The Cosmic Detectives

How scientists in Scotland helped discover gravitational waves

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Foreword

Global team solves universal mystery

From Sherlock Holmes to Rebus, there is a long history of famous Scottish fictional detectives. In 2015, however, a “cosmic detective” story unfolded that would rival the adventures of them all.

The first direct detection of gravitational waves from the merger of two massive black holes, more than a billion light years from the Earth, became a global media phenomenon when it was announced in February 2016. This remarkable discovery was made by two giant interferometers known as Advanced LIGO, the most sensitive scientific instruments ever built. It vindicated Albert Einstein’s General Theory of Relativity and has been widely hailed as one of the greatest scientific breakthroughs of the Century. The human story of how we discovered gravitational waves also stretches far across both space and time. First, it reaches back one hundred years to Einstein’s pioneering prediction of these tiny ripples in the fabric of the Cosmos – which he believed were too elusive ever to be detected – and since then across many decades of ingenuity and determination as – one by one – the huge technological barriers to making such an insanely difficult measurement were overcome. The discovery, and the research that made it possible, also spans the globe – the result of a worldwide collaboration featuring thousands of scientists in dozens of countries. In this sense, it represents a triumph for the vision and commitment of funding agencies to invest long-term in a project so challenging that many were sure it would never succeed.

This cosmic detective story has its own strong Scottish connections – from the origins of the LIGO project to the scientists now leading the design and operation of Advanced LIGO and shaping the future of this exciting new field. And here we tell the tale of Scotland’s place in the discovery of gravitational waves by highlighting the contributions of some of the players involved.

The achievements of the LIGO team have been recognised with many international awards and prizes – including the award of the Royal Society of Edinburgh’s President’s Medal to the Scottish academics who shared in the discovery, most of whom are profiled in this special issue. The President’s Medal was also awarded to Dr Iain Martin (University of Glasgow), the late Dr Gavin Newton (University of Glasgow), Professor Nicholas Lockerbie (University of Strathclyde) and Dr Jonathan Gair (University of Edinburgh). In addition, Dr Angus Bell and Mr Russell Jones (both University of Glasgow) shared with the rest of the LIGO engineering team the 2016 Paul F. Foreman Team Engineering Excellence Award of the Optical Society of America. The LIGO project also benefits from major contributions by numerous students and other research staff, who also share the international prizes.

In Conan Doyle’s The Adventure of the Dancing Men Sherlock Holmes states that “What one man can invent another can discover”. Our tale is one of astonishing invention that led to remarkable discovery. Let the story begin!

Martin Hendry MBE FInstP FRAS FRSE is Professor of Gravitational Astrophysics and Cosmology at the University of Glasgow, where he is currently also Head of School. His main research interests are in the analysis of astronomical surveys, including the development of optimal methods for ‘multi-messenger’ astronomy, combining data from both electromagnetic telescopes and gravitational-wave observatories. He is a passionate advocate for education and public outreach and currently chairs the EPO Group of the LIGO Scientific Collaboration. In 2015, he was awarded the MBE for his services to the public understanding of science.
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Editorial Team:
All articles written by Peter Barr
Production Editor Jenny Liddell, The Royal Society of Edinburgh
Designer Emma Quinn
Printer Mackay & Inglis Ltd

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If you would like more information, please contact: sciencescotland@theRSE.org.uk
The Royal Society of Edinburgh, 22–26 George Street, Edinburgh EH2 2PQ

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Gravitational Waves

What really happened?

At 9:51am (Greenwich Mean Time) on September 14, 2015, something happened which will change the way we look at the Cosmos. A window opened in the sky which showed us an event which occurred more than one billion years ago, generating 50 times more luminosity (or light power) than all the stars and galaxies combined, as two black holes collided in the depths of outer space, to produce a single, even bigger spinning black hole.

Within a fraction of a second, the collision released nearly six million trillion trillion kilograms of energy, or three times the mass of the Sun. To put this in perspective, the Sun converts only two billionths of a trillionth of its mass into electromagnetic radiation every second, so work out for yourself how long it would take to generate the same amount of energy.

