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Search of Astrophysical results with LIGO from the Science runs S1 to S5

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ABSTRACT

The gravitational wave detectors especially LIGO has attained its design sensitivity and up gradation has virtually reached near the completion. The gravitational wave search is in progress and hopefully result will be possible in due course of time.

We discuss the recent attempts to detect various classes of signals which include un-modelled sub second burst of gravitational radiation like from core collapse supernoval and γ-ray burst engine. A stochastic background of gravitational waves of cosmological origin would provide a new idea about early universe. We discuss current attempts to detect gravitational waves from these sources and know about future prospectus of these searches.

Keywords

Gravitational waves; Neutron Stars; Black Holes; Gravitational wave detectors.

Academic Discipline And Sub-Disciplines

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SUBJECT CLASSIFICATION

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1. INTRODUCTION

Gravitational waves are the ripples which propagate as strain waves in space time with the velocity of light. Gravitational waves are produced by accelerating massive and dense objects. Close binary system of compact objects like white dwarf, neutron stars and black holes of any size are most prominent astrophysical sources. Gravitational radiation is an exotic prediction of general relativity proposed by Albert Einstein. Its study is presently considered as a challenging task in theoretical physics and collective efforts are made to gather and analyze all kinds of related informations. The signal received from the astrophysical sources significantly increase our understanding of universe. The only experimental evidence for gravitational waves come from timing of binary pulsar system [1,2]. These systems consists of two neutron stars orbiting each other. The first double pulsar PSRB 1913 + 16 was discovered by Hulse & Taylor in 1974 [3- 5].

The detection of gravitational waves will usher in a new era of astronomy. Their detection will help us to study strong field gravity around black holes and in the early universe and provide probes of the neutron star equation of slate.

The Laser interferometer gravitational wave observatory (LIGO) at present is one of the major projects to detect the gravitational waves. It consists of three multi Kilometer ground based interferometres. The Hanford Washington WA site has two Co-Located and Co-aligned interferometers, one with 4Km long arm and another with 2 Km long arm referred as H1 and H2 respectively. The Livingston, Louisiana LA site has one interferometer with 4Km arm called as L1. These detectors are Michelson interferometer with Fabry- Perot arm cavities. Gravitational waves when passes through these interferometer change the relative lengths of the arms which is being observed as a change in the output light intensity. LSC, a worldwide network of institutions is supporting research in all aspects of LIGO science.

Till date, LIGO has competed six science runs. LIGO performed its first science run S1 in 2002. After the completion of S5, two LIGO detectors with 4 KM arm H1 and L1 were taken offline for upgrades based on the knowledge of the noise source, which limit the performance of initial LIGO; subsequently the upgrades (Enhanced LIGO) will improve their sensitivity by roughly a factor of 2. The third detector H2 was left online in tandem with GEO 600 to observe the gravitational waves until the upgrades are complete.

Searches of gravitational waves with LIGO are classified into four broader categories based on the nature of signal. We shall precisely elaborate the highlights of science runs S1 to S5 to explain Astrophysical results with LIGO.

2. ASTROPHYSICAL RESULTS

Prior to the advent of large scale interferometric detectors, limited efforts were in place to produce astrophysical results. The Caltech 40m detector was put in place to search gravitational wave emission from Pulsar J 1939 + 2134[6]. Prototype detectors were used to set an upper limit on the strain of gravitational wave burst [7]. The Graching detector was used to search for periodic signals from pulsars. However, with large scale detectors taking data and vastly improved sensitivities push upper limit on source population. The recent results have generally been split into four broad areas based on the nature of signal.

