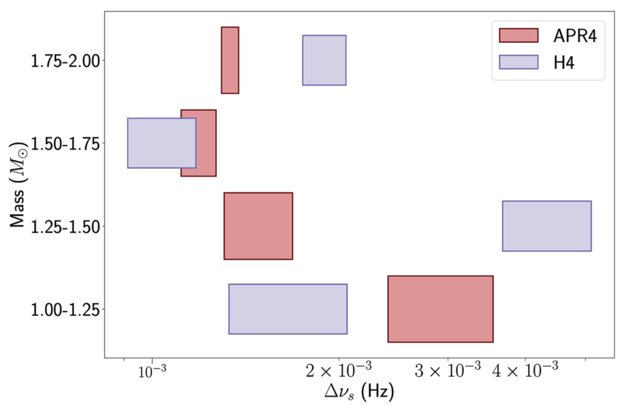

Figure 4. Sensitivity of neutron star glitches at iFAR ≥ 10 years during O3a run for EoS APR4 and H4 considering Vela pulsar as a distance and spin frequency reference. The source is assumed to be uniformly distributed in our galaxy and has uniform distribution in orientation.

from the NS glitches is in the high-frequency part of the cWB search. Here we consider the Cowling approximation[20] which gives the upper limit on the frequency, which is a conservative choice as the detector loses sensitivity at high frequencies. For the current study, we consider the NS masses are in the range of 1–2 $M_\odot$ and the radius of the NS is determined by the APR4 (soft) and H4 EoS.[1] **Figure 2** shows the distribution of GW frequency and damping time for two EoS, APR4 and H4, as a function of NS mass and EoS in Cowling approximation.

The peak amplitude h_0 of short-transient GW emitted by the source at distance d can be determined by GW luminosity.[15]

$$h_0 = 7.21 \times 10^{-24} \left(\frac{1\text{kpc}}{d}\right) \left(\frac{\nu_s}{10\text{Hz}}\right)^{1/2} \left(\frac{\Delta\nu_s}{10^{-7}\text{Hz}}\right)^{1/2} \times \left(\frac{1\text{kHz}}{\nu_{gw}}\right) \left(\frac{0.1\text{s}}{\tau_{gw}}\right)^{1/2} \quad (3)$$

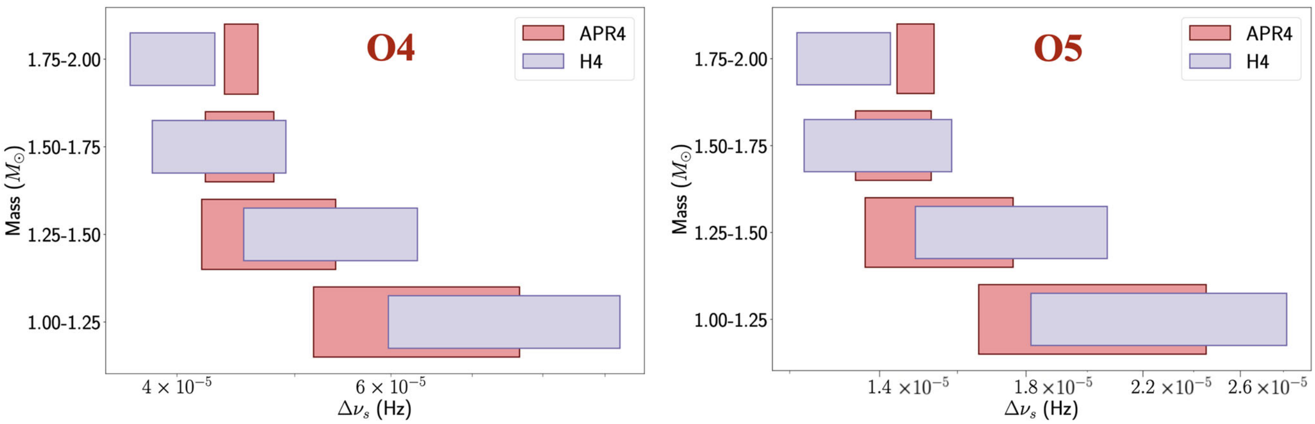

Figure 5. Sensitivity of neutron star glitches at iFAR ≥ 10 years for O4 (left) and O5 (right) power spectral density. The source is assumed to be uniformly distributed in our galaxy and has uniform distribution in orientation, keeping the Vela pulsar as a reference.

We present the sensitivity at 50% detection efficiency and iFAR ≥ 100 years in terms of detachable glitch size by assuming Vela pulsar as a reference in distance and spin. We also assume all the glitch energy is being converted to GW. The injections are distributed uniformly in the sky direction with an optimal orientation of the inclination angle (face on). We show the results for various NS masses and two EoS (soft and hard) in **Figure 3**.

To study the prospects of detecting GW signals from glitching pulsars in future observing runs of Advanced LIGO and Advanced Virgo detectors, we generated Gaussian colored noise as background for the fourth (O4) and fifth (O5) observing runs.[21] Here we injected the waveforms uniformly over the galactic disk. We chose the orientation to be uniform over the range of inclination angles. In **Figures 4** and **5** we show the comparison of the upper limit on glitch magnitude observable during O3a run and for O4, O5 sensitivity at an iFAR ≥ 10 years. The detectable glitch size for the O3 run is around 10^{-3} Hz, whereas the actual glitch size varies between 10^{-9}and10^{-4} Hz. The sensitivities obtained during the O3 run are thus not in the range where the detection would be expected at the energy scale of pulsar glitches like Vela pulsar. Future observing runs can show an improvement of an order of magnitude for the detectable glitch size.

4. Conclusion

We have interpreted the all-sky short-duration high-frequency search in terms of the detectable glitch size of NSs. During the O3 run, we have searched for the short transient GW burst signals emitted by NSs, keeping Vela as a reference in distance and spin frequency. No significant events were found by the all-sky short-duration search for the O3 run. For the third observing run, we require the glitch size of the order ≈ 10^{-4} Hz to confidently detect 50% of events for optimally oriented sources which are distributed uniformly in all-sky direction at iFAR ≥ 100 years. At the same time, the sources which are distributed uniformly in galactic disk with orientation uniform over the full range of inclination angles require an order ≈ 10^{-3} Hz to be observed with O3 run sensitivity. Improvements in the detector sensitivities for the next observing run can probe the NS's glitch size. For the fourth and fifth observing runs, we expect to probe glitch sizes down to 10^{-5} Hz; these glitch sizes are expected for the most extreme scenario.

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Conflict of Interest

The authors declare no conflict of interest.

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