Gravitational-wave astronomy: observational results and their impact

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Abstract
The successful construction and operation of highly sensitive gravitational-wave detectors is an achievement to be proud of, but the detection of actual signals is still around the corner. Even so, null results from recent searches have told us some interesting things about the objects that live in our universe, so it can be argued that the era of gravitational-wave astronomy has already begun. In this paper I review several of these results and discuss what we have learned from them. I then look into the not-so-distant future and predict some ways in which the detection of gravitational-wave signals will shape our knowledge of astrophysics and transform the field.

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Prologue

It has been 50 years since Joseph Weber first embarked on a serious experimental program to try to detect gravitational waves (GWs) directly [1], motivated by the possibility of detecting signals from sources such as a core-collapse supernova or a binary neutron star [2]. The intervening years have seen great advances in technologies and new techniques for detecting GWs, from much-improved ‘Weber bars’ to highly sensitive broadband interferometers, Doppler tracking of spacecraft such as Cassini [3], long-term campaigns to monitor pulse arrival times from stable pulsars [4] and mature plans for long-baseline interferometer networks in space (namely LISA [5] and DECIGO [6]). In parallel, after the discovery of the first binary pulsar in 1974 [7], radio pulse timing campaigns with a number of short-period binary pulsars have provided compelling ‘indirect’ evidence for the existence of gravitational radiation as well as precise experimental tests of the general theory of relativity [8]. Theoretical work and numerical modeling have provided a much better
understanding of the likely GW signatures of the original leading source candidates—core-collapse supernovae [9] and binary neutron stars [10]—as well as many other expected or plausible GW sources, including binary systems with supermassive or stellar-mass black holes, short-period white dwarf binaries, non-axisymmetric spinning or perturbed neutron stars, cosmic strings, early-universe processes, and more. (General overviews of GW sources may be found in [11, 12], for instance.) And here is what our direct searches have yielded so far: nothing.

The lack of a directly detected signal is not surprising, based on our limited knowledge of source populations and on the current sensitivity levels of the detectors. Further instrumental improvements are on the way, including substantial upgrades to the current large interferometers, proposals to build additional interferometers, pulse timing measurements of more pulsars for longer time spans with better precision and eventually the launch of space missions to open up the low-frequency window that is certain to be rich with signals. According to current schedules, we are sure to be detecting signals and doing GW astronomy around the middle of the coming decade.

However, in this paper I will argue that we are already doing GW astronomy. In the next section I will summarize and interpret several completed searches for which the lack of a detectable signal provides some relevant information about the population and/or astrophysics of plausible sources. I will then project forward to the time when signals are detected and discuss what we may learn from them, and how they will fundamentally change the field of GW astronomy.

1. The impact of null results published so far

In 1969 Weber claimed that his detectors had produced definitive evidence for the discovery of gravitational waves [13], the first in a series of claims by him that could not be reproduced by others and were ultimately discredited [14]. Nevertheless, his attempts inspired an experimental community that continued to improve the detection technologies, cooling bars to cryogenic temperatures to minimize thermal noise and exploring other detection methods [15].

Large cryogenic bar detectors—ALLEGRO [16], EXPLORER [17], NAUTILUS [18], NIOBE [19], and AURIGA [20]—began operating for extended periods with good sensitivity in the 1990s. Analyzing the data from two or more detectors together substantially reduced the false alarm rate from spurious signals in the individual detectors (from mechanical vibrations, cosmic rays, etc) and enabled searches for weaker and less-frequent transient signals. This culminated in the 1997 formation of the International Gravitational Event Collaboration (IGEC) [21]. Around the same time, GW searches with prototype interferometric detectors (e.g. [22]) gave way to the commissioning and eventual operation of the full-scale interferometers TAMA 300 [23], LIGO [24], GEO 600 [25] and Virgo [26], which have by now surpassed the bars in searching for ‘high-frequency’ GW signals (above $\sim$10 Hz). Also, the past several years have seen advances in using multiple millisecond pulsars to search for GW signals at frequencies around $10^{-9}$–$10^{-7}$ Hz by the Parkes Pulsar Timing Array, NANOGrav, and European Pulsar Timing Array projects [4, 27, 28].