The only evidence of this cataclysmic event, however, was not a giant explosion but mirrors moving such a small distance that you’d need a giant magnifying glass to be able to see it – a millionth of a millionth of a hair’s width, lasting just a few hundred milliseconds. You could blink your eyes and miss it, but that tiny movement was one of the most important milestones in the history of science – the first evidence of a phenomenon first dreamed up in the mind of Albert Einstein 101 years ago, called gravitational waves.

Einstein may have done all his sums right, but even he did not expect the evidence would ever be found. But as Professor Sheila Rowan, Director of the Institute for Gravitational Research (IGR) at Glasgow University pointed out, Einstein would also have been surprised that General Relativity has played such an important role in so many modern devices, including GPS navigators, not even dreamed of in his time.

Even though the first detection of a gravitational wave may have seemed more like a whimper than a bang, it is only dramatic events such as colliding black holes or neutron stars, or massive stars collapsing, that make the mirrors move enough for us to detect any movement at all. Any object which accelerates produces gravitational waves, including human beings, but these are too small to detect. In fact, it isn’t even remotely possible to build a machine that can spin an object fast enough to produce a detectable gravitational wave – even the world’s strongest materials would fly apart at the rotation speeds such a machine would require.
Since we can’t generate detectable gravitational waves on Earth, the only way to study them is to search the distant Universe for evidence of the incredibly massive objects that undergo rapid accelerations – e.g., neutron stars and black holes.

**Theory plus teamwork**

To understand the types of gravitational waves that different objects may produce, LIGO scientists have defined various categories of gravitational wave events, each with a unique “fingerprint” or characteristic vibrational signature, and the first detection was a Compact Binary Inspiral Gravitational Wave, produced by the merger of two massive black holes.

Black holes have come together fairly frequently since time began, but we could not observe a collision or prove it had happened until a group of scientists – from countries all around the world, including Scotland – got together to develop a completely new kind of detector which is capable of “sensing” ripples in the fabric of space-time caused by gravitational waves.

The detectors may have come up with the data, but it was scientists around the world who built the tools: “To make this fantastic milestone possible took a global collaboration of scientists – from laser and suspension technology developed for our UK/German GEO600 detector was used to help make Advanced LIGO the most sophisticated gravitational wave detector ever created,” said Professor Jim Hough, Associate Director of the Institute for Gravitational Research at Glasgow University.

LIGO uses the physical properties of light and of space itself to detect gravitational waves – a concept first proposed in the early 1960s. Each detector has two “arms”, each 4km long, positioned at right angles to each other. In the L-shaped interferometer, the laser light is split into two beams that travel back and forth down the arms (four-foot-diameter tubes kept under a near-perfect vacuum). The beams are used to monitor the distance between the mirrors – suspended on pendulums for seismic isolation – at the ends of the arms. When a gravitational wave passes by, stretching and squashing space, it lengthens and shortens the arms, changing the time it takes the laser beams to travel through the arms.

This means that the two beams are no longer “in step” and produces what is called an interference pattern – which is why the detectors are known as “interferometers”.

According to Einstein’s theory, the distance between the mirrors will change by a tiny amount when a gravitational wave passes by the detector, which can register a change in the lengths of the arms smaller than one-tenth-thousandth the diameter of a proton (10^{-19} m). And one of the great challenges is to isolate real astronomical signals from sources of noise that could mimic – or simply drown out – the signal.

Advanced LIGO is a major upgrade that has increased the sensitivity of the instruments, increasing laser power, reducing noise and enabling them to probe a larger volume of the Universe.

**Mirror, mirror**

LIGO (the Laser Interferometer Gravitational-wave Observatory) is the world’s largest gravitational-wave observatory and one of the world’s most sophisticated physics experiments. The detectors have also been described as “the most sensitive scientific instruments ever constructed.”

There are two LIGO detectors, both located in the USA, thousands of kilometres apart, funded by the National Science Foundation (NSF), designed and run by Caltech (the California Institute of Technology) and MIT (the Massachusetts Institute of Technology). The LIGO Scientific Collaboration (LSC) is a group of more than 1,000 scientists from more than 90 universities and research institutes in 15 countries, including the GEO Collaboration (which involves Germany, the UK and Spain), and the Australian Consortium for Interferometric Gravitational Astronomy.

The LSC also works closely with the French–Italian Virgo Collaboration which, as well as having its own detector (currently being commissioned), uses data from the LIGO detectors.