1) Unmodelled burst
2) Compact binary coalescences
3) Continuous quasi monochromatic emission
4) Stochastic sources

Unmodelled Bursts

Unmodelled burst are generally taken as any transient signal for which there is no good theoretical model. Search for un-modeled burst include Supernovae core collapse and gamma ray burst engines and these searches typically focus on detecting generic waveforms with durations in the range 1-100 ms. Data received by LIGO during science run S1 was for gravitational wave bursts of between 4 to 100 ms and within the frequency band 150 to 3000 Hz [8]. Data from all three detectors was analyzed. No reasonable candidate event was found despite of the fact a 90% confidence upper limit on the event rate of 1.6 events per day was set. The search was of 50% detection efficiency, to burst with amplitude of

$h_{rss} \sim 10^{-19} – 10^{-17}$ Hz$^{-1/2}$.

During science run S2 the sensitivity got improved and advanced analysis techniques allowed sensitivity to signals in the frequency range 100-1100 Hz and in the amplitude range $h_{rss} \sim 10^{-20} – 10^{-19}$ Hz $^{-1/2}$ [9]. Again no signal was received, but a 90% upper limit of 0.26 event per day was set for strong burst.

Science run S3 produced two searches for burst sources. One used the 08 days of triple coincidence data from LIGO detectors to search for sub second burst in the frequency range 100-1100 Hz [10], and it being sensitive to signals of amplitude over $h_{rss} \sim 10^{-2}$ .15.5 day of data for science run S4 were searched for sub second burst in the frequency range of 64 -1600 Hz [11]. This was sensitive to signals with $h_{rss} \le 10^{-20}$ and set a 90% confidence rate upper limit of 0.15 per day.
These result indicate astrophysical limit on source ranges and energies.

The frequency range for the all sky burst search was split into two during first year of S5 data. A low frequency search covered the most sensitive region between 60 - 200 Hz [12] and a high frequency search covering 1- 6khz (this being an un-triggered burst search looked at frequencies above 3 kHz [13]. The high frequency search set a 90% upper limit on the rate of 5.4 events per year for strong events. The low frequency search analyzed more data and set an event rate limit of

3.6 events per year. The second year of S5 data was analyzed with GEO 600 ad Virgo VSR1 [14] to search for burst over the whole 50 – 6000 HZ band. After combining this with earlier S5 results gave hrss upper limit for a variety of simulated waveforms of 6×10^{-22} $Hz^{-1/2}$ to 2×10^{-20} $Hz^{-1/2}$ and a 90% confidence event rate for signals between 64 -2048 Hz of less than two per year.

Compact Binaries Coalescences

Modelled burst are generally meant as inspiral and coalescence stages of binaries of compact objects like neutron stars and black holes. The majority of inspiral searches make use of matched filtering in which a template bank of signal models is built [15, 16]. These templates are then cross correlated with the data and statistically significant triggers.

The first search for an inspiral signal with data from LIGO science run S1 looked for compact object coalescences with component masses between 1-3 $M_\odot$ and was sensitive to such sources [17]. It gave a 90% confidence level upper limit on the rate of 170 per year per MWEG.

For the S2 LIGO analysis, the search was split into three categories covering neutron star binaries, black hole binaries and primordial black hole binaries in the galactic halo. Neutron star binary search took fifteen days of data with coincidence between either H1 and L1 or H2 and L1 [18]. It had a range of ~ 1.5 MPC which spanned the local group of galaxies and gave a 90% event rate upper limit on systems with component masses of 1-3 $M_\odot$ of 47 per year per MWFG. The BH binary search looked for systems with component masses in the 3-20 $M_\odot$ range using same data set as the neutron star binary search [10]. This search had a 90% detection efficiency for sources out to 1MPC and set a 90% rate upper limit of 38 per year per MWFG. The third search looked for low mass (0.2-1 $M_\odot$) primordial blackhole binaries in a 50Kpc radius halo surrounding the Milky Way [19]. The search for Neutron star NS-BH Black holes binaries in S3 LIGO data was meant to search for systems with components masses in the range 1-20 MO and analyzed 167 hours of triple coincident data and 548 hours of H1 – H2 data to set the upper limit [20].

