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The Discovery of Gravitational Waves

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Introduction

The 2017 Nobel Prize for Physics was awarded to the three persons who had made *"decisive contributions to the LIGO detector and the observation of gravitational waves"*. Lord Kelvin [1], who had been the professor of natural philosophy (physics) at Glasgow University for over 50 years and was a close scientific colleague of Clerk Maxwell, would have been very proud of the rôle that his university had played in this important scientific breakthrough. As acknowledged explicitly by Nobel Laureate, Barry Barish, in his Nobel lecture at the 2017 awards ceremony, this rôle was in designing an essential component of the gravitational wave detectors, namely the suspension system to isolate the LIGO mirrors from local ground disturbance.

History of Gravitational Waves

In the 17th century, Isaac Newton (1642–1727) had determined that the force of gravity declined as the inverse square of distance. He conjectured that there was something, not material, which was carrying the force from one body to another. In 1692, he wrote to Richard Bentley (1662 – 1742), later Master of Trinity College, Cambridge:

> *Tis unconceivable that inanimate brute matter should (without the mediation of something else which is not material) operate upon & affect other matter without mutual contact… That gravity should be innate, inherent & essential to matter so that one body may act upon another at a distance through a vacuum without the mediation of anything else by & through which their action or force may be conveyed from one to another is to me so great an absurdity that I believe no man who has, in philosophical matters, any competent faculty of thinking can ever fall into it.* [2]

In the 19th century, Clerk Maxwell established the equations governing electricity and magnetism and deduced from them that electromagnetic waves travelled at the speed of light. He proposed that light itself was an electromagnetic wave. Hertz, in 1887/88, showed, experimentally, electromagnetic disturbances being transmitted across his laboratory and having all the properties of waves. This confirmed Maxwell's theory.

In 1896, J.J. Thomson discovered the electron. The acceleration of electrons, whose electrical effect also falls off as an inverse square law, caused them to emit electromagnetic waves. By analogy, since gravity also falls off as an inverse square law, it was conjectured that the acceleration of masses would cause gravitational waves to be emitted (gravitational radiation) and that these gravitational waves, although very different from electromagnetic waves, would also travel at the speed of light.

In 1915 [3], over one hundred years ago, Einstein published his *'General Theory of Relativity'* (giving a new and revolutionary theory of gravity). He showed that an accelerating body does indeed emit gravitational waves. It was the stretching and squeezing of the fabric of four-dimensional space-time (three dimensions of space and one of time) which caused gravitational effects to be passed on from one body to the next. This was the *"…the mediation of something else."* which Newton had conjectured in 1692.

In a paper of 1916 [4], Einstein estimated that the magnitude of gravitational waves would be extremely weak, so weak indeed that he concluded that their magnitude would have a practically vanishing value (in Einstein's own words *"…in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß"* [5]).

Distinguishing 'signal' from 'noise'

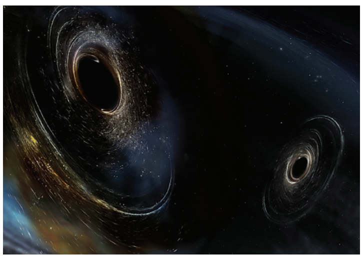

Figure 1: Two Black Holes merging

It was therefore expected that gravitational waves would be extremely weak by the time they reached the Earth even if the gravitational waves had arisen from such extreme events as the acceleration and final violent merger of two black holes.

Indirect methods (namely the loss of energy of two stars circulating round each other resulting in the slowing of the orbital period) had suggested that gravitational waves existed (and carried away energy from such stars). However, there was no *direct* detection.

If a *direct* 'signal' could be detected, it would be a tiny movement caused by the passage of a gravitational wave through suitable apparatus. Special equipment would be required which was capable of suppressing 'earthly noise' [6]; thus attenuation of such noise would be an essential requirement. At the same time, the apparatus would also have to be sensitive enough to detect a very weak signal coming from sources outside the solar system.

