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Search for gravitational waves from low mass compact binary coalescence in 186 days of LIGO's fifth science run

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We report on a search for gravitational waves from coalescing compact binaries, of total mass between 2 and $35M_\odot$, using LIGO observations between November 14, 2006 and May 18, 2007. No gravitational-wave signals were detected. We report upper limits on the rate of compact binary coalescence as a function of total mass. The LIGO cumulative 90%-confidence rate upper limits of the binary coalescence of neutron stars, black holes and black hole-neutron star systems are 1.4×10^{-2}, 7.3×10^{-4} and $3.6 \times 10^{-3}\ \mathrm{yr}^{-1}\,\mathrm{L}_{10}^{-1}$, respectively, where L_{10} is 10^{10} times the blue solar luminosity.

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In November 2005 the three first-generation detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) reached design sensitivity and began a two-year period of observations (known as the fifth science run, or S5) which concluded in October 2007 [1]. One of the most promising sources of gravitational waves for LIGO is a compact binary coalescence (CBC), the inspiral and merger of binary neutron stars (BNS), binary black holes (BBH), or a black hole-neutron star binary (BHNS) [2–7]. These systems spiral together as they emit energy in the form of gravitational waves, finally merging to form a single object, which then settles down to equilibrium. Ground-based gravitational-wave detectors are most sensitive to waves with frequencies between ~40 and 1000 Hz, corresponding to the late stages of inspiral and merger. In this paper we report the results of search for gravitational waves from binaries with total mass between 2 and $35M_\odot$ and a minimum component mass of $1M_\odot$ in LIGO observations between November 14, 2006 and May 18, 2007. The results of a search for these systems in data taken from November 4, 2005 to November 14, 2006 were reported in Ref. [7]. From May to October 2007, the Virgo gravitational-wave detector operated in coincidence with the LIGO detectors [8] and the LIGO data from this period are being analyzed together with the Virgo data. The joint analysis requires significant modifications to our analysis pipeline; therefore results of this search will be reported in a subsequent publication. In contrast, the results presented here were obtained with substantially the same analysis pipeline used in Ref. [7].

No gravitational-wave signals were observed during this search and so we report upper limits on CBC rates using the upper limits of Ref. [7] as prior rate distributions. We summarize the analysis procedure and we present the search results and upper limits on CBC rates derived from LIGO observations in the period November 4, 2005 to May 18, 2007.

The data-analysis pipeline.—The data-analysis pipeline used in this search is fundamentally the same as that of Ref. [7]; thus here we only describe the major components and highlight differences to the previous search, referring to Refs. [6,7] for details. The most substantial change in this analysis is a modification to the way in which the significance of candidate events is compared to instrumental noise background. In previous searches, the noise background was computed *using the entire observation period* by introducing an artificial time shift between data recorded at the two LIGO observatories. The observation

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[*] http://www.ligo.org

period is split into six four-week segments and one 18-day segment (referred to as ‘‘months’’) and the instrumental background is measured *independently in each month*, as the detector behavior varied over the course of the S5 run. Candidate triggers are therefore compared to a background that better reflects the instrumental behavior at the time of the candidate. Each month was searched independently for gravitational-wave candidates and in the absence of detections, the results from the months are combined (together with the results from Ref. [7]) to set an upper limit on the CBC rate.

We search for gravitational-wave signals when at least two of the LIGO detectors were operational. This comprised a total of 0.28 yr when all three detectors (the 4 and 2 km Hanford detectors, denoted H1 and H2, respectively, and the 4 km Livingston detector, denoted L1) were operational (H1H2L1 coincident data), 0.10 yr of H1H2 coincident data, 0.02 yr of H1L1 coincident data, and 0.01 yr of H2L1 coincident data. Noise correlations between the colocated H1 and H2 detectors cause our method of estimating the instrumental background using time-shifted data to fail, and so we do not search data when only the H1H2 detectors are operating. Approximately 10% of data is designated *playground* and used for tuning our search pipeline.

