The present gravitational wave detection effort

Keith Riles for the LIGO and Virgo Scientific Collaborations
Randall Lab, University of Michigan, Ann Arbor, MI 48109-1040, USA
E-mail: kriles@umich.edu

Abstract. Gravitational radiation offers a new non-electromagnetic window through which to observe the universe. The LIGO and Virgo Collaborations have completed a first joint data run with unprecedented sensitivities to gravitational waves. Results from searches in the data for a variety of astrophysical sources are presented. A second joint data run with improved detector sensitivities is underway, and soon major upgrades will be carried out to build Advanced LIGO and Advanced Virgo with expected improvements in event rates of more than 1000. In parallel there is a vigorous effort in the radio pulsar community to detect nHz gravitational waves via the timing residuals in an array of pulsars at different locations in the sky.

1. Introduction

Einstein's General Theory of Relativity predicts the existence of gravitational waves, disturbances of space-time that propagate at the speed of light and have two transverse quadrupolar polarizations [1]. Their amplitude is usually parametrized by a dimensionless strain h representing the induced fractional change in distance between two test masses.

The search for gravitational waves has many motivations. First, is fundamental scientific curiosity about new phenomena. More prosaically, one can use graviational radiation to test general relativity. For example, one can test the tranverse and quadrupolar nature of the radiation, and one can test whether or not the radiation travels at the speed of light (massless graviton). One can also directly probe highly relativistic phenomena, such as black-hole formation. Perhaps more intriguing is the new view one gains of the universe. Gravitational waves cannot be appreciably absorbed by dust or stellar envelopes, and most detectable sources are some of the most interesting objects in the universe. More generally, gravitational wave astronomy opens up an entirely new non-electromagnetic spectrum. Astronomy has found surprises since the mid 20th-century, as non-optical light bands have been explored, from the radio to gamma rays. New surprises likely await in the exploration of the gravitational spectrum.

The radiation arises at lowest order from quadrupolar motions [1]. Specifically, the radiation can be described by a metric tensor disturbance $h_{\mu\nu}$ that depends on the time derivative of the source quadrupole:

$$h_{\mu\nu} \quad = \quad \frac{2\,G}{rc^4}\frac{d^2}{dt^2}\Big[I_{\mu\nu}\Big], \tag{1}$$

where G is Newton's gravitational constant, r is the distance to the source, c is the speed of light, and $I_{\mu\nu}$ is the source's reduced quadrupole tensor [1]. Given the tiny multiplying constant, the source quadrupole's 2nd time derivative must be enormous to give detectable effects far from the source, implying enormous masses ($\sim M_\odot$) with relativistic motions, such as two neutron stars in a coalescing binary system, as discussed below.

Strong indirect evidence already exists for gravitational wave emission. The famous Hulse-Taylor binary system, consisting of an observed pulsar with 17-Hz radio emission in an 8-hour orbit with an unseen neutron star companion, has shown a small but unmistakable quadratic decrease in orbital period ($\sim$40 seconds over 30 years), in remarkably good agreement with expectation from gravitational wave energy loss [2]. The gravitational wave emission frequency ($\sim$70 μHz) is far too low to be observed directly by present gravitational wave detectors, but if we were to wait about 300 million years, the system would eventually spiral into a spectacular coalescence easily visible with present gravitational wave detectors.

Perhaps our best hope for gravitational wave discovery lies with corresponding binary systems in the numerous galaxies far away from us, but there are large uncertainties in estimated coalescence rates for compact binary coalescence of systems containing neutron stars (NS) and/or black holes (BH). For example, a recent paper [3] estimates a 90% CL range of 2.9×10^{-2}–0.46 per year for initial LIGO detection of a NS-NS, NS-BH, or BH-BH coalescence.