The search for wide range of binary system with components consisting of primordial BH, NS & BH with masses in the range mentioned above was conducted on the combined S3 & S4 data [21]. 788 hours of S3 data and 576 hours of data were used and no reasonable gravitational wave candidate was found. The highest mass range for BH binary system was set at 40 $M_\odot$ for S3 & 80 $M_\odot$ for S4. S4 data has also been used to search for ring downs for perturbed BH. The search was very sensitive to ring downs from 10-500 $M_\odot$ black holes out to a maximum range of 30 MPC and produced a best 90% confidence upper limit on the rate of ring downs to be 1.6×10^{-3} per year per for the mass range 85 -390 $M_\odot$. Figure 1 show the distance to which in spirals could be detected by LIGO as a function of mass in S3& S4 search. Figure1 also shows the cumulative luminosity in L_{10} as a function of distance. No inspiral were detected. Based on the instrument sensitivity the expected detection rate was < 0.01 yr^{-1} (NS-NS) and < 0.1 yr^{-1} (BH – BH).

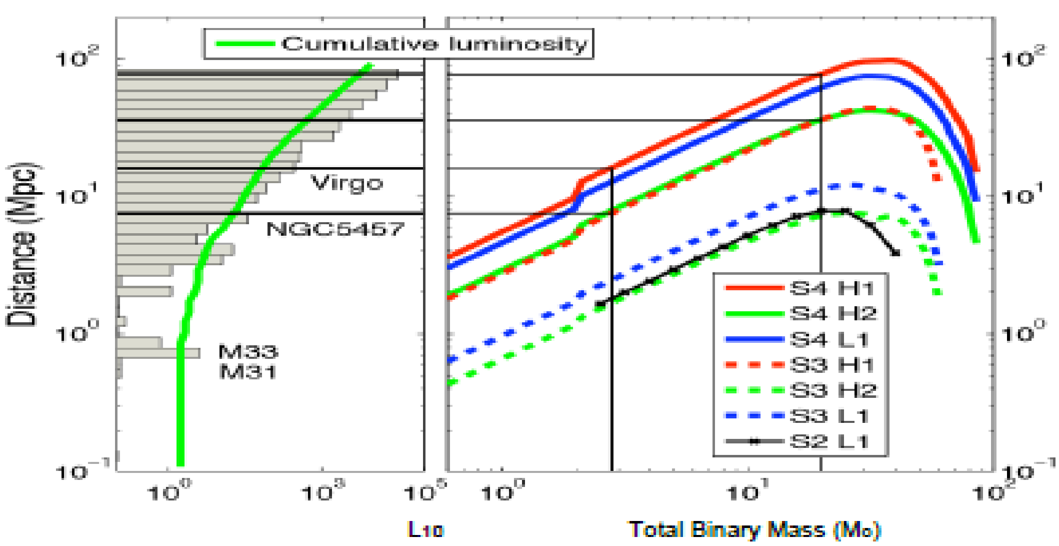

Fig 1: Cumulative luminosity and maximum distance for detecting inspirals vs. binary mass in the S3 and S4 runs

Data from the first year [22] and second year of S5 [23] have been searched for low mass binary coalescences with total mass in the range 2-35 $M_\odot$. The second year search results have produced more stringent upper limit with 90% confidence rate for neutron star binaries as 1.4×10^{-2} for BH binaries as 7.3×10^{-4} and for Ns –BH system as 3.6×10^{-3} per year per L_{10} . The entire S5 data was also used to search for higher mass binary coalescence with component mass between 1-99 $M_\odot$ and total mass of 25-100 M . No signal was seen, but a 90% confidence upper limit rate on mergers of BH binary system with component masses between 19 and 28 $M_\odot$ and with negligible spin was set at 2.0 MPC^{-3} Myr^{-1} [24].

