Gravitational Wave Detections Usher in a New Era of Astronomy

by Jonathan Ziprick and Gabor Kunstatter

We live in an exciting time for research in gravity. Gravitational waves (GWs), the ripples in the fabric of spacetime predicted by Einstein a hundred years ago, have finally been detected experimentally. The first detection of GWs, emitted by the merger of two massive black holes, was made by LIGO (Laser Interferometer Gravitational-wave Observatory) in 2015 [1], and there have been six detections in total. The most recent two, one of which provides the first signal from the merger of two neutron stars, were confirmed by the Virgo interferometer [2]. These observations are amazing feats of modern technology that mark the advent of gravitational-wave astronomy, a new way of looking out into the cosmos by observing gravitational rather than electromagnetic radiation. They therefore raise the possibility of discovering new phenomena that have until now remained hidden. This monumental achievement earned the 2017 Nobel prize in physics for Rainer Weiss, Barry Barish and Kip Thorne, the three main contributors to this research.

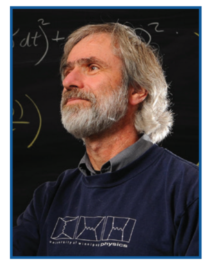
Summary

Since this article was submitted there have been further exciting developments in the field of observational black hole physics:

- **At this point LIGO has at least ten solid gravitational wave observations of compact object mergers https://www.ligo.org/news/index.php#O3resumes**
- **Upgraded LIGO, with 40% increase in sensitivity started runs on April 1 https://www.ligo.org/news/pr-O3resumes.pdf**
- **In February, 2019, LIGO received funding for a $35 million upgrade, called "Advanced LIGO Plus", due to be completed by 2024 https://www.ligo.caltech.edu/news/ligo20190214**
- **The international Event Horizon Telescope revealed an image of the event horizon of the supermassive black hole at the center of a galaxy (Messier 87) 55 million light-years from Earth. https://eventhorizontelescope.org**

It is important to highlight the important contributions to the success of the GW experiments made by Canadian physicists. Interpretation of GW measurements requires many precise numerical simulations of dynamical, three dimensional solutions to the full Einstein equations that describe the merger of heavy compact objects such as black holes and neutron stars. These simulations provide templates to which observed signals are compared in order to determine the values of the physical parameters in a given event and search for potential deviations from Einstein's theory. Such calculations are notoriously difficult and were in fact impossible until a breakthrough in numerical relativity by South African and Canadian physicist Frans Pretorius [3], currently at Princeton. Dr. Pretorius received his MSc at the University of Victoria under Werner Israel, who can arguably be credited with establishing the strong general relativity community that exists in Canada today. Dr. Pretorius' PhD was obtained at the University of British Columbia under Matt Choptuik, another world leader in numerical relativity. In addition, substantial numbers of the required templates for black hole mergers were first obtained [4] by the numerical relativity group of Harald Pfeiffer (Max Planck Institute) while he was at the Canadian Institute for Theoretical Physics (CITA) at the University of Toronto. Luis Lehner's group at the Perimeter Institute of Theoretical Physics (PI), while not formally part of the LIGO collaboration, provided simulations of neutron star mergers that are important for the interpretation of this class of events. During his first years in Canada Dr. Lehner was also associated with the University of Guelph. At the time of writing, CITA is the only Canadian institution that belongs to the eighty (institutional) member LIGO collaboration. Given the strength of the Canadian relativity community as a whole and its considerable contributions to the field, direct involvement in LIGO by Canadian institutions will hopefully grow substantially in the near future.