Other candidate transient sources of gravitational waves include supernovae and gamma ray bursts (some of which may well be coalescing binary systems). If we are fortunate, electromagnetic transients will be seen simultaneously by other astronomers, allowing more confident gravitational wave detection with lower signal-to-noise ratio (SNR). Potential non-transient gravitational wave sources include rapidly spinning neutron stars in our own galaxy, emitting long-lived continuous waves, or a cosmological background of stochastic gravitational waves, analogous to the cosmic microwave background radiation. Results from searches for both transient and long-lived gravitational-wave sources will be discussed below.

2. LIGO and Virgo Detectors

2.1. Principles of Operation

The principles of gravitational wave interferometry are described in detail by Saulson [1]; only a brief summary is provided here. A Michelson interferometer with orthogonal arms is a natural gravitational wave detector in that a wave incident along the normal to the plane of the arms can induce a quadrupole distortion (differential arm length change) to which the interferometer is designed to be most sensitive. More generally, the sensitivity of the interferometer to a gravitational wave depends on the wave's direction of incidence and polarization. The antenna pattern of sensitivity is broad, giving good sky coverage, but at the expense of directional precision for transient sources.

The sensitivity of conventional Michelson interferometers to gravitational wave strain can be increased via several techniques. Methods used in the LIGO and Virgo detectors include km-scale arms, Fabry-Perot cavities in those arms to enhance phase sensitivity to the passage of a gravitational wave, and "recycling" of laser power via the insertion of a mirror between the laser and beam splitter, in order to increase effective light power and thereby decrease shot noise at high frequencies. The response of a "power-recycled Michelson interferometer" to gravitational waves is inherently broad-band (relative to the narrow bandwidth of a resonant bar detector [1]), allowing searches for broadband transients and reconstruction of waveforms.

There exists now a global interferometer network, consisting of not only the LIGO and Virgo interferometers (the most sensitive at present), which are the main focus of this report, but also the GEO 600 interferometer near Hannover, Germany [4] and the TAMA 300 interferomter in Tokyo [5]. In general, the larger the number of interferometers that can detect a source, the greater the confidence of that detection will be, and the better the precision with which the radiation parameters can be determined, *e.g.*, source direction and wave polarization.

2.2. The LIGO and Virgo Interferometers, Data Runs, and the Future

The LIGO detector consisted until summer 2009 of three power-recycled Michelson interferometers: two in Hanford, Washington (H1 with 4-km arms, H2 with 2-km arms) and one in Livingston, Louisiana (L1 with 4-km arms). The LIGO interferometers, as configured during the fifth science run (S5) from November 2005 through September 2007, are described in detail elsewhere [6]. Commissioning the interferometers to meet the 4-km design requirement of an integrated root-mean-square strain sensitivity below 10^{-21} over a 100-Hz band demanded many years of effort, but yielded detectors that surpassed this requirement by more than a factor of two. A more ambitious target strain sensitivity curve was also surpassed over most of the detector bandwidth, as shown in Figure 1.

During the LIGO commissioning phase, a large number of engineering and science data runs were taken, both for carrying out astrophysical searches and for evaluating detector performance and stability during sustained running. The nearly 2-year S5 run at design sensitivity has led to many publications that continue to appear. A selected sampling of these results will be presented below. The progress in LIGO commissioning can be seen in the ever improving sensitivities shown in Figure 1 from one science run to the next.

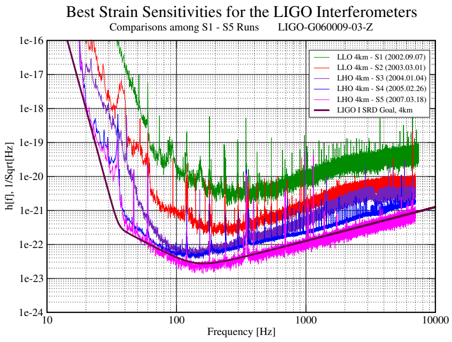

Figure 1. History of LIGO strain noise spectra.

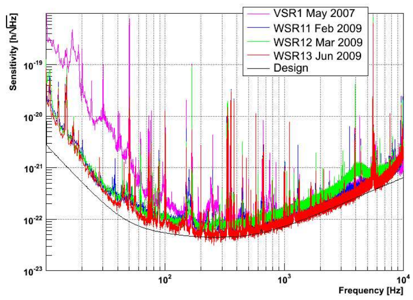

Figure 2. History of Virgo strain noise spectra.

