Final Project

Surfing through the history of gravitational waves

PHYS320 — Introduction to Astrophysics

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The first-ever detection of gravitational waves on 14 September 2015 was both a wonderfully satisfying conclusion to a theory hundreds of years in the making and just the first step into a better understanding of one of the principal underlying forces of the universe.

The journey towards the detection of these elusive waves starts in 1665 with Sir Isaac Newton, who notoriously conjectured that the force of gravity is inversely proportional to the square of the distance. Monumental as it was and still is, this law did not fully describe how gravity acts and more specifically did not explain how it propagated. Consolidating a theory that fully explained gravity's properties turned out to be a source of contention for many years, with many big names in physics and science in general joining the discussion. However, to avoid this becoming a history paper, we will only mention Einstein's take on the topic and two of the many contributions that led up to it.

One of the first minds to approach this topic was English mathematician Oliver Heaviside. In 1893 he published "A Gravitational and Electromagnetic Analogy", an article in which he theorized that gravitational force could propagate like electromagnetic force. This laid the basis for French mathematician Henri Poincaré who, in 1905, after redefining the Lorentz transformations to conform to relativistic time-space geometry, expanded on this analogy, stating that all forces were affected by these translations and therefore, in the same way that accelerating charged particles produces electromagnetic waves, accelerating masses should produce gravitational waves.[3] Poincaré's theory would prove to be a stepping stone for Einstein's reasoning on the matter. In 1915 Einstein published his general theory of relativity, in which he stated that the analogy with electromagnetism does not hold up because an equivalent to an electric dipole, a "dipole of masses", does not make physical sense as there is no such thing as a negative mass.[3] He then went on to assert that gravity was not a force but instead a manifestation of the curvature of space-time continuum due to mass and plainly said, that gravitational waves were ripples in this continuum. Einstein would however go back and forth on his belief that these waves could exist for the next 15 years, this uncertainty was caused mainly by the difficulty in the choice of coordinate system (don't I know it) and the complexity of the equations that he was manipulating. In the end, he would become convinced of their existence, as stated in his 1936 paper "On gravitational waves" in which he settled on utilising cylindrical symmetry in his proof. This however is beyond the scope of this paper.

Unfortunately, the shakiness in Einstein's belief of their existence and the several failed attempts after his death to experimentally prove their existence cast an air of pessimism on this field of study which would not be lifted until 1974. In that year Russell Hulse and Joseph Taylor were conducting a survey on the PSR 1913+16 pulsar using data from the Arecibo Observatory in Puerto Rico when they noticed a variation in the periodicity of the pulses of 8–80 μs on a time scale of 0.3230 days.[5] All previous pulse period fluctuations of the same magnitude had been observed on a time scale of several years. This led them to believe that the variation in periodicity of the pulses was attributable to the effects of Doppler shifting one might see if the pulsar was orbiting around another mass. Using the fact that the pulses were being red/blueshifted they were able to infer the pulsar's radial velocity and consecutively the mass of PSR 1913+16's orbital companion which was found to be similar to the pulsar's (mass function of $0.13\,\mathrm{M}_\odot$). Hulse and Taylor had discovered the first pulsar binary. At the time limited data and observations prevented them from specifying the nature of the pulsar's companion but it was later found to be a neutron star.

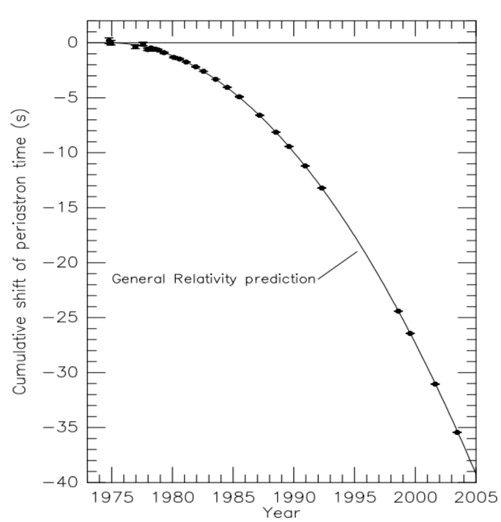
It was immediately recognised that this discovery opened the door for many studies, specifically studies on relativistic effects, and this opportunity was taken up by Taylor and his partners L. A. Fowler and P. M. McCulloch. Together, they continued collecting and analysing data from the binary and in 1979 published a study with their measurements of the general relativity effects of the binary.