The GW detections provide remarkable confirmation of the theory of general relativity, which treats space and time on an equal footing, merged together into a four-dimensional geometry called *spacetime*. In this view



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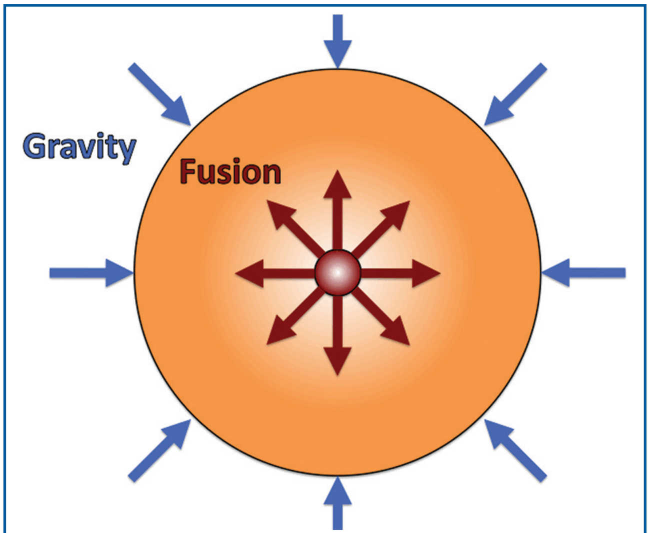

Fig. 1 The balance between gravity pushing inward, and fusion pushing outward, keeping a star radius at equilibrium. Credit: Britton Olson

gravity is seen not as a force, but as the effect of curvature in the spacetime geometry. Objects with mass create curvature, and this curvature in turn affects how these objects move. In the famous words of physicist John Wheeler: "Spacetime tells matter how to move; matter tells spacetime how to curve."

In general relativity, it is the geometry of spacetime that provides the field analogous to the electromagnetic field in Maxwell's theory. Just as charges moving up and down in a radio antenna generate electromagnetic waves, accelerating masses generate GWs in the spacetime geometry. More concretely, as these waves travel they alter the local spacetime curvature causing physical changes in length and the rate of time flow, both very counterintuitive phenomena. This is happening all around us, but the effect is unimaginably small for ordinary objects. In order to have GWs large enough for detection, incredibly massive objects such as black holes or neutron stars must orbit each other at speeds comparable to that of light. These are fascinating objects which are not fully understood and GWs provide invaluable insight into their nature.

Black holes and neutron stars are the end state of the ordinary stars which light up the night sky. Stars are born in stellar nurseries, massive clouds of mostly hydrogen gas. Some regions of the gas start by chance with a higher density and increased gravitational attraction, drawing in more gas and increasing the density even further. Eventually gravity becomes strong enough to fuse hydrogen into helium giving off massive amounts of energy, and a star is born. Fusion in the star core generates an outward pressure that keeps the star from collapsing in on itself, illustrated in Fig. 1.

Eventually all of the fuel is used up and a star reaches the end of its lifecycle, with the end state dependent on the initial mass of the star. Much of the stellar mass is ejected in a supernova as the core collapses. Stars that begin with 10 to 29 solar masses leave behind a core of 1.4 to 3 solar masses that collapses into a neutron star, with quantum mechanical *neutron degeneracy pressure* balancing against gravity to prevent further collapse. For stars having more than 29 solar masses before the end stage, it is generally believed that nothing can stop gravitational collapse, and the end state is a black hole.

Neutron stars are incredibly dense: a one teaspoon sample of neutron star material would weigh one billion tonnes on earth! Some neutron stars, known as *pulsars*, have a very strong magnetic field and rotate rapidly (up to 1000 times per second). As observed from earth, pulsars send a beam (or pulse) of electromagnetic radiation in very precise intervals. The first (indirect) evidence of GWs came in 1971 when R. Hulse and J. Taylor observed a binary system of a pulsar orbiting around a neutron star. Because of the precision of the pulsar period data, Hulse and Taylor were able to accurately calculate the period of orbit. According to general relativity, two stars in orbit will spiral closer together at increasing speed as gravitational energy is radiated away in GWs. Observations continue to this day, and the calculated change in period fits incredibly well with theory (see Fig. 2).