1 Lord Kelvin, OM, FRS, FRSE (1824-1907), along with Lord (Sir George) Stokes, FRS (1819-1903), were the U.K.'s most prominent physicists of their time, both becoming Presidents of the Royal Society; Stokes from 1885-90 and Kelvin from 1890-95. Kelvin and Stokes were both close scientific colleagues of James Clerk Maxwell, FRS, FRSE (1831-79) who became the first Cavendish Professor of Physics in Cambridge in 1871.

2 Isaac Newton's reply (25 February 1692/3) to Richard Bentley, 189.R.4.47, ff. 7-8, Trinity College Library, Cambridge, UK

3 Einstein A. (1915), "The Foundation of the General Theory of Relativity", http://einsteinpapers.press.princeton.edu/vol6-trans/158

4 Einstein A. (1916); "Approximative Integration of the Field Equations of Gravitation", http://einsteinpapers.press.princeton.edu/vol6-trans/213

5 See Einstein article above

6 created by tremors within the earth arising from earthquakes, traffic or even someone walking past the apparatus or even the vibration of its components.

→

The sensitivity requirements would therefore be at the extreme end of the possible as the ripple in the fabric of space-time would, it was estimated, change the length of even a 4km-long detection arm by less than 10^{-18} of a metre, being less than one ten-thousandth (10^{-4}) of the width of a proton! To put this in perspective, this feat would be the equivalent of measuring the change in the distance to the nearest star by one hair's width.

Mathematical modelling

The equations of Einstein described the effect, on the geometry of four-dimensional space-time, of the presence of matter.

Advances in computer power and growing familiarity with Einstein's equations had enabled theoretical plots (of frequency against time) to be drawn for the wave-forms emitted during the merger of two black holes or two neutron stars, e.g. depending on their different masses and the orientation of their orbits.

The Laser Interferometer Gravitational-wave Observatories (LIGO)

Interferometers were made famous by the Michelson and Morley experiment of 1887. They showed that the speed of light was (counterintuitively) the same for all observers and a constant of Nature.

Figure 2: LIGO Hanford Observatory in Washington State

The construction of the LIGO interferometer observatories extended technology to its limit.

Each observatory was designed with two arms (each one 4km long) placed at right angles to each other, along which the laser beam, split into two, was shone. It was then reflected (multiple times) by the mirrors (at each end of the arm) before the two separate light beams were recombined.

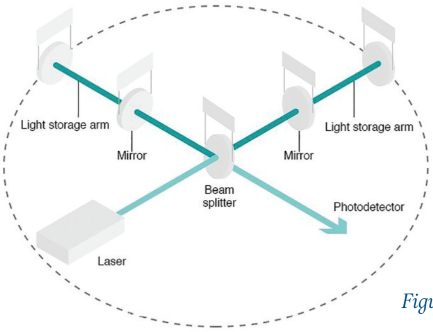

Figure 3: Interferometer Principles

When a gravitational wave passed through the interferometer the stretching and squashing of the fabric of space alternately lengthened and contracted the two arms.

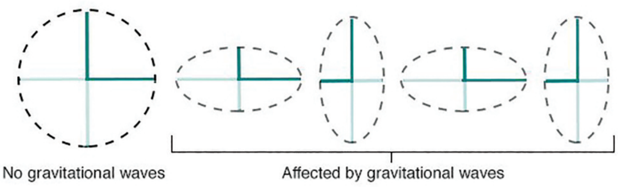

Figure 4: Stretching and squeezing of spacetime

The two light beams then took different times to travel through the arms; the two beams were no longer 'in step' and this was observed as a change in the interference pattern.

The mirrors were suspended from fibres forming a pendulum – a system that was designed in Glasgow. It was a 'four-stage' pendulum (i.e. one pendulum suspending another and so on, four times). This was done so as to make the bottom pendulum very insensitive to the movement of the top pendulum or of the surrounding environment. This attenuated as much as possible the clutter of noise originating from earth, while letting any signals, coming from outside the solar system, stand out above the noise.

The interferometer had therefore to meet extreme requirements!

Detection of Gravitational Waves

Attempts were made from the 1960s onwards, at first using different technology and then using laser interferometry, to detect such gravitational waves – but without success.