The Virgo detector consists of a single power-recycled Michelson interferometer with 3-km arms in Cascina, near Pisa. The interferometer is described in detail elsewhere [7]. As with LIGO, many years of commissioning were required to bring the interferometer to its present sensitivity, shown in Figure 2, together with the sensitivity achieved in 2007 during the first Virgo science run VSR1 which was coincident and coordinated with the last several months of the LIGO S5 run. Note that the Virgo sensitivity is now better than the LIGO sensitivity at low frequencies, offering potentially better range for low-frequency young pulsars and binary black hole mergers.

New science runs (LIGO S6 and Virgo VSR2) are to begin in July 2009 and run until approximately the end of 2010, but with scheduled interruptions for commissioning. Virgo VSR2 sensitivity should be improved over the full band compared to that of VSR1 (see Figure 2), while LIGO S6 sensitivity should be improved by up to a factor of two over S5 sensitivity at frequencies above several hundred Hz. The shutdown for Advanced LIGO and Virgo upgrades will likely occur in late 2010 or early 2011, leading eventually to dramatic improvements in expected gravitational wave event rates for those 2nd-generation detectors [8].

3. Results from Searches for Gravitational Waves

A sampling of results to date from searches in the LIGO S5 data will be presented here. Analyses of LIGO and Virgo data are carried out by working groups focusing on four distinct source types: 1) binary inspirals, 2) unmodeled bursts, 3) continuous waves, and 4) stochastic background. Results from these four efforts will be discussed in turn below.

3.1. Binary Inspiral Searches

Searches for binary inspiraling neutron star systems enjoy the benefit of well understood expected waveforms, which allows matched Wiener filtering to be applied, giving optimal SNR. Binary black hole binaries, especially for rapidly spinning black holes, are not as well understood. Nonetheless a phenomenologically defined set of templates offers near-optimal SNR [9]. Searches have been carried out using matched filter template banks spanning a broad volume in binary system parameter space, ranging from primordial black holes with less than 1 $M_\odot$ to systems containing black holes with masses greater than 30 $M_\odot$. No evidence of excess events has been seen in an analysis of the 1st year S5 data, leading to upper limits on event rates for various binary systems [9]. Figure 3 shows some resulting rate limits (events per year per 10^{10} "blue"stars) *vs.* total system mass for BH-BH systems and *vs.* black hole mass for NS-BH systems.

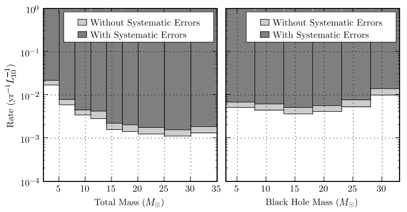

Figure 3. Upper limits on binary inspiral rates.

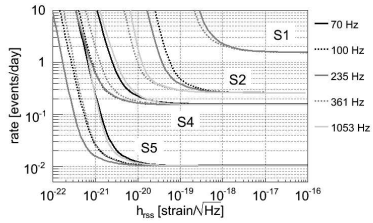

Figure 4. Upper limits on burst rates.

3.2. Unmodeled Burst Searches

Searches for unmodeled bursts have been carried out in the S5 data for both triggered sources, including gamma ray bursts detected by satellites, and untriggered sources (all-sky). An especially interesting triggered source was GRB 070201, a short hard gamma ray burst with a reconstructed position consistent with M31 (Andromeda). The absence of any plausible signal in LIGO data at the time of the burst and the nearness of M31 make it very unlikely that the GRB was a binary merger in M31 [10]. More likely it was an SGR giant flare in M31.