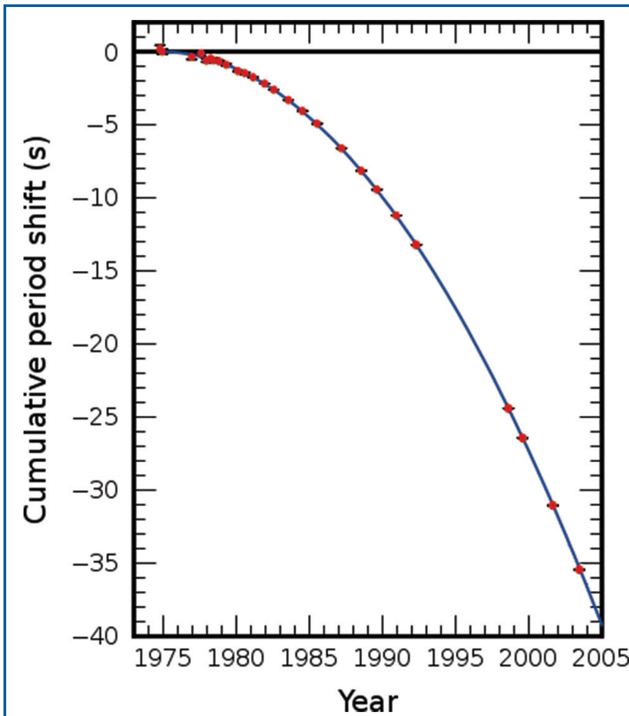

Fig. 2 Observed data points (in red) and the prediction according to general relativity (solid line) of the Hulse-Taylor binary pulsar system orbital period. Source: Weisberg, J.M.; Taylor, J.H. (July 2005). "The Relativistic Binary Pulsar B1913+16: Thirty Years of Observations and Analysis".

For this contribution Taylor and Hulse were awarded the 1993 Nobel prize in Physics.

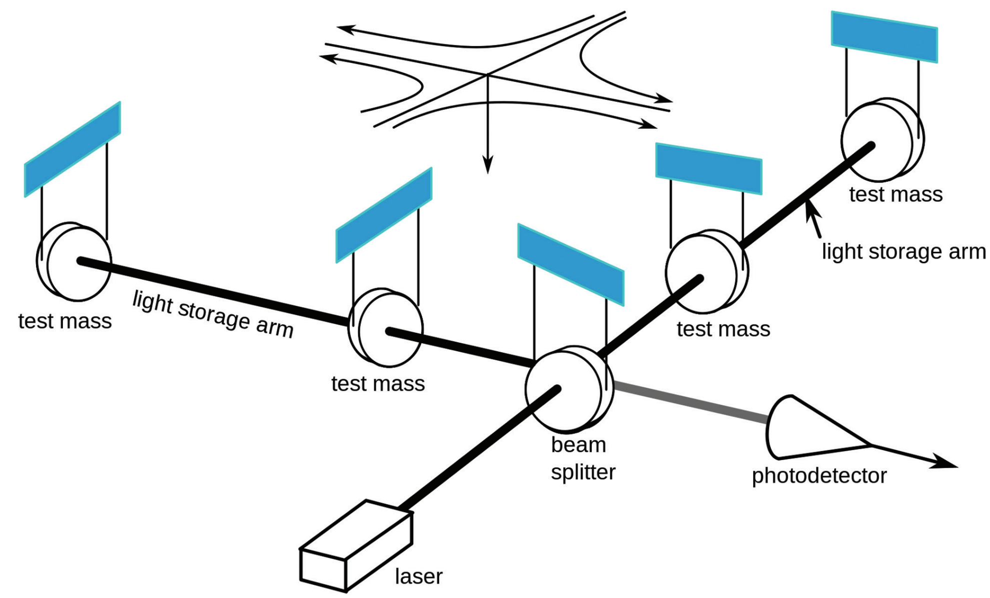

Fig. 3 Diagram of a LIGO interferometer. Source: LIGO-Caltech

Black holes form from stars so massive that gravity overcomes all other forces. General relativity predicts that the collapse process continues until a single point of infinite density forms at the centre, causing a divergence in the spacetime curvature (i.e. a *singularity*) at the centre. Surrounding the singularity is a region known as the event horizon, which represents the point of no return. Within the bounds of the event horizon even light moving 'outward' gets pulled back toward the centre, like a fish trying to swim up a waterfall. Generally in physics, we assume that nothing that can be measured locally should be infinite, so the singularity implies that Einstein's theory must no longer be valid near the black hole core. In this sense, GR predicts its own demise. The resolution is thought to be that when curvature becomes very large, gravity should follow the rules of quantum rather than classical mechanics. However, *there is no established quantum theory of gravity.* This is an active field of research and one can hope that gravitational waves coming from black holes will offer some experimental signatures to give insight for developing such a theory.