However, the LIGO interferometers were progressively upgraded. In 2015, with the exploitation of the latest technology, including the multi-stage suspension system designed in Glasgow, the resulting improved sensitivity of the apparatus was finally able to distinguish 'signal' from 'noise'. This level of sensitivity, combined with the power emitted during the merger two black-holes[7], finally provided a means of *direct* detection.

Direct detection of gravitational waves was achieved, for the first time, on 14 September 2015.

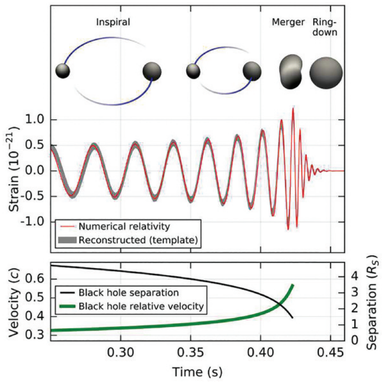

Figure 5: The waveform and key physical characteristics of the first detection event – from the merger of two black holes – detected on 14 September 2015

There was about a 7 milli-second delay between the detections, as the gravitational wave-front travelled between observatories; one observatory being on the West coast (Washington State) of the U.S.A. and the other being on the East coast (Louisiana).

This first detected event involved one black hole with a mass equivalent to about thirty-six suns merging with another black-hole with a mass of about twenty-nine suns. The merged black hole only had a mass of sixty-two suns. Therefore, an energy loss equivalent to three times the sun's mass had been radiated away as gravitational energy and in a fraction of a second. This awesome coalescence involved nearly six million trillion trillion kilograms of matter being converted into gravitational-wave energy in less than a second!

Furthermore, it was determined that the merger had occurred at a distance of more than one billion light years.

The signal received very closely fitted the theoretically predicted waveform that would be produced if two back-holes merged.

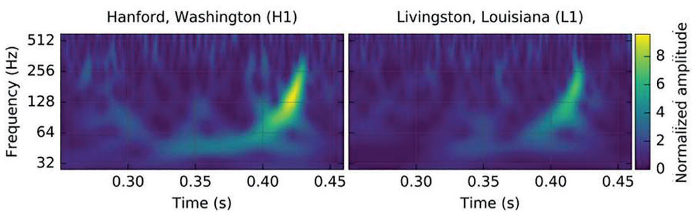

Figure 6: 'Chirp' waveform of the first detected event

7 where the power produced from such a merger was more than ten times the combined light power from all the stars and galaxies in the observable universe.

A second and third detection were made before the end of 2015, although only one of these events was significant enough to be claimed as a definite detection.

These were such historic events that they resulted in the award of the 2017 Nobel prize to the three LIGO pioneers, namely Rainer Weiss, Kip Thorne and Barry Barish.

By 2017, the Virgo observatory in Pisa had also been upgraded. During 2017, three further black hole merger detections were reported – including one event, on August 14th 2017, that was detected by both LIGO observatories and by Virgo. Only three days later, on August 17th, a further detection was made, by the three observatories (simultaneous apart from the time taken by the wave-front to travel the distance between them). This wave was identified as that coming from two merging neutron stars. For the first time there was also evidence (from telescopes) of electromagnetic radiation emanating from the same source. Thus, it was the first event observed using both gravitational and electromagnetic radiation.

Evidence that the waves came from the merger of two black holes and that it was a real astrophysical event

Part of the reason for the evidence that the very first detection (on September 14th 2015) represented a real astrophysical event was that the signal was detected at both observatories simultaneously (apart from the 7 millisecond delay for the wave to travel between observatories).

The peak frequency of the signal's wave-form was about 150 Hz showing that the two black holes were very close before they finally merged. Based on the estimated total mass of the two merging objects, a pair of neutron stars would not have been massive enough to have matched the observed wave-form.

Extensive tests were done on the ability of the interferometers to distinguish signal from noise. It was estimated that the chance of a noise event triggering the detection was exceedingly small. In fact, a signal as strong as that detected would, it was estimated, only occur by chance (a 'false-alarm'), less than once in about 200,000 years of data i.e. the statistical significance was more than five sigmas.

This was convincing evidence that gravitational waves had been detected and that they had emanated from the merger of two black holes.