The LIGO Laboratory is also working closely now with scientists at the Inter-University Centre for Astronomy and Astrophysics, the Raja Ramanna Centre for Advanced Technology and the Institute for Plasma Research, to establish a third Advanced LIGO detector in India, which could be operational early next decade and would greatly improve the ability of the global detector network to identify and locate the sources of gravitational waves. There is a further collaboration with the KAGRA project in Japan, which is building a detector in the Kamioka mine that should be operational within a few years.
Scientists estimate that the black holes detected on September 14, 2015 were about 29 and 36 times, respectively, the mass of the Sun. When they collided, they converted about the equivalent of three times the mass of the Sun into gravitational waves within a fraction of a second – with a peak power output of about 50 times that of the whole visible Universe.
According to general relativity, two black holes orbiting each other lose energy by emitting gravitational waves, causing them to gradually come closer together over billions of years – then much more quickly in the final few minutes. During the final fraction of a second, the two black holes collide at nearly half the speed of light and form a single, bigger black hole, converting a significant proportion of their combined mass into energy – the effect observed by LIGO.

The discovery was not just the end of a project to prove Einstein’s ground-breaking theory, but also marked the beginning of gravitational-wave astronomy as a revolutionary new means to explore the frontiers of our Universe: “This detection is the beginning of a new era. The field of gravitational-wave astronomy is now a reality,” said Gabriela Gonzalez, Professor of Physics and Astronomy at Louisiana State University, who was the LSC spokesperson at the time.

Virgo spokesperson Fulvio Ricci added: “This is a significant milestone for physics but, more importantly, merely the start of many new and exciting astrophysical discoveries to come.”

“With this discovery, we humans are embarking on a marvellous new quest: the quest to explore the warped side of the Universe – objects and phenomena that are made from warped space-time. Colliding black holes and gravitational waves are our first beautiful examples,” said Kip Thorne, Caltech’s Richard P. Feynman Professor of Theoretical Physics.

Human beings first used their eyes to look up at the heavens, then later on invented telescopes and more advanced detectors able to “see” things not visible to the naked eye, including infrared and X-rays, etc. Nothing escapes from inside a black hole, not even gravitational waves, but the evidence provided by LIGO enables us to understand what is happening very close to the black holes, and also confirms that we now have a new way to study the Cosmos and see things far beyond our wildest dreams.
Gravitational Waves

Why does it matter?

Detecting gravitational waves was the climax of five decades of research and the climax of many scientific careers. The discovery was also universally described as one of the great milestones in physics and astronomy, because it verified a major prediction of Albert Einstein’s 1915 General Theory of Relativity and thus advanced our understanding of the Cosmos and how it was formed.

In the process of developing the instruments required to detect gravitational waves, there have also been several practical spin-offs, including new technologies to monitor the distribution of oil underground and even new devices to measure erosion in buildings and defects in eyes – all developed by scientists working in Scotland.

Scientists who ask for funds for fundamental research are questioned long and hard about the benefits of what they do, and often struggle to justify projects, especially if there is no short-term prospect of concrete results. If they emphasise the innovative spin-offs which this important research may produce, and the business that this will create (especially jobs, profits, exports, etc.), they are usually much more successful in getting the funding they need.

But even though they generate business and also improve human life, the spin-offs from the quest for gravitational waves are only one very small part of the story – no matter how much value they add to the project. Perhaps the greatest contribution of the project is that it will lead to the creation of an entirely new field of science. Now that the detectors (the Laser Interferometer Gravitational-wave Observatory, or LIGO) have been proved to work, planning can start to develop the next generation of bigger and better detectors, to see the Universe in ways we could hardly imagine before Einstein’s Theory was published. And who knows what discoveries and spin-offs will come in the future?

“Even though it was not the objective at the start, we should not underestimate the future applications,” says Professor Sheila Rowan, the Director of the Institute for Gravitational Research (IGR) at the University of Glasgow. “We have already seen some unexpected spin-offs. Einstein was not thinking of the economic impact of his theory, but when it comes to relativity, you never know what you’ll discover – including the unknown unknowns.”
Rowan highlights several of the spin-offs emerging from Scotland. For example, Professor Giles Hammond, of the University of Glasgow, has developed very small micro-electro-mechanical systems (MEMS) devices that can be used as ultra-sensitive, portable gravimeters for use in applications such as seismography – the same kind of technology used to detect gravitational waves can be used to detect very small variations in the strength of gravity, and thus may help to predict volcanic eruptions.