Currently there are three observatories working together to detect gravitational waves: two LIGO detectors in Hanford, WA and Livingston, LA, each with 4km arms, and the Virgo detector in Pisa, Italy with 3km arms. Having multiple interferometers gives more confidence in results since they are obtained independently at each location, and also helps to pinpoint where the signal originated. These measurement devices can detect a change in length between the mirrors of 10^{-19}m, or about 1/10000 the width of a proton. LIGO is planning to add a third detector in western India by 2023, and other organizations around the globe are planning future detectors and getting funding in place.

Modern gravitational wave detectors are giant laser interferometers that use the interference of light as a measurement tool. A simple sketch of the main components is given in Fig. 3. The components include a laser source, beam splitter, two long arms with mirrors at the end and a photodetector. This video explains how a laser beam is sent down the two different arms, reflects off the mirrors at either end, and recombines before reaching the photodetector. When the mirrors are at equilibrium the two beams exhibit destructive interference and no signal is observed. If the mirrors are displaced, the two beams no longer cancel each other, and the displacement can be measured by the intensity of light hitting the photodetector.

LIGO initially ran from 2002 to 2010 at a lower sensitivity than it has now, but did not find any detections. While this was disappointing, it was not entirely unexpected since the volume of space within detection range had a low probability of neutron star or black hole mergers over that time span. After the initial run, modifications were made over the next several years to increase sensitivity. The improvements included a more powerful laser capable of producing photons with shorter wavelength (increasing the measurement precision), and a seismic isolation system to better isolate the mirrors from vibrations in the surrounding area (eliminating experimental noise). This improved the sensitivity by a factor of 10, increasing the volume of space which could be observed by a factor of 10^3. Detections were now 1000 times more likely to be found. Advanced LIGO began running in September, 2015, and as luck would have it, the first gravitational wave was detected just a few days later! Further improvements are still in progress, and at full sensitivity, LIGO expects about 40 detections per year from neutron star sources alone.

The first detection by LIGO in September 14, 2015 obtained signals from the merger of two black holes of 29 and 36 solar masses to form a final black hole of 62 solar masses. The process ejected three solar masses worth of energy in GWs. A video illustrating the merger of two black holes and resulting GWs can be found here. The merger took place in a galaxy 1.3 billion light years away, but since only two detectors were operational at the time, the location of the source could not be triangulated with high precision. The form of the observed waves confirmed that general relativity accurately describes the black hole merger, and also provided evidence that these observations were indeed achievable: GW astronomy had arrived! Interestingly, the frequency of the observed GWs is within the audible range for humans; an audio file along with images of the data can be found here.

On August 17, 2017, GWs from the merger of a binary neutron star system were observed by Virgo and both LIGO detectors. Remarkably, 1.7 ms later the Fermi Gamma-ray Space Telescope detected a gamma ray burst emanating from the merger. With these four separate detections, the direction of the source was determined accurately and 70 observatories around the globe were notified so that they could search this location in the sky for further signals. A great deal was learned about neutron star mergers from this event alone. Physicists confirmed the theoretical prediction that neutron star mergers are a source for short gamma ray bursts, and that such events produce gold, lead and other heavy elements. It also provided confirmation that general relativity accurately describes the merger of neutron stars.

As of the date this article was written, there have been six GW observations by LIGO in total, with the last two being detected by Virgo as well. A list of these detections and the resulting publications is available on the LIGO website. This is only the beginning. GW astronomy is an exciting new field that will develop and mature over the coming years and decades. As technology improves and more detectors are built, we will be able to see farther out into space, observing signals that originated further back in time. If we can look back far enough, we can hope to uncover some insight into the Big Bang. More accurate data might show deviations from the predictions of general relativity, revealing clues to the quantum nature of gravity. We may even observe exotic phenomena such as cosmic strings, or something completely unforeseen! It is a rare occurrence in physics for an entirely new field of observational science to emerge, and GW astronomy is sure to play an important role in our efforts to learn more about gravitation and the mysterious objects that lurk in the universe.

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