Continuous Quasic Non-Chromatic Emission

The possible signals of gravitational waves from spinning NS will be week, but continuous and quasi monochromatic, so that it can in principle be detected by heterodyning the data to follow the pulsar phase. The known pulsar search uses catalogs of pulsars to search for gravitational waves in this manner Figure 2 shows the upper limit from the most recent searches for gravitational waves from 78 known pulsars [25].

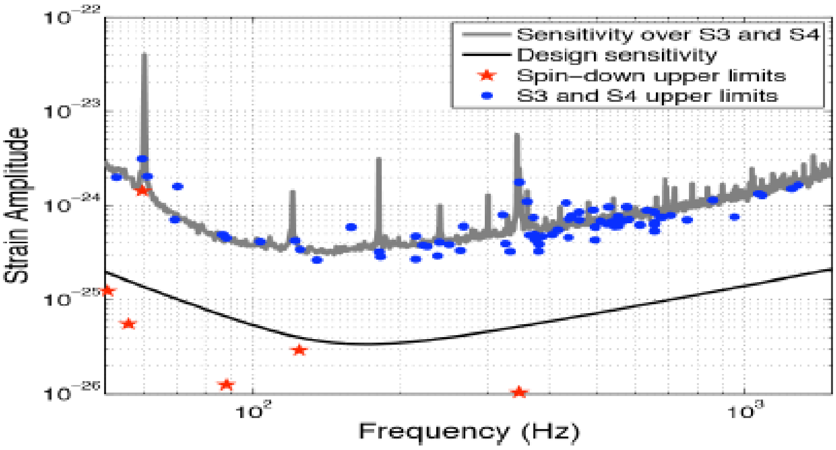

Fig 2: Upper limits (circles) from the S3 and S4 data on GW emission by 78 known pulsars. The spin-down limits (stars) are the expected signal amplitudes if the observed spin down was due entirely to gravitational-wave emission. Also shown are the expected sensitivities based on the S3 and S4 data and for one year of data at design sensitivity

For some pulsars astrophysically interesting sensitivities are being reached for some pulsars. For example the equatorial ellipticity of PSRJ 2124-3358 is constrained to be less than 10^{-6}. There are some semi targeted searches which may be potential sources in which some source signal parameters are known. For example neutron stars in X-ray binary system or sources in supernova remnants. The target oriented search can be the most sensitive as they are able to perform coherent integration over long stretches of data. Due to neutron star population, the estimate of amplitude of the strongest gravitational wave pulsar observed at Earth will be $h_0 \leq 10^{-24}$ [26]. The various search techniques used to produce these results look statistically significant [27, 28, 29].

A targeted search during science run S1 was performed for gravitational waves from then fastest millisecond pulsar J 1939 + 2134 [30]. This analysis and the subsequent LSC known pulsar searches assumed that gravitational waves emitted have exactly twice its rotational frequency. All the data from LIGO and GEO600 was analyzed and no evidence of the signal was realized. On the basis of data from most sensitive detector L1 giving a value of 1.4×10^{-22}, a 95% degree of belief upper limit on the gravitational wave strain amplitude was set.

During science run S2 the number of known pulsars searched by LIGO had gone to 28, although all being isolated pulsars. The lowest 95% upper limit on gravitational waves amplitude was 1.7×10^{-24} for PSRJ 1910-5959D and the smallest upper limit on ellipticity was 4.5×10^{-6} for the relatively close pulsar PSRJ 2124-3358 at a distance of 0.25 KPC.

In S3 and S4, using LIGO data the number of sources searched was increased to 98. This include many pulsars within binary systems. The lowest 95% upper limit on gravitational wave amplitude was 2.6×10^{-25} for PSRJ 1603 -7202 and smallest ellipticity was again for PSRJ 2124-3358 at just less than 10^{-6} [25]. The upper limit of the crab pulsar was found to be only 2.2 times above that from the spin down limit. Three semi coherent all sky continuous wave searches were performed on S4 LIGO data, looking for isolated neutron star in the frequency range from -1×10^{-8} Hz S^{-1} [31]. The Einstein's home project was also used to search the data from S4 which consisted of 300 hours of H1 data and 210 hours of L1 data. The search performed an analysis on 30 hour stretches of this data and covered the frequency range of 50-1500HZ. Approximately 6000 years of computational time spread over about 100,000 computers were required to perform the analysis. No gravitational candidate was found although the result suggest that 90% of sources with strain amplitude greater than 10^{-23} would have been detected by the search efforts.