Over the past decade, dozens of papers have been published to report results from searches for various types of GW signals. Aside from a few hints of excess event candidates that were not confirmed, all searches so far have yielded null results. From these are derived upper limits on the rate and/or strength of GW signals reaching the detectors, or alternatively on the possible population of sources. In this section I highlight several of these results which represent significant steps toward gravitational-wave astronomy. Many of these signals are
expected to be detectable by the current instruments only if they originate relatively nearby; therefore, we begin by exploring our cosmic neighborhood.

1.1. Getting to know our neighbors better

Our galaxy is thought to contain $10^8$–$10^9$ neutron stars [29], of which a few thousand have been detected as radio or X-ray pulsars. A rapidly spinning neutron star can emit periodic gravitational waves through a number of mechanisms, including a static deformation that breaks axisymmetry [30], persistent matter oscillations (e.g. r-modes) [31], or free precession [32].

The Crab pulsar, at a distance of about 2 kpc, is a particularly interesting neighbor. With a current spin frequency of 29.7 Hz and spin-down rate of $-3.7 \times 10^{-10}$ Hz s$^{-1}$ [33], its energy loss rate is estimated to be $4 \times 10^{31}$ W. This powers the expansion and electromagnetic luminosity of the Crab Nebula, but the energy flows in this complex system are difficult to pin down quantitatively [34], leaving open the possibility that a significant fraction of the energy could be emitted as gravitational radiation. Palomba has estimated that the observed braking index of the pulsar spin-down constrains this fraction to be no more than 40% [35]. The LIGO Scientific Collaboration (LSC) used data from the first 9 months of LIGO’s S5 science run to search for a GW signal from the Crab pulsar and, finding none, were able to set an upper limit of 8% of the total spin-down energy, using X-ray image information to infer the orientation of the pulsar spin axis and assuming that the GW emission is phase-locked at twice the radio pulse frequency [36]. Analysis of the full S5 data [37] has improved this limit to just 2%. This observational result directly constrains the properties of the Crab pulsar and the energy balance of the nebula.

The LSC and the Virgo Collaboration (now analyzing data jointly) have also searched for periodic GWs from all known pulsars with spin frequencies greater than 20 Hz and sufficiently precise radio or X-ray pulse timing to allow a fully-coherent search, again assuming that the GW emission is phase-locked at twice the pulse frequency. The analysis [37] considered 115 radio pulsars (including 71 in binary systems) that were timed during the LIGO S5 run by the Jodrell Bank Observatory, the Green Bank Telescope and/or the Parkes radio telescope, along with the X-ray pulsar J0537$-6910$ which was monitored by the Rossi X-ray Timing Explorer (RXTE). For each pulsar, a 90% upper limit was placed on the GW amplitude in terms of the parameter $h_0$, which represents the strain amplitude that would reach the Earth in the ‘plus’ and ‘cross’ polarizations if the pulsar spin axis were oriented optimally. Figure 1 shows these upper limits, which are remarkably small numbers in themselves. The lowest upper limit is $2.3 \times 10^{-26}$, obtained for pulsar J1603$-7202$. J0537$-6910$ is the only pulsar besides the Crab for which the upper limit from this analysis reaches the spin-down limit, assuming that the moment of inertia is within the favored range of $(1$ to $3) \times 10^{38}$ kg m$^2$.

Assuming the neutron stars to be triaxial ellipsoids, these amplitude limits may be re-cast as limits on the equatorial ellipticity $\varepsilon$. Pulsar J2124$-3358$, at a distance of $\sim$200 pc and GW frequency of 404 Hz, yields the strictest upper limit, $\varepsilon < 7.0 \times 10^{-8}$. One may ask whether the perfect or near-perfect axisymmetry of these neutron stars is due to the properties of the neutron star material. It has long been thought that conventional neutron stars could support an ellipticity up to a few times $10^{-7}$ [38], but recent work suggests that the pressure in the crystalline crust suppresses defects [39] and ellipticities of up to $\sim$4 $\times$ $10^{-6}$ are possible in a conventional neutron star. Most of the pulsars in the S5 analysis have $\varepsilon$ limits below that level, meaning that these neutron stars, at least, are closer to axisymmetric than required by the intrinsic material properties.
1.2. When the neighbors are disturbed...