The future

Observatories in India and Japan will soon join Virgo and the two American LIGO observatories. The successful detection opens up a whole new field of investigation namely *'gravitational wave astronomy'*. The future for astronomy is exciting and gravitational wave astronomy is only just beginning.

All pictures in the above article are 'Courtesy of LIGO'.

Mary Fairfax Somerville (1780-1872), the woman who 'checkmated' James Clerk Maxwell

by **Professor Elisabetta Strickland** [1], Professor of Mathematics, University of Rome "Tor Vergata".

Figure 1: Mary Somerville (courtesy Wikipedia)

Mary Somerville

During 2017, renewed interest in Mary Somerville was perfectly illustrated by the decision of the Royal Bank of Scotland to use Mary's image on their new ten-pound plastic banknote, in circulation from the month of October 2017. She was voted for (via Facebook) by over four thousand people. The students and alumni of Somerville College, Oxford, campaigned for this choice. Being one-hundred and forty-five years after her death in 1872, recognition was long-overdue.

The competition was very strong. In addition to Mary Somerville, two Scottish scientists, both outstanding in their fields, competed to have their image on the banknote namely, Thomas Telford, FRS, FRSE (known as the 'Colossus of Roads' who also designed bridges, including the famous Menai Suspension Bridge) and James Clerk Maxwell, FRS, FRSE; but Mary won the vote.

Prominent Scientist

More than two centuries ago, Mary Fairfax Somerville, the Scottish mathematician, after an unpromising childhood, slowly became recognised as one of the most prominent scientists in Great Britain, so well-known that, when she died in 1872, her obituaries described her as *"The Queen of Sciences"*.

Mary Somerville spent a large amount of her life exchanging ideas with researchers in the most advanced scientific areas of her time, namely mathematics, astronomy, physical science and geography.

She published four well-reputed books concerning these disciplines. She was commissioned to write them by the *Society for the Diffusion of Useful Knowledge*, an interesting organisation which, during the Victorian age, promoted the production of readable texts on scientific topics for an increasing literate and educated population; a reflection of the growing focus on science which occurred in the nineteenth century.

Her success as an author, as a mathematician and an astronomer, was only possible because of her powerful intellect and the stubborn way in which she pursued her studies, ignoring her lack of academic background and providing a successful example of self-education.

History

She was raised in Burntisland, a small seaport on the coast of Fife in Scotland and, by her own admission, at nine years old, she was a "wild creature", who spent her time roaming the countryside and seashore near her home, observing sea creatures and birds, collecting things and learning the name of the plants around her house.

Her mother believed that her daughter had just to learn domestic chores such as how to feed the poultry and take care of the family cow, so she only taught Mary the catechism of the Kirk of Scotland and how to read the Bible.

1 Professor Elisabetta Strickland published, in 2017, a biography of Mary Somerville, *'The Ascent of Mary Somerville in 19th Century Society'*, Springer.

When she was ten years old, her father returned from a long voyage as an officer of the British Navy and discovered that Mary's reading skills were minimal and she could not write.

So Mary was sent to a school, but after one year she returned home, as she could not stand the teaching techniques which were "close to torture". She continued her wandering existence, but at least she had increased reading skills that allowed her to enjoy a small number of books in her family's home.

Passion for Science

Mary's interest for mathematics had had its first outburst during a party: she was thirteen years old and was paging through a fashion magazine when she came across a puzzle which had x's and y's in the solution. After asking a friend, she found out that the puzzle involved something called 'algebra', so he decided to study the subject. In order to obtain the required books, she conspired with her brother's tutor, who gave her what she needed, namely Bonnycastle's 'Algebra', which at that time was in use to teach mathematics in schools.

Mary, from that point onwards, was on her way. As her family could not ignore forever her aptitude for studying, she was allowed to move to the house of her grandfather in Edinburgh. There Mary turned into a charming and elegant young lady. However, in addition to practicing the piano, painting and following cooking lessons she did not neglect her studies; she concentrated on understanding Euclid.

Family opposition

Her family's dislike of her serious study forced her to marry her cousin Samuel Greig at the age of twenty-four. As her new husband shared her family's low opinion of her passion for science, her pursuit of mathematics became even more difficult. However, her marriage was not a long one, as Samuel Greig died in 1807.