In 2004, Taylor published a similar study with Joel M. Weisberg in which they looked at the same binary and came to similar conclusions. We will look at data from this study instead as their access to more advanced equipment and a longer study period (30 years versus 4 years) yielded more precise results. Taylor and Weisberg found that the period of the orbit was $P = 0.322997448930 \pm 0.0004$ days and that it was decaying in time with an observed derivative $P_b = -2.4184 \pm 0.0009 \cdot 10^{12} s/s$.[7] General relativity predicts that a binary star system in orbit loses energy in the form of gravitational radiation. Loss of gravitational energy means a loss in orbital energy which can be directly observed in orbital shrinkage. In an article titled “Gravitational Radiation from Point Masses in a Keplerian Orbit” published in 1963 physicists Peter and Mathews had determined that the rate of orbital decay according to general relativity was given by:[6]

$$\dot{P}_{b,GR} = -\frac{192\pi G^{5/3}}{5c^2}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1-e^2\right)^{-7/2}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)m_p m_c\left(m_p+m_c\right)^{-1/3}$$

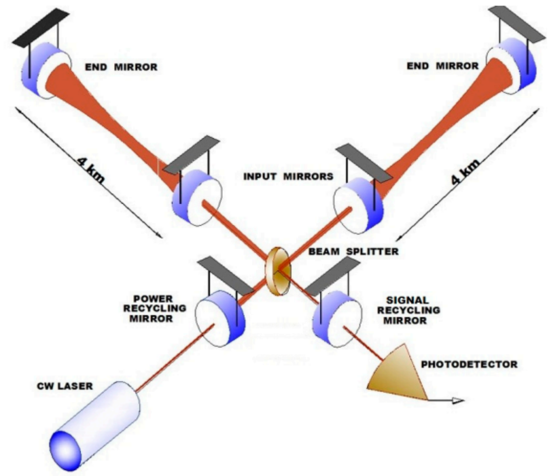
where m_p is the mass of the pulsar and m_c the mass of the orbital companion.

After correcting their observed value for the relative acceleration between the solar system and binary pulsar system, Joel and Taylor confirmed that the observed orbital decay matched the predicted one within 0.21 percent. In 1979, this was the first indirect experimental proof of the existence of gravitational waves. In 1993 Taylor and Hulse were awarded the Nobel prize for