Searches for untriggered double- and triple-coincident burst events in the LIGO interferometers in the first year of S5 data were also unsuccessful in detecting a signal. Efficiencies have been determined from simulations using a variety of *ad hoc* phenomenological waveforms with the waveform strengths parametrized in terms of the "root sum square of h", $h_{\rm RSS}$, defined according to

$$(h_{\rm RSS})^2 \quad = \quad \int [|h_+(t)|^2 + |h_\times(t)|^2]\, dt, \tag{2}$$

where $h_+(t)$ and $h_\times(t)$ are the "+" and "×" quadrupolar polarizations of the detectable strain waveforms [1]. Figure 4 shows rate upper limits (events/day) for sine-Gaussian bursts *vs.* $h_{\rm RSS}$ for the first year of S5 data, along with corresponding limits for earlier science runs [11].

3.3. Continuous Wave Searches

Searches have been carried out in S5 data for continuous gravitational waves from known pulsars using matched-filter templates based on precise radio or X-ray timing. These targeted searches with integration times longer than a year yield strain amplitude sensitivities below 10^{-25} across a broad band. Figure 5 shows S5 upper limits on strain for 116 known pulsars [12], along with the corresponding limits from S4 for a subset of 78 pulsars. An especially interesting result is that for the Crab pulsar, where the upper limit on energy loss rate due to gravitational radiation is about 2% of the Crab's total known energy loss (inferred from its slowing of spin).

Searches have also been carried out for unknown spinning neutron stars in any direction on the sky. To search every direction and frequency with long integration times is computationally intractable because of the need to make direction-dependent Doppler modulations due to the Earth's motion. So sensitivity must be sacrificed via incoherent methods, such as summing many strain powers measured over short integration times. All-sky upper limits on strain for circularly and linearly polarized continuous waves are shown in Figure 6 for the 50-1100 Hz band, based on the first eight months of S5 data [13] using thousands of summed powers with coherence times of 30 minutes. Comparable limits were found over a broader band (50-1500 Hz) using an early-S5 pilot run of the Einstein@Home distributed computing project looking at coincident outliers among 28 coherent observation times of 25-hour durations [14].

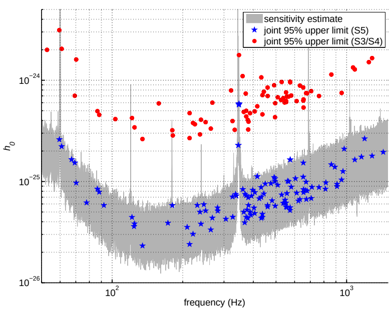

Figure 5. Limits on strain amplitude from known pulsars.

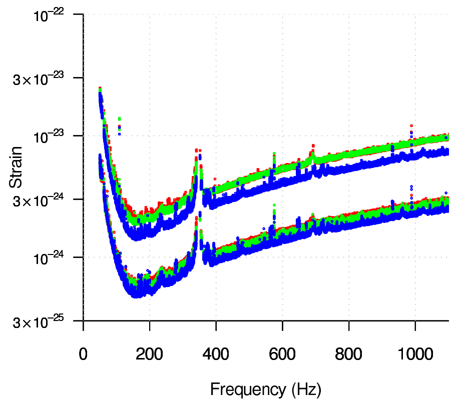

Figure 6. All-sky limits on strain amplitude from unknown pulsars.

3.4. Stochastic Background Searches

A primordial isotropic gravitational wave background is predicted by most cosmological theories, although the predicted strengths of the background vary enormously. It is customary to parametrize the background strength *vs.* frequency f by its energy density normalized to the critical energy density $\rho_{\rm crit}$ of the universe:

$$\Omega_{\rm gw}(f) \quad = \quad \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\rm gw}(f)}{d\,ln(f)} \tag{3}$$

Searches for this radiation are carried out via measured cross-correlations in pairs of interferometers, where large spatial separation reduces sensitivity to high frequencies, but mitigates disturbances due to common environmental noise sources. Analysis of the early-S5 LIGO data from the Hanford H1 and Livingston L1 interferometer correlations leads to a preliminary 90% upper limit on a constant $\Omega_{\rm gw} < 9.0 \times 10^{-6}$ in the band 42-177 Hz, improving upon previous indirect limits derived from analysis of big-bang nucleosythesis [15].