Post-Newtonian (PN) theory provides accurate models of the inspiral waveform predicted by general relativity up to the innermost stable circular orbit (ISCO) [9–16]. The frequency of the waveform from the low mass binaries targeted in this search sweeps across the sensitive band of the LIGO detectors. Therefore, we search for signals from our target sources by match filtering the data with PN templates terminated at ISCO. This method is suboptimal if a true signal differs from our template family due to unforeseen physical effects. Matter effects in BNS and BHNS are not included in our templates, but are expected to be important only at higher frequencies [17,18]. We construct template banks [19] of restricted second order PN waveforms in the frequency domain [10,20,21] such that no more than 3% of the signal-to-noise ratio (SNR) is lost due to the discreteness of the bank [22]. A ‘‘trigger’’ is generated if the matched-filter SNR of the strain data filtered against the template exceeds a threshold of 5.5 [23]. We demand that triggers are coincident in time of arrival and mass [24] in at least two of the three LIGO detectors. When all three detector are operating we can obtain (in principle) four possible types of coincidence: H1H2L1 triple coincident triggers and three different double coincident types: H1H2, H1L1 and H2L1. We discard H1H2 double coincident triggers, due to the problems estimating the background for these triggers and discard H2L1 triggers when the H1 detector is operating nominally (since the 4 km H1 detector is more sensitive than the 2 km H2 detector). Coincident triggers are subjected to consistency checks using signal-based vetoes [25–27]. Times of poor detector data quality are flagged using environmental and auxiliary data; triggers from these times are also vetoed [7]. We construct two categories of data-quality vetoes depending on the severity of the instrumental artifact being flagged. In our primary search and upper limit computation we veto coincident triggers that fall in times from either category. We also consider detection candidates in data with only the most severe category applied in case a loud signal is present that may otherwise be vetoed. Surviving triggers are clustered in time and ranked by an effective SNR statistic, which is computed from the trigger’s matched-filter SNR and the value of the χ^2 signal-based veto for that trigger [6]. After discarding playground data and times in both veto categories, a total of 0.21 yr of triple coincident data (H1H2L1), 0.02 yr of H1L1 coincident data, and 0.01 yr of H2L1 coincident data remain. In the absence of a detection, these data are used to compute upper limits on the CBC rate.

The rate of instrumental noise artifacts is measured by time-shifting data from the Livingston and Hanford observatories (H1 and H2 data are kept fixed with respect to each other). The data are offset by more than the light-travel time between observatories; thus triggers which survive the pipeline are due to noise alone. We performed 100 such time shifts to obtain a good estimate of the noise background in our search. CBC signals of higher mass contain fewer gravitational-wave cycles in the sensitive band of our detectors; our signal-based vetoes are not as powerful. High-mass templates are therefore more sensitive to nonstationary noise transients and hence our false alarm rate (FAR) for these system is larger. In order to account for this mass-dependent behavior we compute the background for three different mass regions and compare foreground and background within each of these ranges. Specifically, in each region we count the number of background triggers with effective SNR greater than or equal to a given foreground trigger; dividing this number by the amount of background time analyzed gives us the FAR for that trigger. This allows us to define a single detection statistic for every trigger in each of the mass categories. The FAR can then be directly compared to obtain a ranking of the significance of the triggers, regardless of their mass [7].

Search results.—The seven months of data were analyzed separately using the procedure described above. No gravitational-wave candidates were observed with a FAR significantly above those expected from the noise background. The loudest trigger in this search was a triple coincident trigger with a FAR of 6 per year. This is consistent with the expected background, since we searched 0.21 yr of data. The second and third loudest triggers had FAR values of 10 and 11 per year, respectively. Although we did not have any detection candidates, we exercised our follow-up procedures by examining any triggers with a FAR of less than 50 per year. This exercise prepares us for future detections and often identifies areas where our search pipeline can be improved to exclude noise transients.