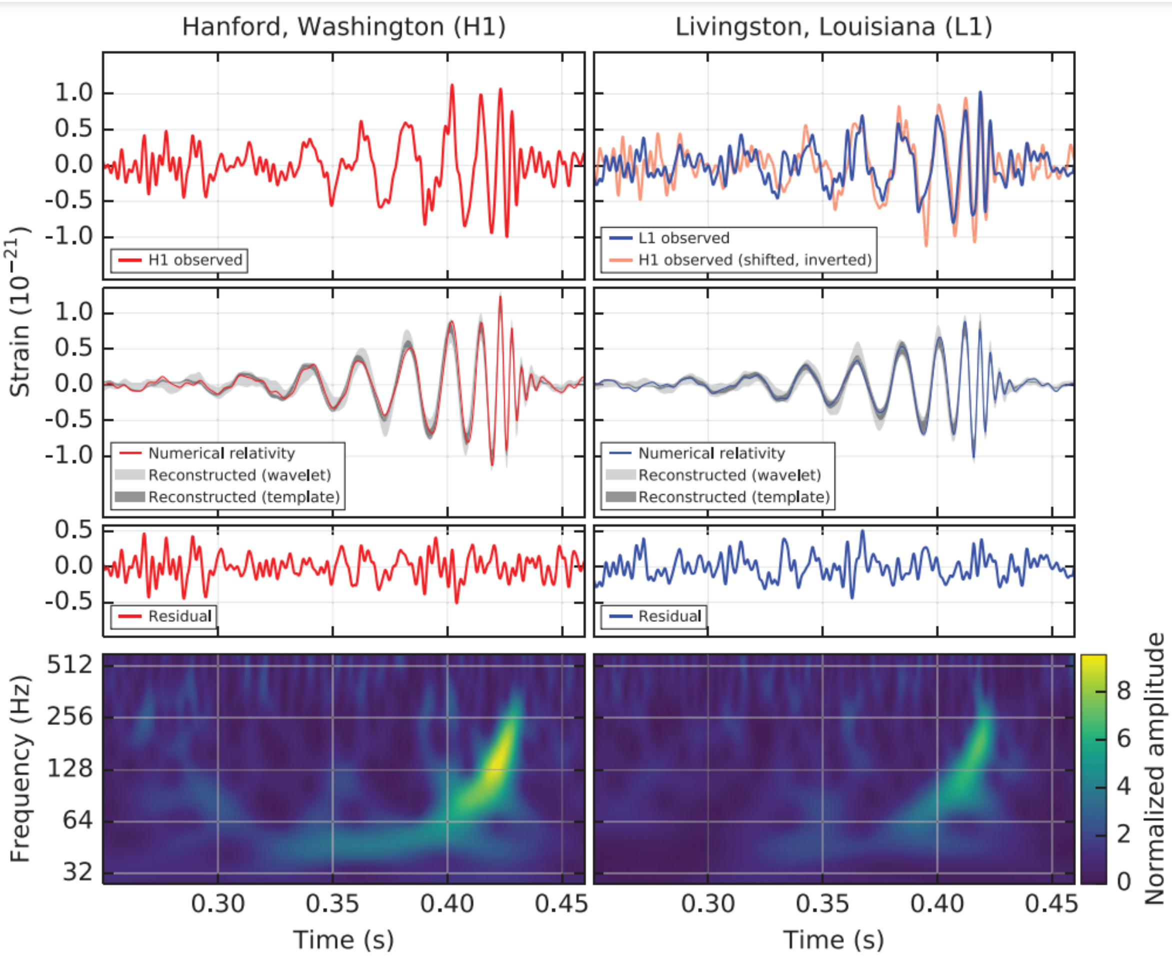
Orbital decay of PSR B1913+16.[8]

their discovery of the PSR 1913+16 pulsar binary because of the impact it had on gravitational physics.



Advanced LIGO interferometer design model.[3]

With renewed interest in the field came more research and more funding for experimental equipment that could directly detect gravitational waves. At this time the National Science Foundation funded a collaboration project between MIT and Caltech called the "Laser Interferometer Gravitational-Wave Observatory" (LIGO). Construction of two inteferometers, one in Hanford in Washington State and one in Livingston, Louisiana, began in 1994.[3] These interferometers consisted of a laser that shot a beam of monochromatic light at a beam splitter, in this case a semi-reflective surface, which would reflect part of the light and would allow another part to pass through. The two beams of light would travel 4 km before encountering a mirror and being reflected back where they would be recombined at the beam splitter and then arrive at a photo-detector. The distances are calibrated so that, in absence of gravitational waves the two beams of light would arrive at the photodetector out of phase, therefore yielding no signal. Two of these devices were necessary to rule out any false signals that could be caused by local seismic waves. The two interferometers operated from 2002 to 2010 in conjunction with TAMA 300 in Japan, GEO 600 in Germany and Virgo in Italy, but did not detect any gravitational waves during these years. In 2010 a five year upgrade to the two LIGO's began to reduce any noise that could interfere with the detection, such as physical vibrations from the environment and nanometer-scale changes in the shapes of optics, and only in Febrauary 2015 did Advanced LIGO become active again with the false alarm rate now estimated to be less than 1 event per 203 000 years. On September 14, 2015 at 09:50:45 UTC, the LIGO in Hanford and Livingston detected a signal 10 ms apart, the time taken for light to travel the 4000 km between the two



Signals from the two LIGO observatories, measured in strain (shift in space travelled by the laser light) and frequency of the gravitational wave.[1]

devices. A gravitational wave passing through the interferometer had caused one of the arms to stretch by an order of magnitude 10^{-21} m, 10000 times smaller than a proton, and the other to shrink in length by the same amount. The two beams of light hit the photo-detector no longer perfectly out of phase and a signal was produced. A gravitational wave had just been detected for the first time in history.