4. Searches with Pulsar Timing Arrays

An entirely different effort is underway in the radio astronomy community to detect stochastic gravitational waves by way of precise pulsar timing. Very-low-frequency waves (∼nHz) in the vicinity of the Earth could lead to a quadrupolar pattern in the timing residuals from a large number of pulsars observed at different directions on the sky. Several collaborations have formed in recents years to carry out the precise observations required: 1) The Parkes Pulsar

Timing Array (Australia) [16], 2) the European Pulsar Timing Array (U.K., France, Netherlands, Italy) [17], and 3) Nano-Grav (U.S.A.) [18]. These searches aim to improve upon the existing limit of $\Omega_{\rm GW}(\rm nHz) < 10^{-8}$ [16] by two orders of magnitude and perhaps discover radiation from binary supermassive black holes in the cores of distant galaxies.

5. Summary

Unfortunately, gravitational waves have not yet been detected directly. But limits obtained have become astrophysically interesting, and not all S5 / VSR1 searches have been completed. Moreover, searches in the more sensitive S6 / VSR2 data are just beginning. Advanced LIGO and Virgo promise major sensitivity improvements with orders of magnitude increase in expected event rates, offering a near guarantee of discovery [8]. There is a distinct possibility, however, that the first direct detection will come not from interferometers operating in the audio band, but from precise pulsar timing measurements in the nHz band.

Acknowledgments

The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory and the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Educación y Ciencia, the Conselleria d'Economia, Hisenda i Innovació of the Govern de les Illes Balears, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, The National Aeronautics and Space Administration, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

References

[1] Saulson P 1994 *Fundamentals of Interferometric Gravitational Wave Detectors* (Singapore: World Scientific)
[2] Weisberg J M and Taylor J H 2005 in *Binary Radio Pulsars* ed Rasio F A and Stairs I H, *Astron. Soc. Pacific Conf. Ser.* vol 328 (San Francisco: Astron. Soc. Pacific)
[3] Shaughnessy R O, Kalogera V and Belczynski K 2009 Binary compact object coalescence rates: The role of elliptical galaxies *Preprint* arXiv:0908.3635
[4] Willke B 2002 *Class. Quant. Grav.* **19** 11
[5] Takahashi R 2004 *Class. Quant. Grav.* **21** S403
[6] Abbott B P *et al.* 2009 *Rep. Prog. Phys.* **72** 076901
[7] Acernese F *et al.* 2005 *Class. Quant. Grav.* **22** S869
[8] Losurdo G in these proceedings
[9] Abbott B P *et al.* 2009 *Phys. Rev. D* **79** 122001
[10] Abbott B P *et al.* 2008 *Ap. J.* **681** 1419
[11] Abbott B P *et al.* 2009 Search for gravitational-wave bursts in the first year of the fifth LIGO science run *Preprint* arXiv:0905.0020
[12] Abbott B P *et al.* 2009 Searches for gravitational waves from known pulsars with S5 LIGO data *Preprint* arXiv:0909:3583
[13] Abbott B P *et al.* 2009 *Phys. Rev. Lett.* **102** 111102
[14] Abbott B P *et al.* 2009 *Phys Rev. D* **80**— 042003
[15] The preliminary result presented at TAUP has been recently superseded by a final S5 result $\Omega_{\rm GW} < 6.9 \times 10^{-6}$ in Abbott B P *et al.* 2009 *Nature* **460** 990
[16] Manchester R N 2008 *AIP Conf. Proc.* **983** 584
[17] Janssen G H, Stappers B W, Kramer M, Purver M, Jessner A and Cognard I 2008 *AIP Conf. Proc.* **983** 633 in *40 years of pulsars, millisecond pulsars, magnetars, and more*
[18] Jenet F *et al.* 2009 The north american nanohertz observatory for gravitational waves *Preprint* arXiv:0909.1058