Professor Siong Heng of the IGR, the co-Chair of the ‘burst’ working group at LIGO, has been working with Dunfermline-based company Optos to develop new techniques for detecting physical defects in eyes, using similar algorithms to those used for reducing the “noise” which interferes with gravitational waves.

Historic Scotland is using laser interferometers to detect and measure erosion in buildings, and Stuart Reid, Professor of Experimental Physics at the University of the West of Scotland, has applied the same technology used to calibrate the mirror suspensions (key components of the laser interferometers) to “nanokick” stem cells, helping them to grow new bone, blood or muscle. (For more details, please see story on page 44.)

These innovative solutions have emerged thanks to other breakthroughs in technology, while building the detectors. For example, to make the interferometers work more efficiently, you have to isolate the laser beam inside a vacuum, and this has led to advances in vacuum tube technology. Improvements in mechanical and optical bonding may lead to advances in applications such as photonics on, both the ground and in space. The laser beam may cause variations in power which lead to false alarms in the search for real gravitational waves, so the challenge is to make it as stable as possible, and this is what makes possible some new techniques for surgery, using similar lasers. The LIGO detectors have to measure tiny changes in the distance between their mirrors and this has also led to advances in studying the mechanical and optical properties of various materials used to make the highly reflective coatings for the mirrors, and for the mirrors themselves.

“Fundamental research does bring benefits,” says Rowan, “but these are not so obvious or recognised enough. It’s sometimes easy to put science in a box, but we should never forget that it underpins everyday life...”
The human factor

Another major factor in LIGO’s success is the fact that so many scientists from countries all over the world are involved, from graduate students to senior professors – all of whom have dedicated years of their lives to work on something which may never bear any fruit, even though it may be of great fundamental importance.

Mindful of this global dimension, and the fact that the project might have gone on forever without proving Einstein’s great theory, Professor Harry Collins of the University of Cardiff has studied the collaboration since it began, to see what lessons can be learned for future projects on such a massive international scale.

As well as the importance of teamwork and collaboration among different countries, there are fundamental scientific lessons to learn: “The LIGO project is a touchstone of how science works,” says Professor Martin Hendry, Head of the School of Physics and Astronomy at the University of Glasgow and Chair of the LIGO Education and Public Outreach Group. “Many scientists doubted we would ever detect gravitational waves, including Einstein himself. That is why the project is such a good example of the need for verification, because no matter how much you want a theory to be true, you have to verify the data before you can prove it.”

More detections

After waiting 50 years to detect gravitational waves, the second discovery happened just 16 weeks later, on December 26, 2015 – another instance of compact binary coalescence 1.4 billion light years away. Unlike the first detection (where the signal was obvious against the background ‘noise’ of the instruments), it was not immediately clear that there was a gravitational-wave signal embedded in the data – the signal was weaker because it came from smaller black holes, and harder to see because it lasted for a second compared to 0.2 seconds. In January 2017, a third event was detected, about twice as far away as the first two events.
Some media reports suggest that after gravitational waves were detected for the first time (at 9:51 am Greenwich Mean Time on September 14, 2015), it took just three minutes to “see” what had happened, using powerful data analysis tools. But those three minutes stretched to months before the international team of scientists working for LIGO (the Laser Interferometer Gravitational-Wave Observatory) were confident enough to make the public announcement on February 11 the following year.

Three minutes after it happened, in fact, the only thing they knew was that a “candidate event” had been recorded by the instruments. According to the data, gravitational waves had travelled at the speed of light through Space, after two black holes collided and merged, about a billion years ago. The scientists had been waiting for decades for evidence of gravitational waves, but this was just the first step in a rigorous process that would take a thousand people in the LIGO Scientific Collaboration (LSC) several months to confirm, sometimes even doubting they were dealing with genuine data – suspecting that the whole thing was another training exercise designed to test their technical and human resources.