Soft gamma repeaters (SGRs) are believed to be magnetars, i.e. neutron stars with very strong magnetic fields [40]. SGRs are observed to emit intense flares of soft gamma rays at irregular intervals which may be associated with ‘starquakes’, abrupt cracking and rearrangement of the crust and magnetic field. These events could excite quasinormal modes of the neutron star which then radiate gravitational waves [41]. The fundamental mode, at a frequency of around 1.5–3 kHz, is expected to be the most efficient GW emitter although other nonradial modes may also participate.

The LSC have used LIGO data to search for GW bursts associated with flares of SGRs 1806–20 and 1900+14, including the December 2004 giant flare of SGR 1806–20 [42]. A first analysis [43] treated the flares individually, setting upper limits on GW energy as low as a few times $10^{45}$ erg, depending strongly on the waveform assumed. The best of these limits (for signals in the most sensitive range of the instruments, 100–200 Hz) are within the range of possible GW energy emission during a giant flare, $10^{45}$ to $10^{49}$ erg, according to modeling by Ioka [44]. Unfortunately, the giant flare occurred between LIGO science runs, and the less-sensitive data available at that time only yield upper limits on GW energy emission of $5 \times 10^{47}$ erg and above.

A later paper re-analyzed the ‘storm’ of SGR 1900+14 flares that spanned a period of $\sim 30$ s on 29 March 2006 [45]. This analysis ‘stacked’ the data around the times of the individual flares in order to gain sensitivity under the assumption that many or all of the flares had an associated GW burst at a common relative time offset. Two scenarios were considered to choose the relative weighting of the flares: one in which the GW burst energy is assumed to be proportional to the electromagnetic fluence of each flare, and the other in which all
large flares are assumed to have more-or-less equal GW burst energy. This analysis yielded per-burst energy upper limits as low as $2 \times 10^{45}$ erg, an order of magnitude lower than the limits set for this storm by the earlier single-burst analysis.

These searches are just beginning to address the few existing models of GW emission by SGRs, and are motivating new modeling of SGRs and their disturbances. Stronger constraints (if not a detection) will be obtained when another giant flare occurs while the GW detector network is operating with good sensitivity, and/or from searches using ordinary flares from closer SGRs such as the recently discovered SGRs J0501+4516 [46, 47] and J0418+5729 [48], which may both be less than 2 kpc away.

1.3. Listening for invisible neighbors

As noted previously, only a small fraction of the hundreds of millions of neutron stars in our galaxy are visible to us in radio waves, x-rays or gamma rays. It is quite plausible that one or more nearby, unseen neutron stars have a large enough asymmetry and spin rate to be emitting periodic gravitational waves at a detectable level. A general argument, originated by Blandford and extended in a 2007 paper by the LIGO Scientific Collaboration [49], starts with the (very optimistic) assumptions that all neutron stars are born with a high spin rate and spin down due to GW emission alone, and concludes that the strongest signal that we can expect (in an average sense) to receive on Earth would have $h_0 \simeq 4 \times 10^{-24}$, independent of frequency and $\varepsilon$. Knispel and Allen have greatly refined this analysis [50], replacing Blandford’s simple assumptions about the neutron star population with a detailed simulation of the birth, initial kick and subsequent motion of neutron stars in the galaxy. For a nominal ellipticity of $10^{-6}$, they find that the maximum expected GW signal amplitude (with the same optimistic assumptions about neutron stars spinning down due to GW emission) is around $10^{-24}$ over the frequency range 100–1000 Hz.

The LSC have published two all-sky searches for periodic GW signals using data from the early part of the S5 run, one using the semi-coherent ‘PowerFlux’ method [51] and the other using the substantial computing power provided by the Einstein@Home project to carry out longer coherent integrations on a smaller data set [52]. These searches had comparable sensitivities, both slightly surpassing the Knispel and Allen model expectations (with $\varepsilon = 10^{-6}$) for pulsars with favorable orientations and GW signal frequencies in the vicinity of 200 Hz. Thus, periodic GW searches may be on the verge of detecting unseen neutron stars, or at least constraining models for the population of such objects in our galaxy.

