Strategies and goals for stochastic gravitational wave background searches with Advanced LIGO and Advanced Virgo

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The Advanced LIGO detectors commenced observations in September of 2015, while Advanced Virgo will come on-line in 2016. They will approach their target sensitivities over the subsequent years. A major goal for LIGO and Virgo will be to detect or set limits on a stochastic background of gravitational waves. A stochastic background of gravitational waves is expected to arise from a superposition of a large number of unresolved cosmological and/or astrophysical sources. A cosmologically produced background would carry unique signatures from the earliest epochs in the evolution of the Universe. Similarly, an astrophysical background would provide information about the astrophysical sources that generated it. LIGO and Virgo observations should be able to probe interesting regions of parameter space for these models. Presented here is an outline of LIGO and Virgo's search strategies for these signals. Also discussed is how global electromagnetic noise (from the Schumann resonances) could affect this search; possible strategies to monitor and subtract this potential source of correlated noise in a the global detector network are explained.

Keywords: Gravitational wave detection; cosmology; astrophysical backgrounds.

1. Introduction

A consequence of Einstein's general theory of relativity are gravitational waves, a perturbations to spacetime that travel away from their source at the speed of light. When numerous small gravitational wave signals overlap and add together they will form a stochastic gravitational-wave background (SGWB). A stochastic gravitational-wave signal is formed from the superposition of many events or processes that are too weak and too numerous to be resolved individually, and which combine to produce a stochastic gravitational-wave background (SGWB). Cosmological sources, such as inflation, pre-Big Bang models, or cosmic strings, could create a SGWB. Astrophysical sources can also create a SGWB; this background could be produced over the history of the Universe from compact binary coalescences, supernovae, and neutron stars. As Advanced LIGO[1] and Advanced Virgo[2] conduct their observations a major goal will be to measure the SGWB. The detailed search plans for LIGO and Virgo as they enter the advanced detector era are articulated in *The LSC-Virgo White Paper on Gravitational Wave Searches and Astrophysics.*[3] The following is a summary of these search strategies by LIGO and Virgo as they attempt to observe a SGWB.

The spectrum of a SGWB is usually described by the dimensionless quantity $\Omega_{gw}(f)$ which is the gravitational-wave energy density per unit logarithmic frequency, divided by the critical energy density ρ_c ($\rho_c = 3c^2H_0^2/8\pi G$, where H_0 is the present value of the Hubble constant) to close the universe,

$$\Omega_{gw}(f) = \frac{f}{\rho_c}\frac{d\rho_{gw}}{df} \ . \tag{1}$$

Theoretical models of the SGWB in the observation band of LIGO and Virgo are characterized by a power-law spectrum which assumes that the fractional energy density in gravitational waves has the form

$$\Omega_{gw}(f) = \Omega_\alpha \left(\frac{f}{f_{ref}}\right)^\alpha \ , \tag{2}$$

where α is the spectral index and f_{ref} is a reference frequency. Cosmologically produced SGWBs are typically approximated by a power law in the LIGO frequency band, $\alpha = 0$, while $\alpha = 3$ is characteristic of astrophysical models.

The method by which LIGO and Virgo have attempted to measure the SGWB is, in principle, not difficult; optimally filtered correlations from the output strain data from two detectors are calculated.[4,5] Initial LIGO[6] and initial Virgo[7] have used this method on their data to set upper limits on the energy density of the SGWB.[8–10] No signal was detected, but the results constrain the energy density of the SGWB to be $\Omega_0 < 5.6 \times 10^{-6}$ at 95% confidence[10] in the 41.5–169.25 Hz band. The advanced detectors are expected to ultimately have about 10-times better strain sensitivity than the initial detectors; the low frequency limit of the sensitive band is also extended from 40 Hz down to 10 Hz. Furthermore, the number of detectors operating in a worldwide network will increase, eventually including sites at LIGO-Hanford, LIGO-Livingston, Virgo, GEO-HF (at high frequencies)[11], KAGRA (Japan)[12], and potentially LIGO India.[13] The significant strain sensitivity improvements and wider bandwidth will enable real breakthroughs in the searches for the SGWB, with a potential sensitivity of $\Omega_0 < 6 \times 10^{-10}$. The detection of a cosmologically produced SGWB would be a landmark discovery of enormous importance to the larger physics and astronomy community. The detection of an astrophysically produced SGWB is not unlikely and would also be of great interest.