In the absence of detection candidates, we use our observations to set an upper limit on the CBC rate. We follow the procedure described in [28–30] and use the results reported in Ref. [7] as prior information on the rates. We present five different classes of upper limits. The first three limits are placed on binaries of neutron stars and/or black holes assuming canonical mass distributions for BNS [$m_1 = m_2 = (1.35 \pm 0.04)M_\odot$], BBH [$m_1 = m_2 = (5 \pm 1)M_\odot$], and BHNS [$m_1 = (5 \pm 1)$, $m_2 = (1.35 \pm 0.04)M_\odot$] systems. We also present upper limits as a function of the total mass of the binary and, for BHNS binaries, as a function of the black hole mass. We combine the results from each of the seven months, along with the prior results from the first year analysis, in a Bayesian manner, using the same procedure as described in [7].

We first calculate upper limits on BNS, BBH and BHNS systems assuming the objects have no spin, and summarize the results Tables I and II. The rate of binary coalescences in a galaxy is expected to be proportional to the blue light luminosity of the galaxy [31]. Therefore, we place limits on the rate per L_{10} per year, where L_{10} is 10^{10} times the blue solar luminosity (the Milky Way contains ~1.7 L_{10} [32]). To calculate the search sensitivity, the analysis was repeated numerous times adding simulated signals with a range of masses, distance and other astrophysical parameters to the data. Table II shows the sensitivity of the LIGO detectors to coalescing binaries quoted in terms of the horizon distance, i.e., the distance at which an optimally oriented and located binary would produce an SNR of 8. There are a number of uncertainties which affect the upper limit calculation, including Monte Carlo statistics, detector calibration, distances and luminosities of galaxies listed in the galaxy catalog [31] and differences between the PN templates used to evaluate efficiency of the search and the actual waveforms. The effects of these errors on the cumulative luminosity are summarized for the BNS search in Table I. We marginalize over all of the uncertainties [28] to obtain a posterior distribution on the rate of binary coalescences.

In Fig. 1, we show the derived distribution of the rate of BNS coalescences. The distribution is peaked at zero rate because there are no detection candidates. We include the distribution for all searches previous to this one (which is our prior). In addition, we present the result that would be obtained from each month, were it analyzed independently of the others and of the previous searches. This provides an illustration of the amount that each month contributes to

TABLE I. Detailed results from the BNS search. The observation time is the time used in the upper limit analysis. The cumulative luminosity is the luminosity to which the search is sensitive above the loudest event for each coincidence time. The errors in this table are listed as one-sigma logarithmic error bars (expressed as percentages) in luminosity associated with each source error.

Coincidence time	H1H2L1	H1L1	H2L1
Observation time (yr)	0.21	0.02	0.01
Cumulative luminosity (L_{10})	490	410	110
Calibration error	23%	23%	26%
Monte Carlo error	3%	7%	10%
Waveform error	31%	32%	31%
Galaxy distance error	16%	16%	3%
Galaxy magnitude error	19%	19%	17%

TABLE II. Overview of results from BNS, BBH and BHNS searches. D_{horizon} is the horizon distance averaged over the time of the search. The cumulative luminosity is the luminosity to which the search is sensitive above the loudest event for times when all three LIGO detectors were operational. The first set of upper limits are those obtained for binaries with nonspinning components. The second set of upper limits are produced using black holes with a spin uniformly distributed between zero and the maximal value of Gm^2/c.

Component masses ($M_\odot$)	1.35/1.35	5.0/5.0	5.0/1.35
D_{horizon} (Mpc)	~30	~100	~60
Cumulative luminosity (L_{10})	490	11 000	2100
Nonspinning upper limit ($\text{yr}^{-1}\,L_{10}^{-1}$)	1.4×10^{-2}	7.3×10^{-4}	3.6×10^{-3}
Spinning upper limit ($\text{yr}^{-1}\,L_{10}^{-1}$)	$\cdots$	9.0×10^{-4}	4.4×10^{-3}