1.4. Listening to the galaxy next door

On 1 February 2007, the extremely intense gamma-ray burst GRB 070201 was detected by detectors on the Konus-Wind, INTEGRAL, MESSENGER and Swift satellites. The initial position error box from the relative arrival times of the bursts [53] intersected the spiral arms of M31 (the Andromeda galaxy), raising the intriguing possibility that it originated in that galaxy, only $\sim 770$ kpc away. Furthermore, the leading model for most short-hard GRBs such as this one is a binary merger involving at least one neutron star [54]. Such an event would also emit strong gravitational waves.

At the time of the GRB, the two detectors at the LIGO Hanford Observatory were collecting science-mode data, while the other large interferometers were not. The LSC searched this data for both an inspiral signal leading up to the merger and for an arbitrary GW burst associated with the merger itself [55]. No plausible signal was found, and from the absence of a detectable inspiral signal at that range, a compact binary merger in M31 was
ruled out with >99% confidence. The LIGO null result, along with a refined position estimate for the GRB [56], helped to solidify the case that this was most likely an SGR giant flare event in M31 [57].

1.5. Checking out a monster sighting

In 2003 a team of radio astronomers reported evidence for the discovery of a supermassive black hole binary in the bright radio galaxy 3C 66B [58], which is located about 90 Mpc from Earth. Their claim was based on very long baseline interferometry (VLBI) observations of the galaxy, in which the radio core of the galaxy was seen to move slightly over the course of 15 months in a manner consistent with an elliptical orbit with a period of 1.05 year. This suggested the presence of a binary system with a total mass near $5 \times 10^{10} M_{\odot}$. Remarkably, such a system would also be expected to merge in $\sim 5$ years due to energy loss by GW emission.

Jenet et al determined that pulsar timing could be used to check this claim since the gravitational waves from the binary would cause pulse time-of-arrival variations of up to several microseconds [59]. They analyzed 7 years of archival Arecibo timing data for PSR 1855+09 and found no such variation, definitively ruling out the proposed binary system in 3C 66B.

1.6. Catching a merger anywhere in the sky

Binary neutron star systems are benchmark sources for ground-based GW detectors because binary pulsars give a glimpse of the population (see discussion in [60]) and efficient GW emission during the inspiral phase just before merging makes them detectable out to considerable distances, currently tens of megaparsecs. Black-hole-and -neutron-star (BHNS) and binary black hole (BBH) systems with stellar-mass black holes can be detected at even greater distances; population synthesis studies suggest that the net detection rates for those sources are likely to be comparable [61, 62]. Because GW detectors have wide antenna patterns, signals from these events can be detected from essentially anywhere in the sky and at any time.

The most sensitive search published to date for these sources used LIGO S5 data and templates for binary inspirals with total mass up to $35 M_{\odot}$ [63]. No significant signal candidate was detected. The LSC interpreted this null result using a population model based on the assumption that the rate of mergers in each nearby galaxy is proportional to its blue light luminosity, as a tracer of massive star formation. The upper limits obtained from a total of 18 calendar months of LIGO data, in units of merger rate per year per $L_{10}$ (defined as $10^{10}$ times the blue light luminosity of the Sun), were 0.014, 0.0036 and 0.000 73 for binary neutron star, BHNS and BBH systems, respectively, calculated assuming black hole masses of $5 \pm 1 M_{\odot}$. These limits are still far from the theoretically expected rates [64], but are motivating the numerical relativity community to improve waveform calculations and the data analysis community to find better ways to search for inspirals with higher masses, significant spin and/or high mass ratio [65, 66].

1.7. Being vigilant for arbitrary bursts

Supernova core collapse and several other plausible signals are not modeled well enough to use matched filtering, either because the astrophysics is not completely known or because the physical parameter space is too large to effectively cover with a template bank. Even for the important case of BBH mergers, which numerical relativity calculations are now modeling
with considerable success [67], the physical parameter space allows for a wide variety of waveforms. Thus it is important to search for arbitrary transient signals (bursts) in the GW data, and data analysis methods have been implemented which robustly detect a wide range of signals without advance knowledge of the waveform.