She gained economic independence and she could get back to her studies, raising at the same time two children.

Professor William Wallace, FRSE, Professor of Mathematics at the University of Edinburgh, helped her to assemble a library of all the most important works in mathematics and astronomy at that time. By that means, she got into reading, understanding and, in due course, mastering the book 'Mécanique Céleste' by Laplace (known as the 'French Newton'); one of the most advanced books in mathematics and astronomy at the time.

Second marriage

However, as her family was still deeply worried about her interest in the differential calculus, Mary was convinced to marry another cousin, William Somerville. This time she was lucky, her new husband was a learned army surgeon who was supportive of her studies and recognised her superior intellect.

When he was appointed to a post in London, they moved to fashionable Hanover Square in Mayfair and there she became acquainted with a set of learned friends, such as the astronomer Sir William Herschel and his son Sir John Herschel, FRS. These personal contacts were invaluable in building her career and reputation.

In 1826, Somerville published a study on magnetism in the Philosophical Transactions of the Royal Society of London, entitled *'On the Magnetizing power of the More Refrangible Solar Rays'*. Her paper earned her admission, in 1835, to the Royal Astronomical Society. Together with the astronomer Caroline Herschel (sister of William and aunt of John), they were the first women to be so admitted.

The Mechanism of the Heavens

After Somerville published her study on magnetism, she was commissioned by Lord Brougham, QC, FRS[2], founder of the *Society for the Diffusion of Useful Knowledge*, to write an account of Laplace's *Mécanique Céleste* thereby making more widely known the latest scientific knowledge emanating from European pens.

Mary spent the years from 1827 to 1831 writing the commissioned book, which came out in print with the title *'The Mechanism of the Heavens'*.

Figure 2: Mary Somerville sculpture by Chantrey, Courtesy of the Royal Society

Although she could not become a Fellow of the Royal Society herself (owing to the restrictions of the time on women becoming Fellows), in 1840, a bust of her was commissioned by the Royal Society from the most eminent sculptor of the day, Francis Chantrey. It stands in the premises of the Royal Society.

She continued writing after this initial success and published *'On the Connexion of the Physical Sciences'* in 1846, *'Physical Geography'* in 1848 and *'On the Molecular and Microscopic Science'* in 1869.

Her work earned her the Victoria Medal. Sir Robert Peel advised the Crown to grant a civil pension of two-hundred pounds a year for Mary in recognition of her eminence in science and literature. The then Prime Minister, Lord John Russell, added one hundred pounds a year to her pension.

Italy

Following her husband's retiral to Italy for health reasons, her life was rather nomadic. She spent many years traveling around Europe and spent thirty years in Italy, where she lived in Florence, Rome, Venice, Turin, La Spezia and finally in Naples.

Her husband William died in 1860. She found her grief difficult to cope with. But she had her two daughters Martha and Marie Charlotte and the only surviving son of her first marriage, who was a barrister in London and exchanged letters with his mother during all his life.

She died in 1872 at the age of ninety-two and is buried in the English Cemetery of Naples and is commemorated by a statue in Naples.

Recognition

The number of honours she received was extensive. She became a member of all the important scientific academies of her times even in Italy. Somerville College in Oxford was named after her in 1879. An asteroid belt, a crater on the moon and a room in the Scottish Parliament are also named after her.

Connection with Clerk Maxwell

William Clerk (a relative of James Clerk Maxwell) was a friend of Mary and is mentioned in her memoirs.

A portrait of Mary Somerville hangs in Maxwell's Edinburgh birthplace as does a fine collection of etchings of eminent mathematicians and astronomers. This collection was originally owned by Sir John Hershel, who, as a close friend of Mary, had, no doubt, shown her his collection.

Conclusion

The choice of a woman for the Scottish banknote (and the choice of Jane Austin for the corresponding English banknote) represents a significant one for all women who have succeeded in developing their own abilities, demonstrating that they are capable of assuming a higher place in the intellectual world than that usually accorded to them.

2 Sir Henry Brougham (1778-1868) who, as well as being the founder of the Edinburgh Review and being Lord Chancellor (1840-1842), was also interested in science and had himself contributed several scientific papers to the Royal Society.

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