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Searching for Gravitational-Wave Bursts with LIGO

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We present recent results from searches by the LIGO Science Collaboration for bursts of gravitational-wave radiation. These include directed searches for bursts associated with observed sources (gamma-ray bursts, soft gamma repeaters) and untriggered searches for bursts from unknown sources. We also present the status of newer investigations, such as coherent network methods. We show methods for interpreting our search results in terms of astrophysical source distributions that improve their accessibility to the wider community.

1 Introduction

The Laser Interferometer Gravitational Wave Observatory (LIGO) is in the middle of a lengthy science run (S5) in the search for gravitational-wave (GW) signals. One class of signals are short-duration ($< 1s$) "bursts" of gravitational-wave energy. The LIGO Science Collaboration (LSC) is continuing searches from these GW bursts started in previous science runs. The first section reviews some recent results from these LIGO-only searches. The next section covers new work on network-based burst searches, looking towards the addition of Virgo and other observatories. The last section covers methods for presenting GW burst search results in terms of rate limits on astrophysical source distributions.

2 Recent LIGO GW Burst Searches

Unlike the well-modeled waveforms for longer-duration GW signals from pulsars and the inspiral phase of binary compact object mergers, GW bursts are poorly modeled at present. Searches for GW burst signals thus must remain sensitive to a large range of signal waveforms. We divide the searches into two classes. One class are untriggered searches that examine all sky locations at all observation times. The other class are directed searches for GW burst signals associated with astronomically-identified source candidates such as Gamma-Ray Bursts (GRBs) of known sky location and observation time.

2.1 All-Sky Untriggered Burst Search

The initial untriggered burst search for LIGO run S5 uses the same approach as in previous such LIGO burst searches[4]. The search starts with a wavelet decomposition of the gravitational-wave channel data into time-frequency maps. Samples ("pixel") from these maps that have excess signal power relative to the background are identified. Such pixel clusters that are coincident in time and frequency between all three LIGO interferometers are selected as candidate triggers for further analysis. The candidate triggers must then pass a set of signal consistency tests to confirm that consistent waveforms and amplitudes are seen in all interferometers. These same methods are used to measure background rates by processing data with many artificial time shifts between two LIGO sites in Hanford and Livingston.

The LIGO-only burst GW analysis can have significant backgrounds from non-Gaussian transients. A particular problem are environmental transients at the Hanford site. These can induce simultaneous large-amplitude signals in the co-located interferometers (labeled H1 and H2) at that location. Detailed studies of Data Quality (DQ) are required to identify and defined time intervals when such problems are present. This work is assisted by the large number of auxiliary channels of interferometer and environmental sensor data that are recorded during science operation. Longer-duration time periods that have known artifacts or unreliable interferometer data are flagged as DQ Period Vetoes. Short-duration transient events in the auxiliary channels that are found to be coherent with events in the GW channels are flagged as Auxiliary-Channel Event Vetoes. Both veto classes are used to reject GW Burst triggers that coincide with them. These vetoes help remove any large-amplitude outliers in the final GW Burst trigger samples[4].

A detailed analysis of untriggered burst search results from the early part of S5 operation is being completed. We note that our searches in the previous LIGO runs (S1[1], S2[2], S3[3] and S4[4]) did not see any GW burst signals. The S5 run has both greater sensitivity than previous runs and at least 10 times the observation time. As in S4, this initial S5 all-sky GW burst search is tuned by bursts $\ll 1sec$ in duration over a frequency range of 64-1600 Hz. As there are few well-modeled waveforms for bursts from theoretical studies, we use 'ad-hoc' waveforms such as Gaussian-envelope sine-waves (Sine-Gaussians) and Gaussians that mimic the expected transient response to such bursts. We measure our sensitivity to such ad-hoc waveforms in terms of their root-sum-squared amplitude (h_{rss}) which is in units of strain/$\sqrt{\mathrm{Hz}}$ defined as

$$h_{rss} = \sqrt{\int (|h_{+}(t)|^2 + |h_{\times}(t)|^2) dt} \tag{1}$$

For this early S5 analysis, we are achieving detection sensitivities of $h_{rss} < 10^{-21}\mathrm{strain}/\sqrt{\mathrm{Hz}}$. These instrumental sensitivities can be converted to corresponding energy emission sensitivity[5]. Assuming isotropic GW burst with h_+ only polarization on Sine-Gaussian waveforms, we have

$$E_{GW} = (2.1 M_{\odot} c^2) \left(\frac{R}{100\mathrm{Mpc}}\right)^2 \left(\frac{f}{100\mathrm{Hz}}\right)^2 \left(\frac{h_{rss}}{10^{-21}\mathrm{Hz}^{-1/2}}\right)^2 \tag{2}$$