So far the IGEC network of bar detectors is the observation time champion, having collected enough data since 1997 to establish an upper limit of 1.5 per year on the rate of strong GW bursts [68], with looser rate limits on weaker bursts. More recent IGEC data extended their sensitivity to somewhat weaker bursts [69], but with looser rate limits of ∼8.5 per year. On the other hand, LIGO is the sensitivity champion. The latest published burst search results [70], from the first calendar year of the LIGO S5 run, set upper limits on the rate of bursts arriving at Earth as a function of signal waveform and amplitude, expressed as the root-sum-squared GW strain calculated from both polarization component amplitudes at the Earth:

$$h_{\text{rss}} = \sqrt{\int_{-\infty}^{\infty} (|h_+ (t)|^2 + |h_\times (t)|^2) \, dt.}$$

(1)

Figure 2 shows the limits set by burst searches in the S5 run (first calendar year only) and earlier science runs for ‘sine-Gaussian’ waveforms with $Q = 9$ and central frequencies up to ∼1 kHz. The area above each curve is excluded at 90% confidence level, i.e. the curve traces out the 90% upper limit on the rate for a given waveform assuming a hypothetical population with fixed $h_{\text{rss}}$. Sufficiently loud bursts of any form have the same rate limit, 3.75 per year, as the efficiency of the analysis pipeline approaches unity.

The signal strength can also be related in a robust way to GW energy emission from a source at a known or assumed distance $r$. For instance, the S5 first-year search mentioned above would have been sensitive to an event in the Virgo galaxy cluster ($r \simeq 16$ Mpc) that emitted $\sim 0.25 M_\odot c^2$ of GW energy in a burst with a dominant frequency of $\sim 150$ Hz [70]. These searches constrain populations of sources such as binary mergers of intermediate-mass black holes although so far only preliminary quantitative studies have been made with realistic simulated waveforms [71].
1.8. Tuning in to spacetime shivering

The Big Bang may have left behind a stochastic background of gravitational waves, isotropic like the cosmic microwave background (CMB) but carrying information about much earlier fundamental processes in the early universe; see [72] for a review and references in [73] for updates on the details of plausible processes. A stochastic background, isotropic or not, can also be produced by a large number of overlapping astrophysics sources such as binary mergers, cosmic (super)strings or core-collapse supernovae. The GW signal generally has the form of random ‘noise’ with a characteristic power spectrum, though it can be distinguished from true instrumental noise by testing for a common signal in multiple detectors for which the instrumental noise is known to be uncorrelated.

Jenet et al have used pulsar timing to search for low-frequency stochastic gravitational waves in archival and newly obtained data for seven pulsars spanning intervals from 2.2 to 20 years [75]. They detected no signal but placed limits on the GW energy density assuming different power-law distributions as a function of frequency. From these they also derive limits on mergers of supermassive binary black hole systems at high redshift, relic gravitational waves amplified during the inflationary era [76] and a possible population of cosmic (super)strings [77].

The LSC and Virgo have used LIGO data to search for a stochastic GW signal in the vicinity of 100 Hz by measuring correlations in the data from the Hanford and Livingston interferometers to test for a signal well below the noise level of either instrument. A recently published paper [73] used the data from the full S5 science run to set a limit on the energy density in GWs as a fraction of the critical energy density needed to close the universe. The result, assuming a frequency-independent spectrum, was $\Omega_\gamma < 6.9 \times 10^{-6}$ at 95% confidence. This direct limit surpasses the indirect limits from Big Bang nucleosynthesis and the CMB and constrains early-universe models. It also imposes constraints on a possible population of cosmic strings in a different part of the parameter space than the pulsar timing result does.

1.9. Summary: impact of null results

From this sampling of search results, most published in the past few years, one can see the beginnings of rich astrophysics coming out of GW observations. The searches are now placing meaningful constraints on some individual objects and events, source populations (either real or speculated) and the total energy density of gravitational waves in the universe. Many more analyses are in progress, and null results will surely continue to provide interesting information.

2. The (future) impact of detected signals

As I write this sentence, I can see¹ that the two LIGO 4 km detectors and Virgo are all collecting science-mode data at this particular moment (as part of the ongoing S6/VSR2 science run), while AURIGA, EXPLORER and NAUTILUS are also collecting good data. GEO 600 is being upgraded to ‘GEO-HF’ with a focus on improving the sensitivity for frequencies above $\sim 400$ Hz [74] and will collect more data over the next several years. It is possible that the first unambiguous GW signal is in the data already collected but not yet fully analyzed, or will soon be recorded.