Gravitational-wave signals that are too weak to be detected individually combine to form a SGWB. The SGWB that LIGO and Virgo hope to observe could be created from two classes of sources. A cosmologically produced SGWB would be created in the earliest moments of the Universe. There are a host of cosmological processes that could contribute to the SGWB, such as the amplification of vacuum fluctuations following inflation[14], phase transitions in the early universe[15,16], cosmic strings[17–20], and pre-Big Bang models.[21,22] An astrophysically produced SGWB would arise from the ensemble of what would be considered to be standard astrophysical events.[23] In total the astrophysical background would be the result of a broad spectrum of events, including core collapses to neutron stars or black holes[24–27], rotating neutron stars[28,29] including magnetars[30–33], phase transition[34,35] or initial instabilities in young neutron stars[36,37,37,38], compact binary mergers[39–44] and compact objects around supermassive black holes.[45,46] A foreground of astrophysical sources could potentially mask cosmologically produced signals. It may be that an astrophysical background would have different statistical characteristics than the cosmological background, and in that case it could be removed from a search for the cosmological background. However, astrophysical sources may not be numerous enough to create a truly Gaussian and stochastic background; the signals might not overlap in time and frequency.[41] As LIGO and Virgo commence observing in the advanced detector era the cosmologically produced SGWB and the astrophysically produced SGWB are both exciting targets for observation.

Fig. 1 shows the upper-limits that were achieved by initial LIGO-Virgo, the possible spectrum of some sources along with the projected limit using Advanced LIGO and Advanced Virgo.

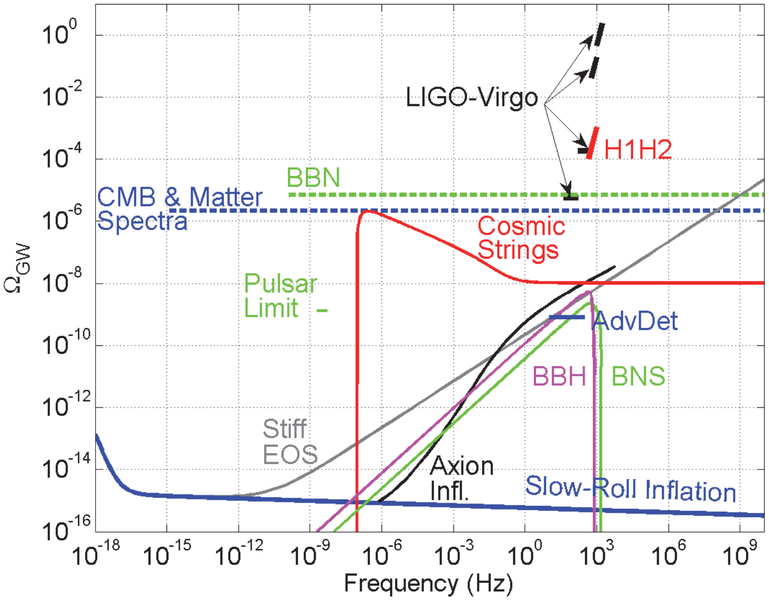

Fig. 1. The above figure[9] shows upper limits from initial LIGO-Virgo SGWB analyses[9,10], as well as the probable limit to be achieved by Advanced LIGO and Advanced Virgo at their target sensitivities and assuming one year of data (labeled AdvDet). Note the the initial LIGO – Virgo results are slightly better than the indirect limits from Big Bang Nucleosynthesis (BBN); note that this only applies over the LIGO observing band (see [8] for a detailed summary). The indirect limits from BBN apply to SGWBs present in the early universe at the time of BBN (and characterized by an $\alpha = 0$ power law), but not to SGWBs of astrophysical origin created more recently (and believed to be characterized by an $\alpha = 3$ power law). The measurements of CMB and matter power spectra provide a similar integral bound in the frequency range of $10^{15} - 10^{10} Hz$. The pulsar limit is a bound on the $\Omega_{gw}(f)$ at $f = 2.8$ nHz and is based on the fluctuations in the pulse arrival times from millisecond pulsars.[47] The Earth's normal mode limits are based on the observed fluctuations in the amplitudes of Earths normal modes using an array of seismometers.[48] Various possible SGWB predictions are given for cosmological and astrophysical sources; see [9] and references therein.