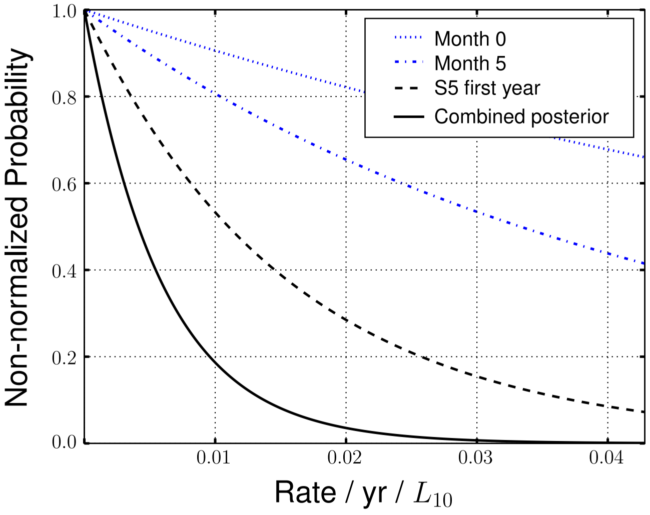

FIG. 1 (color online). The posterior distribution for the rate of BNS coalescences. The dashed black curve shows the rate computed in Ref. [7]. The solid black curve shows the result of this search using the previous analysis as a prior. The figure also shows the rate distributions for two of the individual months computed using a uniform prior. The improvement from month 0 to month 5 is due to increasing detector sensitivity during this search.

the final upper limit result and demonstrates the improvement in sensitivity of the detectors during the search. The upper limit is finally obtained by integrating the distribution from zero to $\mathcal{R}_{90\%}$ so that 90% of the probability is contained in the interval. The results obtained in this way are $\mathcal{R}_{90\%,\mathrm{BNS}} = 1.4 \times 10^{-2}\ \mathrm{yr}^{-1}\,\mathrm{L_{10}}^{-1}$, $\mathcal{R}_{90\%,\mathrm{BBH}} = 7.3 \times 10^{-4}\ \mathrm{yr}^{-1}\,\mathrm{L_{10}}^{-1}$, and $\mathcal{R}_{90\%,\mathrm{BHNS}} = 3.6 \times 10^{-3}\ \mathrm{yr}^{-1}\,\mathrm{L_{10}}^{-1}$.

Additionally we calculate the upper limit for BBH systems as a function of the total mass of the binary, assuming a uniform distribution of the component masses. For BHNS systems, we construct an upper limit as a function of the black hole mass, assuming a fixed neutron star mass of $m_{\mathrm{NS}} = 1.35 M_{\odot}$. These upper limits are shown in Fig. 2.

Finally, we present upper limits on coalescence rates where the spin of the components of the binary is taken into account. Astrophysical observations of neutron stars indicate that their spins will not be large enough to have a significant effect on the BNS waveform observed in the LIGO band [33,34]. Theoretical considerations limit the magnitude of the spin S of a black hole to lie within the range $0 \leq S \leq Gm^2/c$. However, the astrophysical distribution of black hole spins, and spin orientations, is not well constrained. Therefore, we provide a sample upper limit for spinning systems using a spin magnitude and orientation distributed uniformly within the allowed values. This gives upper limits on the rate of BBH and BHNS systems of $\mathcal{R}_{90\%,\mathrm{BBH}} = 9.0 \times 10^{-4}\ \mathrm{yr}^{-1}\,\mathrm{L_{10}}^{-1}$ and $\mathcal{R}_{90\%,\mathrm{BHNS}} = 4.4 \times 10^{-3}\ \mathrm{yr}^{-1}\,\mathrm{L_{10}}^{-1}$. These rates are about 20% larger than the nonspinning rates.

Discussion.—We have searched for gravitational waves from CBCs with total mass between 2 and $35 M_{\odot}$ in LIGO observations between November 14, 2006 and May 18, 2007. No detection candidates with significance above that expected due to the background were found in the search. By combining this search with our previous results, we set a new upper limit on the CBC rate in the local universe which is approximately a factor of 3 lower than that reported in Ref. [7]. This improvement is significant, even though we searched only two-thirds as much data as in Ref. [7]. It is due, in part, to improvements in detector sensitivity during S5 which increased the horizon distance. Moreover, the shorter analysis time and improved stationarity of the data led to many of the months having a less significant loudest event than in the previous search. Both of these effects increased the luminosity to which the search was sensitive, thereby improving the upper limit.