¹ I checked the web page http://www.ldas-sw.ligo.caltech.edu/ligotools/runs/tools/gwistat/, which reports the current status of operating GW detectors, on 29 November 2009.
Besides proving without a doubt that GWs exist and can be detected, even a single detection would give us invaluable information about the source from the waveform properties. In the case of a binary inspiral, the ‘chirp’ rate and possible modulation reflect the component object masses and spins; for the ringdown of a perturbed black hole, the damped-sinusoid frequency and decay rate reveal the mass and spin; for a spinning neutron star, the signal amplitude and polarization content indicate its ellipticity and spin axis inclination; and so on. A signal that does not match any of the standard models could confirm a speculative source type or reveal an unanticipated one. The reconstructed sky position of the source may point to a galaxy and thus pin down the distance. If the signal is associated with an astronomical event or object observed by other means—such as a GRB, optical or radio afterglow, supernova, neutrino detection, or known pulsar—then the complementary information will provide a clearer view of the nature of the source and emission mechanisms.

Preparations are well underway for major upgrades to the ground-based GW detector network in the form of Advanced LIGO [78] and Advanced Virgo [79], which will have an order of magnitude better sensitivity than the current instruments. When these detectors begin operating in 2014 or 2015, we can expect regular detections of binary inspirals and excellent prospects for detecting various other signals. The detection of multiple signals of the same type will enable population surveys that reveal the origin and evolution of such sources. Proposals for other large interferometric detectors, in particular LCGT in Japan [80] and AIGO in Australia [81], would add significantly to the capabilities of the current detector network. Prospects are good for detecting low-frequency signals with pulsar timing arrays on about the same time scale [4], while the space-based detectors are due to be launched some years later to open up the intermediate frequency band. Conceptual designs for ‘third-generation’ ground-based detectors such as the Einstein Telescope (ET) [82, 83] are now being proposed with the goal of improving over the sensitivities of the ‘Advanced’ detectors by another order of magnitude.

A comprehensive discussion of all the possible astrophysics that can be addressed is beyond the scope of this paper (but see the Living Review by Sathyaprakash and Schutz [84], for example). Instead, to illustrate some of the key issues, let us look into a crystal ball (see figure 3) and make some predictions for what the future might hold.

2.1. A wild guess at the future

Near the end of the S6/VSR2 science run, LIGO and Virgo will record a fairly significant inspiral event candidate, with a strength corresponding to a false alarm rate of 1 per 160 years. The best-match template will have masses of $8.2M_\odot$ and $1.46M_\odot$, representing a black hole and a neutron star. The all-sky burst search will also identify this as a candidate, but not the strongest one in that search. The reconstructed sky position will be consistent with three galaxies within 50 Mpc. Prompt follow-up imaging with a robotic telescope will capture a weak, fading optical transient in an elliptical galaxy within the favored sky region. After careful internal review and debate, the LIGO and Virgo collaborations will publish the complete diagnosis of the candidate, calling it ‘cautious evidence for a gravitational-wave signal’.

By 2015, pulsar timing array analyses will have produced greatly improved upper limits on supermassive black hole binary mergers and stochastic background processes, but no detections yet.

In the Spring of 2015, Advanced LIGO and Advanced Virgo will have been mostly commissioned and (I speculate) will begin an 8 month science run while still a factor of ~2 away from their design sensitivities. The GEO-HF detector may continue to operate for
part of that period. The run will yield two black hole–neutron star inspiral candidates, with an expected background of 0.02, and also two binary neutron star inspiral candidates, with a background of 0.03. One of the binary neutron star candidates will have a clear radio afterglow in prompt follow-up observations with radio telescopes. These event candidates will be published together as the first clear detection of gravitational waves. Analysis of these events will also place strong limits on ‘extra’ GW polarization states beyond the two predicted by general relativity.

All-sky searches for burst and periodic GW signals using the same data will yield candidates that look promising but are not significant enough to claim as detections. Greatly improved upper limits will be published on GW emission from known pulsars and on a stochastic background.