During the early part of S5, we are sensitive to $E_{GW} \sim 0.1 M_{\odot} c^2$ at a distance of 20 Mpc for $f = 153$ Hz.

2.2 GRB-triggered Burst Search

We have completed a search for short-duration GW bursts that are coincident with Gamma-Ray Bursts (GRBs) from the data in several previous LIGO science runs (S2, S3 and S4). This analysis used pair-wise cross-correlation of signals from two LIGO interferometers[6]. This approach increased the observation time over that available when all three LIGO interferometer were in science mode. The search targeted bursts with durations 1 to 100 ms over a bandwidth of 40-2000 Hz. There were no GW burst signals found that were associated with the 39 GRBs during the S2, S3 and S4 runs. The sensitivity of this GRB search is similar to that of the untriggered search. During S5, there have been about 10 GRBs per month. Thus, the GRB sample that will be used in the S5 analysis will be much larger.

Table 1: Network in terms of virtual detectors 'plus' and 'cross'.

detector	output	noise var.	likelihood	SNR
plus	X_+	ϵ	$L_+ = X_+^2/g$	$g\langle h_+^2\rangle$
cross	$X_\times$	ϵg	$L_\times = X_\times^2/\epsilon g$	$\epsilon\langle h_\times^2\rangle$

2.3 SGR 1802-20 Search

We have also completed a search for GW signals associated with the Soft Gamma-Ray Repeater(SGR) 1806-20. This SGR had a record flare on December 27, 2004 [7]. During this flare, quasi-periodic oscillations (QPOs) were seen in X-ray data from the RHESSE and RXTE satellites. These QPOs lasted for hundreds of seconds. During this flare, only one LIGO detector (H1) was observing. A band-limited excess-power search [8] was conducted for quasi-periodic GW signals coincident with the flare. No evidence was found for GW signals associated with the QPOs. Our sensitivity to the 92.5 Hz QPO was $E_{GW} \sim 10^{-7}\text{to}10^{-8} M_\odot$ at the 5-10 kpc distance of SGR 1806-20. This is comparable to the total electro-magnetic energy in the flare.

3 The Future of GW Burst Searches

The existing LIGO all-sky untriggered and GRB triggered burst search pipelines have been operating continuously on the acquired science-mode data since the start of the S5 run. These provide for the chance of prompt detection of GW bursts, enabling timely follow-up and investigation. The results are also used to provide identification of false signals from transients, speeding up the data quality and auxiliary-channel veto studies.

In searching for GW bursts, the community is adapting an approach that might be termed "The Network is the Observator". The benefit of having observatories at multiple, widely-separated locations can not be stressed enough. While LIGO-only burst searches have been fruitful, they require intense investigations for environmental and interferometer transients to remove backgrounds. Our previous LSC analyses have not make full use of the constraints that a network of sites can jointly make simultaneously on h_+ and $h_\times$ waveforms. Specifically, the GW burst searches must prepare for the addition of data from the Virgo observatory, and others in the future.

We fully expect to move from the era of upper limits to that of detection. In moving to detection, GW burst searches need to extract the waveform of the signals that are detected. Such waveforms can be compared to those from theoretical predictions for potential identification of the source type. We also should move on to providing interpretations of our GW burst results in terms of rates from astrophysical source distributions.

3.1 All-Sky Coherent Network Burst Search

Instead of looking separately at the response in each instrument, new searches are evaluating the network's response to GW signals. Such "coherent network" techniques will be used by the LSC for the analysis of the S5 data. In particular, they will be used for the analysis of data from joint observation with Virgo.

