The LIGO detections

The dreams of a generation of gravitational-wave physicists and astrophysicists came true on 14 September 2015 at 09:50:45 UTC when a strong signal appeared in the data stream of Advanced LIGO, a few days *before* the official beginning of its first science run. This event, dubbed GW150914, not only launched the era of gravitational wave astrophysics but also presented us with new ways to test the properties of extreme gravity and informed us of the existence of stellar-mass black holes twice as massive as we had ever seen before. A subsequent definite event on 26 December 2015 (thus GW151226) was reported on 15 June 2016, and a likely but not definite event was also recorded on 12 October 2016 (called LVT151012). Gravitational wave astrophysics has begun.

Recall that the passage of a gravitational wave stretches and shrinks distances. When a wave goes past a resonant detector such as the ones Joe Weber constructed, or the Mário Schenberg spherical detector in Brazil, the sphere is driven at the frequency of the wave. If the wave has close to the detector's resonance frequency then the amplitude to which the detector is driven can be enough to pick up via sensors on the surface. When a wave goes past a laser interferometric detector such as Advanced LIGO, the changing arm lengths result in shifting interference patterns that are seen at the output port. Either way, the motions to be measured are minuscule. For example, at its peak the strong event GW150914 reached a strain amplitude, which is the fractional distance change, of only $\approx 10^{-21}$, which means that the 4 km arm lengths of Advanced LIGO changed by roughly 1/200 of the radius of a proton! The weaker event GW151226 reached only about a third of that amplitude. Decades of technological development and instrumental innovation were required for the detection. Resonant mass detectors tend to be most sensitive at ~ 3000 Hz and ground-based interferometers quote a sensitivity range of $\sim 15 - 3000$ Hz.

The implications of the two definite events and one candidate event are profound. They include:

- The first clean tests of the predictions of general relativity in extreme gravity. When the best-fit waveform is subtracted from the GW150914 data, less than 4% of the signal remains. This suggests that there is not substantial room for significant deviations from general relativity. On the other hand, because alternate theories of gravity have not been pursued to the extent that their merger waveforms can be determined numerically, there are still non-GR theories that survive. Such theories include any that deviate from GR only in the presence of matter; for those, confirmation of a NS-NS or NS-BH GR waveform will be critical. Interestingly, because the GW151226 event involved significantly lower-mass black holes than GW150914 and thus had more cycles in the Advanced LIGO sensitivity band, GW151226 provides stronger constraints on deviations from GR in the inspiral than did the stronger GW150914 event.

- The discovery of the two heaviest (and then the single heaviest!) stellar-mass black holes known. Prior to GW150914 the highest mass established for a stellar-mass black hole was $\sim 15\ M_\odot$, but the best estimate for the components of GW150914 were $\sim 29\ M_\odot$ and $\sim 36\ M_\odot$. When they merged, the final mass was $\sim 62\ M_\odot$, which is less than the sum of the original masses because $\approx 3\ M_\odot c^2$ in energy was radiated in gravitational waves. For GW151226 the masses (best guesses around $8\ M_\odot$ and $14\ M_\odot$ with large uncertainties on everything except the chirp mass $M_{\rm ch} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5} = 8.9 \pm 0.3\ M_\odot$) are in the range seen previously from black holes in our Galaxy. The masses for the black holes in LVT151012 was in between these two (but recall that it is not certain that this was real). As more detections roll in over the next several years, we will be able to build up a mass function.

- The rate of double black hole mergers in the local universe is being tightened rapidly. Prior to the detections, the lack of any known BH-BH binaries in our Galaxy and the enormous uncertainties in models meant that the 90% credible rate of double BH mergers was quoted as $0.1 - 300$ Gpc^{-3} yr^{-1}. Combining the evidence from GW150914, GW151226, and LVT151012 has brought the latest 90% credible rate to $9 - 240$ Gpc^{-3} yr^{-1}. That's a factor of 90 increase in the lower limit! Obviously, as the detectors become more sensitive and the discoveries mount, the rate will continue to be refined rapidly.

The origin of these events is still being debated. Whether they came from an isolated binary origin or a dynamical origin, the consensus at this stage is that it is easier to produce the high masses of GW150914 if the stars were in a low-metallicity environment (i.e., the fraction of elements heavier than helium was significantly less than the fraction for the Sun or for the disk of our Galaxy in general). The reason is that stellar winds are largely driven by the interaction of photons with atomic lines, and those lines are obviously more common when there is an abundance of atoms with many electrons. Thus in low-metallicity environments, massive stars can hold onto a greater fraction of their original mass, which makes it easier to form more massive black holes. It will be necessary to accumulate more detections and to look at properties such as the masses, spins, and eccentricities (although these are expected to be undetectable using Advanced LIGO) of binaries to discern their origin.

The future of gravitational wave astrophysics is remarkably bright. Advanced LIGO is now concluding its second science run, and it is hoped that the Advanced Virgo detector will join them towards the end of the run. The third run will start in the fall of 2018, and then runs will continue at a regular rate. The design sensitivity of Advanced LIGO is about 2.5 times greater than what it had in its initial run, which means that the volume of sources probed will be about 15 times larger than it was initially. In addition, other interferometers such as Advanced Virgo, KAGRA, and LIGO-India, and resonant mass detectors such as Mário Schenberg and Mini-GRAIL, will join the hunt. The space-based detector LISA will launch in 2034 and will probe frequencies of $\sim 10^{-4} - 10^{-1}$ Hz, where it will find merging $10^4 - 10^7\ M_\odot$ black holes, extreme mass ratio inspirals of $\sim 10\ M_\odot$ black holes into supermassive black holes, and double white dwarf binaries that might be the precursors of Type Ia supernovae. Pulsar timing arrays are already operating in North America, Europe, and Australia, and they are sensitive to a (likely) stochastic background of orbiting (but not coalescing) $10^8 - 10^{10}\ M_\odot$ black holes in the $10^{-9} - 10^{-6}$ Hz range. Finally, several sensitive cosmic microwave background polarization experiments are operating or planned that will look for the characteristic B-mode polarization of gravitational waves at $10^{-17} - 10^{-15}$ Hz. Overall, gravitational wave science will cover 20 orders of magnitude in frequency, which is essentially the same coverage as electromagnetic astronomy. Insight and surprises await!

For more on my thoughts regarding the first LIGO detection, please read http://www.astro.umd.edu/∼miller/reprints/miller16d.pdf (Miller 2016, GRG, 48, 95).