After further commissioning, Advanced LIGO and Advanced Virgo will resume running at full sensitivity, joined the following year by LCGT and AIGO. I imagine that analysis of 2 years of data will yield the following:

- 15 binary neutron star candidates with a background of 2.2. Two of the candidates will correspond to short-hard GRBs, one of which is localized in a galaxy with a measured redshift of 0.07. Based on this information, the emitted GW energy will turn out to be consistent with the theoretical prediction.
- 18 black hole–neutron star candidates with a background of 4.1. Two of these will correspond to GRBs, one also with a high-energy neutrino.
- Comparison of GW inspiral times with GRB times will confirm that GWs travel at the speed of light.
- Six binary black hole candidates with a background of 1.7. The masses and spins of the candidates will be inferred, giving a preliminary look at their distributions.
- Four burst candidates with a background of 0.15. One of them, with central frequency 310 Hz, will correspond to a weak long GRB with no measured redshift.
A periodic GW signal will be detected from the Crab pulsar, corresponding to 0.12% of the total spin-down energy. This result will be used to constrain models of neutron star formation in supernovae.

Periodic GW signals will also be detected from Sco X-1 (using data collected during a 3 month period with the detectors in a narrow-band configuration) and from five unseen neutron stars.

Stochastic GW searches will detect signals from two low-mass x-ray binaries (LMXBs) besides Sco X-1, and will place much stricter limits on cosmic string models.

Around the same time, pulsar timing analyses will detect GWs from supermassive black hole binary systems in two galaxies, and will rule out another large area of the parameter space for cosmic string models. Gravitational-wave astronomy will thus be in full swing by the time that LISA and DECIGO are launched and open up new frequencies for GW observations.

2.2. Notes on this exercise

It may have been indulgent to speculate so specifically about what the future may bring, and the details are obviously fictional. However, I think the scenario above is actually fairly conservative and illustrates several of the scientific findings that can be derived from the observations. It also reflects many of the issues the GW community will have to deal with, such as borderline-significant event candidates, samples of event candidates with non-negligible backgrounds and the role of information from electromagnetic observations.

3. The impact of detections on the field of gravitational-wave science

The transition envisioned above, from always setting upper limits to being able to claim some detections, will call for some changes in strategy to make optimal use of the detectors and of the data for science results. In this section we discuss a few such areas.

3.1. Tuning choices for advanced detectors

Interferometric detectors may be operated in different ways in order to optimize the noise characteristics according to scientific priorities. For instance, the Advanced LIGO and Advanced Virgo detectors are designed to be limited by quantum noise at low and high frequencies; by reducing the laser intensity, one can reduce the radiation pressure noise at low frequency at the cost of increasing the shot noise at high frequency. Interferometer configurations with signal recycling, such as Advanced LIGO and Advanced Virgo, allow additional tuning options through changing the reflectivity and (microscopic) detuning phase shift of the signal recycling mirror. Optimal tunings have been considered for individual signal types as well as some combinations [85]. Of course, an interferometer can only operate in one mode at a time. Detection of one or more GW signals may motivate re-tuning the interferometer to focus on a certain class of signals, either temporarily or for the rest of the run. It may also be useful to tune different interferometers differently, e.g. one of the Advanced LIGO Hanford interferometers could be optimized for low frequency while the other is optimized for higher frequency.

3.2. Support for additional detectors

The first direct detection of a GW signal will erase any lingering doubts about whether GW detectors really work, and will bring a new focus to the science which can be done with
GW observations. That should make a stronger case for additional detectors on the ground (e.g. LCGT, AIGO, ET) as well as boosting support for detectors in space (LISA, DECIGO). Furthermore, the designs of new detectors may be influenced by the view of what measurements are most important based on what has been detected so far.

3.3. Changes in philosophy

Currently there is a big emphasis in the GW detection community on achieving near-perfect certainty in the first GW signal detection. Typically this results in raising the signal strength threshold so that the false alarm rate is extremely low, but that also reduces the sensitivity of the search. However, having certified one or more events as genuine increases our belief in other candidates of the same type. Thus we can choose to relax the signal strength threshold to include more candidates in a search, even if doing so also includes more background—the benefit from having more real signals in the sample to study may outweigh the negative effects of the additional background.

4. Summary

Many of the GW searches that have been performed in recent years have provided useful astrophysical information despite yielding no confirmed GW signal candidates. Thus, one can say that we are already doing GW astronomy. Actual detections, when they finally start coming, will enable us to address a much wider range of astrophysics questions. And here is what will be exciting: everything.

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