The "constraint likelihood" method [9] has been developed and applied to the all-sky untriggered burst search. Any network of detectors can be described as two virtual detectors,termed 'plus' and 'cross'. These can be parameterized in terms of their output X, noise variance, likelihood L and signal-to-noise ratio (SNR), as in Tb 1. The coefficient g is the network sensitivity factor characterizing the sensitivity to the real component of the wave, while ϵ is network alignment factor expressing the relative sensitivity to the real and imaginary wave components.

For two-location networks, it has been shown[9] that if the detectors are even slightly misaligned the normal likelihood statistic becomes insensitive to the cross-correlation between the detectors. This "two-detector paradox" results in the network alignment factor ϵ being $\ll 1$. This problem can be resolved be introducing a "soft constraint" on the solutions for the h_+ waveform. This technique removes un-physical solutions produced by noise. It does sacrifice a small fraction of the GW signals but enhances detection efficiency for the rest of the sources. The full coherent network analyses also divides the detected energy from all detectors into coherent and incoherent components. A cut on the network correlation (coherent/total) further removes backgrounds from single-detector transients. When compared to our existing all-sky search method for S5, the coherent network search achieves equal or better sensitivity with a very low background rate.

3.2 Network Method for GRB-Directed Search

Coherent network methods can also be applied to the search for GW bursts associated with GRBs. Because there is prior knowledge of the sky locations, and fewer sources than in the untriggered analysis, more computationally intensive methods can be used. A coherent network analysis method[10] has been developed to search for GW bursts at directed time and sky locations. This search uses the technique of Tikhonov Regularization[11] to solve the "two-detector paradox".

Both coherent network searches can also help extract the waveform of the detected signal. These are most successful when either the signal has a large SNR, or testing for the presence of waveforms of specific morphologies.

4 Astrophysical Interpretation

The existing GW burst search results from LIGO and IGEC are reported in terms of detector-centric "Rate vs. Strength" exclusion curves. These methods say nothing about the sources of GW bursts or about the rate of source events. The "Rate", typically in events/day, only refers to the rate observed at the detectors. The "Strength", expressed in terms of h_{rss} in units of strain/$\sqrt{\text{Hz}}$, is again only regarding the GW amplitude at the detector. This strength also reveals little about source quantities such as the absolute luminosity in terms of emitted gravitational-wave energy.

It would perhaps be better to report results in terms of rates from a source population as a function of the intrinsic energy radiated. We note that interpretation, astrophysical or otherwise, is always in terms of a model. The components of such a model would be the source population distribution and the source strain energy spectrum appropriate for GW burst searches. We also need to add in the observation schedule. This is the sidereal time associated with the data that is analyzed, which provides the detector pointing relative to the source population distribution.

We wish to report results in terms of their astrophysical rate vs. strength. The Astrophysical Rate is the event rate in the source population. The Astrophysical Strength is an astrophysically meaningful amplitude parameter such as the radiated energy. We express the bound on the astrophysical rate vs strength

$$R(E) = \frac{k}{T_{obs}\epsilon(E)} \tag{3}$$

where the constant k is set by the number of observed events (0.15 for no observed events), T_{obs} is the total observation time and $\epsilon(E)$ is the efficiency in the population. The efficiency in the population is the ratio of the expected number of observed sources over the total number of sources. The expected number of observed sources is the integral of the source rate distribution over detection efficiency and observation schedule. The total number of sources is the integral