It is hard to understate how groundbreaking this detection was for the advancement of astrophysics and for all the physicists who were finally able to see their life's research culminate with such direct and precise experimental evidence.

Immediately our understanding of the universe was broadened. Analyzing the way the signal increased in frequency in about 8 cycles from 35 to 150 Hz over 0.2 seconds,[1] the researchers were able to infer that those eight gravitational wave cycles originated during four complete orbital revolutions by two very massive bodies in a binary system and that the steadily increasing frequency and amplitude are caused by the two bodies growing closer together and amplifying the gravitational wave energy output (to compensate the energy decrease in the system) in a runaway process which ended when the two bodies merged and the system reached equilibrium [1]. Using Kepler's laws and Einstein's quadrupole formula for the gravitational wave luminosity of a system they were then able to infer the masses and velocities of the bodies that created this so-called chirp and it was concluded that the signal was caused by two inspiraling black holes each approximately 30 times more massive than the Sun that merged together over 1.4 billion light years away. This detection therefore also proved for the first time the definite existence of black hole binaries.

Since then another 4 black hole mergers have been observed through gravitational waves and eventually, we hope to construct a blackhole survey of the universe, just as we do with galaxies. Studying patterns that might arise in this mapping will help us garner more information about black hole formation.[2] For example, it is predicted that around masses 50 solar masses there will be a cut-off, with little to no black holes observed above this mass. This is because it is theorized that the very high pressures in the core of these supermassive stars could eventually lead to the creation of antimatter which would cause a pair-instability supernovae, a huge explosion that would disintegrate the star leaving no remnants behind. This has never been observed but by studying gaps in a future blackhole survey we could get one step closer to proving (or disproving) their existence.

But so much more can be deduced from the information that gravitational waves bring to us. Unlike electromagnetic waves, gravitational waves interact very weakly with matter and are not as susceptible to being absorbed, bent, or refracted. This means they can travel through the universe mostly unimpeded by opaque matter and bring us information from events and objects invisible to EM radiation. They could for example tell us about how structures formed in the very early universe because, unlike photons, they could escape from the opaque plasma. It is because they bring us such relatively undistorted information that we can also use them to study the properties of neutron stars. The insides of neutron stars are still mostly a mystery but using gravitational waves emitted from neutron star mergers to determine their radii to very high precision levels will allow scientists to narrow down which equation of state best describes their interiors. A signal from one such merger was detected on 17 August 2017 and from it, researchers were already able to solve the long-standing question of the origin of gold and other heavy elements in the Universe.

But possibly the most exciting research field that gravitational waves will enable advances in concerns the Hubble constant. A precise value for this constant has yet to be determined but in 2005 Prof. Daniel Holz and Scott Hughes wrote a paper[4] in which they suggested that the constant could be evaluated using a combination of gravitational waves and light just like the one that the neutron star merger provided in 2017. Unlike black hole mergers, neutron star mergers also give out a burst of light along with gravitational waves, which makes them a perfect candidate for Holz and Hughes' method. The formula in question is very simple $H=v/d$, where v is the receding velocity of the neutron stars and can be quite easily calculated using the burst of light and redshift. The difficulty was in calculating the distance d, but by analyzing the shape of the gravitational wave signal they were able to determine how much energy was given off in the merger, and comparing this with the strength of the waves that reached earth they were able to determine the distance. Of course, one measurement is not enough to pinpoint the value but researchers hope to be able to use this method to narrow the measurement of the Hubble constant down to 1% uncertainty, compared to other methods which currently yield a 2 to 3% uncertainty.

It is for this reason, for the enormous impact this will have in studying super-massive celestial bodies, the origin of the universe and gravity itself that the three physicists that had spearheaded the ideation and construction of LIGO, Rainer Weiss, Kip Thorne and Barry Barish, were awarded the Nobel Prize in 2017 for their role in the detection of gravitational waves.

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