Astrophysical estimates for CBC rates depend on a number of assumptions and unknown model parameters, and are still uncertain at present. In the simplest models,

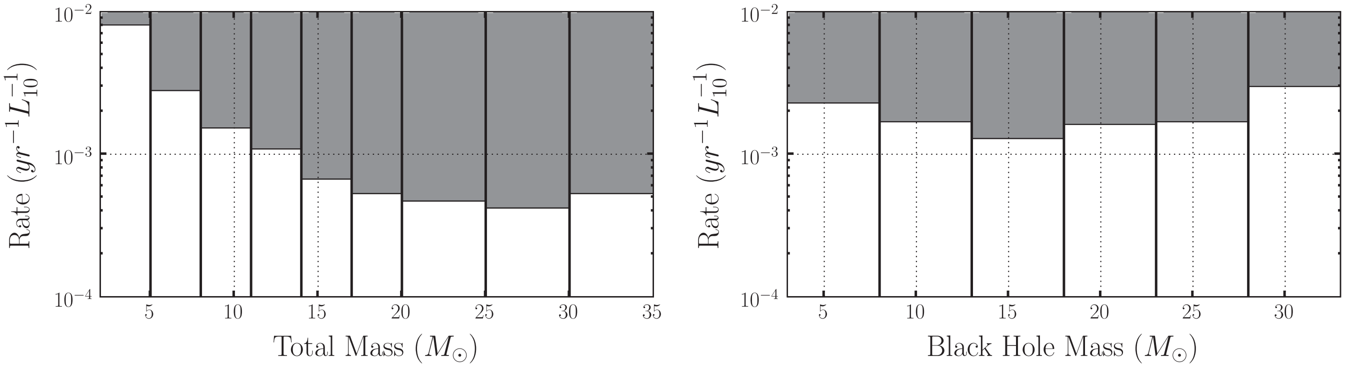

FIG. 2. The marginalized 90% rate upper limits as a function of mass. The upper plot shows limits for BBH systems as a function of the total mass of the system. The lower plot shows limits for BHNS systems as a function of the black hole mass, assuming a fixed neutron star mass of $1.35 M_{\odot}$. Here the upper limits are calculated using only H1H2L1 data since the relatively small amount of H1L1 and H2L1 data makes it difficult to evaluate the cumulative luminosity in the individual mass bins.

the coalescence rates should be proportional to the stellar birth rate in nearby spiral galaxies, which can be estimated from their blue luminosity [31]. The optimistic, upper end of the plausible rate range for BNS is $5 \times 10^{-4}\ \mathrm{yr}^{-1}\,\mathrm{L}_{10}^{-1}$ [35,36] and $6 \times 10^{-5}\ \mathrm{yr}^{-1}\,\mathrm{L}_{10}^{-1}$ for BBH and BHNS [37,38]. The upper limits reported here are $\sim$1–2 orders of magnitude above the optimistic expected rates. With the next run starting in mid 2009, the Enhanced LIGO and Virgo detectors will begin operations with a factor of $\sim$2 increase in horizon distance. The total luminosity searched will increase by a factor of $\sim$10, thereby bringing us close to the optimistic rates. The most confident BNS rate predictions are based on extrapolations from observed binary pulsars in our Galaxy; these yield realistic BNS rates of $5 \times 10^{-5}\ \mathrm{yr}^{-1}\,\mathrm{L}_{10}^{-1}$ [35,36]. Rate estimates for BBH and BHNS are less well constrained, but realistic estimates are $2 \times 10^{-6}\ \mathrm{yr}^{-1}\,\mathrm{L}_{10}^{-1}$ for BHNS [37] and $4 \times 10^{-7}\ \mathrm{yr}^{-1}\,\mathrm{L}_{10}^{-1}$ for BBH [38]. Thus, the expected rates are $\sim$2–3 orders of magnitude lower than the limits presented in this paper. The Advanced LIGO and Virgo detectors, currently under construction, will increase our horizon distance by an order of magnitude or more, allowing us to measure the rate of CBCs in the Universe.

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