In science run S5, first 08 months were used to perform an all sky search for periodic gravitational waves. This search used data from H1 and L1 detectors [32]. 95% strain upper limit of less than 10^{-24} over a frequency band of 200 HZ was achieved. The search could have been sensitive to a neutron star with equatorial ellipticity greater than 10^{-6} within around 500 PC. Einstein @ home was used to search periodic waves of 50-1500 Hz in 860 hours of data from a total span of 66 days of S5 data [33] to look for young pulsar, but saw no significant result. The first approximate 09 months of S5 data was used in searching gravitational waves from crab pulsar [34]. Two 95% upper limit were set, one using astrophysical constraints on the pulsar orientation angle and polarization angle [35].

A semi targeted search was performed with 12 days of S5 data to look in frequency band between 100-300 Hz and covered a wide range of first and second frequency derivatives and no signal was seen [36], but it gave 95 % amplitude and ellipticity upper limit over the band of (0.7 - 1.2) $\times 10^{-24}$ and (0.4 - 4) $\times 10^{-4}$ respectively. These results beat indirect limits on the emission based on energy conservation argument and were also the first results to be cast as limits on the γ - mode amplitude [37].

Stochastic Sources

Stochastic search are conducted for a cosmological or astrophysical gravitational wave background. It can be done by performing a cross correlation of data from pair of detectors at different sites especially H1-L1 and H2-L1 and separate sites are used to minimize the potential for environmental noise [38]. These pair of detectors gave a 90% confidence upper limit of $\Omega_{gw} < 44\pm9^2$ in the frequency band of 40- 314Hz, where the upper limit is in units of closure density of the universe. This limit being better than previous limits but still well above the ΛCDM Cosmology value of the total energy density of the universe of Ω ~1 [39]

There was no stochastic search during S2 run, while as S3 data gave an upper limit that improved on the S1 result by a factor of ~ 10^5. The most sensitive detector pair for this search was H1-L1 for which 218 hours data were used [40]. For gravitational wave background an upper limit was set for three different power law spectra. For flat spectra a 90% confidence upper limit of $\Omega_{gw}(f) = 8.4 \times 10^{-4}$ in the 69 -156 HZ range was set. As per prediction for a super position of rotating neutron star signals, an upper limit of $\Omega_{gw}(f) = 9.4 \times 10^{-4} (f/100Hz)^2$ was set in the range 73 -244 HZ for a quadratic power law and for cubic law, an upper limit of $\Omega_{gw}(f) = 8.1 \times 10^{-4} (f/100Hz)^3$ in the range 76-329 was produced.

During science run S4, 354 hours of H1-L1data and 333 hours of H2-L1 data were used to set a 90% upper limit of Ωgw(f) < 6.5 × 10-5on the Stochastic background between 51-150 HZ [41].
The data of S5 from the LIGO has been used to set a limit on the stochastic background around 100 HZ to be $\Omega_{gw}(f) < 6.9 \times 10^{-6}$ at 95% confidence [42].

3. CONCLUSION

The LIGO detectors have reached to greater order of design sensitivity. Extensive search is being carried out from compact binaries, pulsar, GRBS and other sources. The coming times will see extensive upgrades to both LIGO and other detectors across globe, increasing their sensitivity by up to a factor 15 and bring us into new era of gravitational wave astronomy, which could radically change our understanding of the Universe, expanding knowledge of fundamental physics, cosmology and relativistic astrophysics.

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