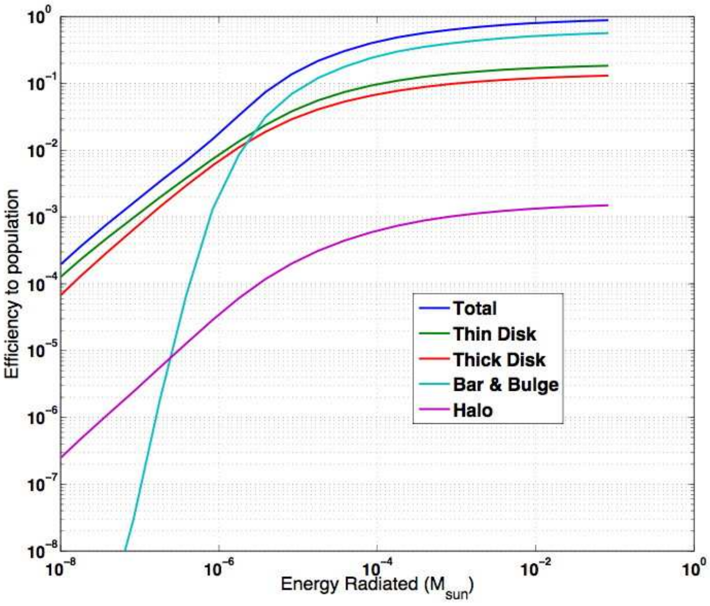

Figure 1: Detection efficiency to the source population for example galactic model. Note how disk components dominate at low levels of intrinsic radiated energy, while bar, bulge and halo components dominate for larger levels of radiated energy.

of the source rate distribution over the observation schedule alone. The source rate distribution will be a function of location, orientation and luminosity.

4.1 Example of Astrophysical Interpretation

It is best to illustrate what an astrophysical interpretation means with an example. We start by choosing a source population. We will assume the source population traces out the old stellar population. We will thus use a Milky Way galactic model with a thin disk, thick disk, bulge, bar and halo that are characteristic of the observed white dwarf population. For a source model, we will assume an implusive event that involves stellar-mass compact objects. These events could be supernovae, accretion-induced collapses(AIC), etc. We will assume an axisymmetric GW bursts and "standard candle" amplitudes where each source has the same absolute luminosity in GW bursts. For the network of detectors, we assume interferometers at the LIGO Hanford, LIGO Livingston and Virgo Cascina sites. Each site has an interferometer (labeled H1, L1 and V1) with a detection sensitivity characterized as a step-function at $h_{rss} \sim 10{-}20\text{Hz}^{-1/2}$. The LIGO Hanford site has an additional interferometer (H2) that has $h_{rss} \sim 2 \times 10{-}20\text{Hz}^{-1/2}$ due to being 1/2 as long as H1. For this example, we will assumed a 100% observation schedule, assuming uniform coverage in sidereal time.

First we calculate the efficiency to the population $\epsilon(E)$ as a function of the energy radiated (E). This is shown in Fg. 1 which has the efficiency broken down by contributions from each galactic model component to the total as a function of radiated energy in solar masses. Note that for radiated energy above 10^{-5} solar masses, contributions from the bar, bulge and halo components dominate, while below 10^{-6} solar masses, the thin and thick disk components dominate.

The efficiency to the population is used to derive the bound on population rate vs. strength. This is shown in Fg. 2 for the example. As different components dominate, the shape of the exclusion curve changes.

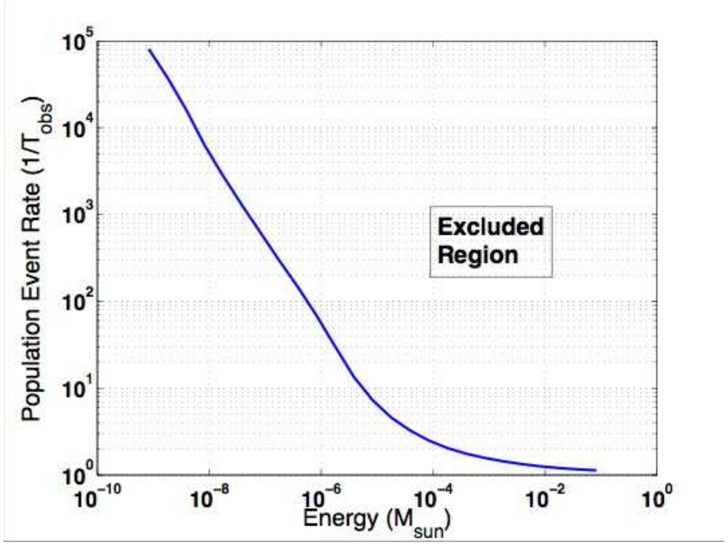

Figure 2: Bound on Population Event Rate as a function of Radiated Energy.

5 Conclusions

The LIGO-based burst searches are well established and already processing the data from the current S5 science run. New network-based techniques have been developed that provide enhanced detection sensitivity and background rejection. These methods show our preparation for joint observation with the Virgo observatory. The introduction of results interpretation in terms of astrophysical source distributions improves their accessibility to the astronomy and astrophysics communities.

Acknowledgments

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