Most predictions about the character of the SGWB have it being isotropic, but there are processes where an anisotropy could be produced.[20,49] LIGO and Virgo also conduct searches that would provide additional information on the anisotropy of the SGWB across the sky, hence providing powerful tools to distinguish between different SGWB models. An astrophysically produced SGWB could be created from binary mergers[39,50,51], core-collapse supernovae[52,53], neutron-star excitations[34,54], persistent emission from neutron stars[55,56], and compact objects around supermassive black holes.[45,46] This astrophysical SGWB could be isotropic or anisotropic, contingent on the rate and redshift distribution of these objects. For instance, the gravitational-wave signals from all neutron stars in the Milky Way could produce an extended and anisotropic SGWB. This type of anisotropic signal would then be detected with higher statistical significance in the anisotropic search than in the isotropic search. The anisotropic search will display the angular content of the SGWB, and could be used to distinguish between different sources of the SGWB. As LIGO and Virgo search for a SGWB an anisotropic search will be an important supplement to the isotropic stochastic search.

The search provides information on the angular content of the SGWB in the form of a map of the gravitational-wave sky, and is therefore a powerful tool for distinguishing among different possible sources of the SGWB. The anisotropic search is a critical follow-up in the isotropic stochastic search.

The anisotropic SGWB search attempts to estimate the energy density of the SGWB, but retains the information on the direction of the source of the energy[57]:

$$\Omega_{gw}(f) \equiv \frac{1}{\rho_c}\,\frac{d\rho_{gw}}{d\ln f} = \frac{2\pi^2 f^3}{3H_0^2}\int d\hat{\Omega}\; H(f)\; P(\hat{\Omega}) \tag{3}$$

where $\hat{\Omega}$ is sky location. The frequency spectrum, $H(f)$, is assumed to be a power law in the observing frequency band of the detectors, namely $H(f) = (f/f_0)^{\beta}$. Cosmological models typically assume $\beta = -3$, while most astrophysical models use $\beta = 0$; once an assumption on the power index β is made the goal is to estimate $P(\hat{\Omega})$. Two different methods have been previously used by LIGO and Virgo, and the goal is to apply them on Advanced LIGO and Advanced Virgo data as well. For the radiometer algorithm, the signals are assumed to have been emitted from a point source

$$P(\hat{\Omega}) = \eta(\hat{\Omega}_0)\delta^2(\hat{\Omega}, \hat{\Omega}_0), \tag{4}$$

while with the spherical harmonic decomposition algorithm it is assumed that the SGWB signal can be expressed as a superposition of spherical harmonics

$$P(\hat{\Omega}) = \sum_{lm} P_{lm} Y_{lm}(\hat{\Omega}). \tag{5}$$

Initial LIGO and Virgo have conducted searches for an anisotropic SGWB[57] No signal was detected; the results constrain the gravitational-wave strain power at 90% CL with values in the range of $2 - 20 \times 10^{-50}$ strain^2 Hz^{-1} and $5 - 35 \times$

10^{-49}strain^2 Hz^{-1} sr^{-1} for pointlike (radiometer) and extended (spherical harmonic decomposition) sources respectively. LIGO and Virgo have also searched for persistent narrowband signals from the Galactic Center, SN1987A, and Sco X-1. No signals were detected, but upper limits were placed on strain as a function of frequency. These types of directional searches are an important part of the observing goals for LIGO and Virgo in the advanced detector era.

The low-mass X-ray binary, Sco X-1, is the brightest source of X-rays in the Earth's sky, aside from the sun. Sco X-1 is also an example of the kind of potential gravitational-wave source that LIGO and Virgo will target with a narrowband radiometer search. Sco X-1 likely contains a neutron star with unknown period; it is very probable that the spin period has been spun up through accretion torque. The phase evolution of the neutron star signal is unknown, and any emitted gravitational waves from the pulsar will be modulated in a complicated way by the binary motion and possibly spin wandering. A signal search based on cross correlation provides a powerful and robust method for possibly detecting this persistent but difficult to model gravitational-wave source. The Sco X-1 targeted radiometer search complements the other efforts by LIGO and Virgo to search for continuous gravitational wave signals from Sco X-1.[58,59]

As LIGO and Virgo enter the advanced detector area and conduct their observations there will be an enhancement of the radiometer search in order to target unknown, narrowband point sources such as rotating neutron stars in binary systems. This will be done by applying a new folded data technique.[60,61] It has been recently demonstrated that data compressed[61] using sidereal folding[60] can be used to facilitate a very efficient narrowband search that observes in all directions and at all frequencies. The all-sky, all-frequency extension to the radiometer will target unknown neutron stars in binary systems as well as all other narrowband searches; these are the type of signals that do not conform to a canonical continuous gravitational wave search, and have required innovative search pipelines in order to possibly detect them.[58,59] The stochastic radiometer provides a sensitive tool for discovering a persistent point source that does not conform to the assumptions made by template-based searches.

2. LIGO–Virgo Observations in the Advanced Detector Era

The Advanced LIGO[1] detectors are the second generation of interferometers designed and built for the two observatories operated by the LIGO laboratory: one at Hanford, Washington, and the other in Livingston Parish, Louisiana. Similarly, Advanced Virgo[2] is the upgrade of the Virgo detector to a second generation instrument, and is located in Cascina, Italy. Compared to the initial detectors, Advanced LIGO and Advanced Virgo are designed to provide a factor of 10 increase in strain sensitivity over a broad frequency band, and to extend the low end of the band to 10 Hz (from 40 Hz).

After three years of Advanced LIGO and Advanced Virgo observations at their target sensitivities the low frequency (less than 200 Hz) sensitivity to $\Omega_{\rm gw}$ should improve by four orders of magnitude. It should be noted that the upper limits to be set on the energy density of the SGWB should evolve rapidly during the commissioning phase for Advanced LIGO and Advanced Virgo. Based on the predicted typical sensitivities and observational runs given in[62], one can expect to improve the S6 upper limit[10] by a factor more than a factor 10 (to $\Omega_{\rm gw} \sim 3 \times 10^{-7}$) in the early commissioning era with 3 months of data. With 6 months of data in the mid era there should be an upper limit of $\Omega_{\rm gw} \sim 2 \times 10^{-8}$. In the late era 9 months of data should allow for an upper limit of $\Omega_{\rm gw} \sim 3 \times 10^{-9}$. Once Advanced LIGO and Advanced Virgo hit their target sensitivity one year of data will allow for an upper limit of $\Omega_{\rm gw} \sim 1 \times 10^{-9}$ (in the 10 Hz to 200 Hz band), while 3 years of data will give a limit of $\Omega_{\rm gw} \sim 6 \times 10^{-10}$. As these numbers show, rapid progress in sensitivity will be made at every commissioning stage. Similar sensitivity advances will also be made with the directional searches. The results of a mock science and data challenge show that Advanced LIGO and Advanced Virgo will be ready and able to make a detection of an astrophysical SGWB within a few years of operations of the advanced detectors, given a high enough rate of compact binary coalescing events.[63]

3. The Schumann Resonances as a Possible Source of Correlated Noise

As Advanced LIGO and Advanced Virgo come on line and work through commissioning to achieve their target sensitivities a source of correlated noise might affect the search for the SGWB. Recent measurements[64] demonstrated that correlated magnetic fields from the Schumann resonances[65] can produce correlated magnetic noise over vast distances, potentially limiting the sensitivity of SGWB searches with advanced detectors. Searches for the SGWB rely on cross-correlations.[4,5] A key premise in past LIGO cross-correlation searches was that the noise in each detector was uncorrelated. Correlated noise creates a systematic bias, which is not reduced with continued integration. However it has been shown that magnetic fields from global Schumann resonances[65] can create magnetic correlated noise in a global network of gravitational-wave detectors.[64] While correlated magnetic noise from the Schumann resonances was too low level to affect SGWB searches with first generation detectors (initial LIGO and Virgo), the results indicate that it might be significant for the advanced detectors, such as Advanced LIGO[6], Advanced Virgo[7], and KAGRA.[12] It has also been shown that noise subtraction methods based on Wiener filtering could be used on LIGO-Virgo data[66]; this assumes that sufficiently sensitive magnetometers can be operated near the LIGO and Virgo sites to measure the magnetic fields from the Schumann resonances. As Advanced LIGO and Advanced Virgo commence observations the intent will be to monitor the globally coherent magnetic fields from the Schumann resonances. LIGO and Virgo are planning to install low noise magnetometers in electromagnetically quiet areas near to the observatories (the combination of intrinsic magnetometer noise and local magnetic field noise must be less than $1pT/\sqrt{Hz}$ in the 10 Hz to 30 Hz band). With this magnetic field data it will be possible to accurately monitor the magnetic field noise, and implement Wiener Filtering methods[66] if noise subtraction is required.

4. Conclusion

Advanced LIGO has started observations in September 2015, while Advanced Virgo will come on-line in 2016. Through the search for a SGWB exciting physics questions will be addressed. An astrophysical background from coalescing compact binary systems could possibly be observed with the LIGO-Virgo network. Many cosmological models will be constrained by observations over the coming years. Much work is presently going on in preparation for the analysis of the observing run data. A mock science and data challenge is continuing to test the search pipeline under numerous scenarios.[63] Correlated electromagnetic noise from the Schumann resonances is a real concern, and is the cause for much commissioning work, experimental investigations, and data analysis research at present.

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