When he first found out about the probable detection, Dr Siong Heng was in China. The news was something Heng had been waiting a long time to hear, but he soon wished he had never even opened the email which gave him the first hint that something important had happened – Heng and his family were on holiday that week. It was hard not to feel the excitement, however, even though it could be yet another false alarm – perhaps another “bump” in the detector. Heng, who is now a Professor in the Institute for Gravitational Research (IGR) based in the University of Glasgow and co-Chair of the ‘burst’ working group, crunching the numbers for LIGO, likes his free time like everyone else, but the email was hard to ignore. When you have a leading role in one of the world’s most advanced scientific experiments, on the brink of discovering something of historic importance, the holiday just has to wait.
The detectors recorded the sequence of events as the black holes were merging.

**Jumping the gun**

“Joseph Weber spent time in the Second World War in a submarine-chaser. If they detected a sub, they dropped a depth charge, and if there was no sub, they still dropped a depth charge – just in case. Weber also missed out on the Nobel Prize for Physics for his work in the development of hydrogen masers. Maybe that explains why he was so keen to announce that he had detected gravitational waves – just in case it was true so he wouldn’t miss getting the credit.”

*Professor Jim Hough*

Heng's colleague Professor Martin Hendry – Head of the School of Physics and Astronomy at the University of Glasgow and the Chair of the Education and Public Outreach Group in LIGO – was also in Beijing for a conference that week, and when they met, the two men exchanged knowing looks, even though they had to contain their excitement in front of other scientists who might spill the beans before the team was ready to make an official announcement. Every individual directly involved in the LSC project had been sworn to secrecy until the results could be verified, and everyone knew that the process could take several months.

The software did its job by identifying what had probably happened, comparing the data with “an extensive bank of theoretically predicted waveforms,” using a process known as “matched filtering” to find the waveform that best matched the data, but no-one could be sure yet if the data did show gravitational waves, or even if the data was what it appeared to be. More checks still had to be made, and no-one could be sure how long the next step would take, or if it would lead to a positive outcome.

Later that day, Heng and Hendry escaped for a beer, and were able to share their excitement in private, but both knew that the waiting game had only begun...
**Blind injections?**

Meanwhile, on the opposite side of the planet, Professor Jim Hough – a veteran “cosmic detective” and the Associate Director of the IGR in Glasgow – and Professor Sheila Rowan, Director of the IGR, were chatting on the phone to a colleague at the University of Cardiff when they heard the first rumours that something momentous had happened. A few days earlier, a burst of gamma rays had been observed by several astronomers and Rowan and Hough were curious to know if that had been detected by LIGO – such phenomena are relatively rare, and among the most energetic and mysterious events in the Universe. Little did they know at first, but something much bigger had happened, and the news was beginning to gather momentum in LSC circles. When the project started, the scientists had thought the first detection would be neutron stars colliding, but this was something even more dramatic, as well as less likely – gravitational waves emitted by the coalescence of two black holes.

“A scientist in Germany emailed to say that he had seen the data,” says Hough, “and even though we didn’t know it straight away, it turned out he had reached the right conclusion.” Rowan and Hough later learned how lucky they had been to detect anything that day. The detectors were supposed to be in “engineering mode,” but fortunately the equipment had been left operating.

Hough, Rowan, Heng and Hendry had been through this nail-biting process before – many times. To tighten procedures and prepare the team for any future public announcement, the project managers had regularly organised what they call “blind injections” – a training exercise like an emergency drill. To stage these dress rehearsals, false data is “injected” into the system to make it seem a candidate event has just occurred, triggering the process of verification. Only a few people know it is only a test run, but the rest of the team must believe it is real so that they behave exactly the same as they would if it had really happened. And the process goes down to the wire – until the academic paper is written to describe the false “discovery” and present the “evidence,” ready to make the official (fictitious) announcement, with everyone convinced the announcement is real.

“A thousand people are involved in the process,” says Heng, “so you need to be sure and communicate clearly before going public.” Heng also says the blind injections make people calmer and “sociologically less likely” to spread any rumours. “It makes us more grounded,” he adds, “and more scientifically rigorous in our approach.” Sometimes, the exercises also lead to technical improvements and statistical refinements, to fine-tune the whole operation, learning from experience.

Hough recalls one blind injection, when he and the rest of the team had been “fooled” till the very last moment. “Data colleagues had almost finished writing the paper,” he says, “when we were invited for a celebration drink. But I knew straight away that it wasn’t the real thing when they used plastic glasses and offered us all sparkling wine – not champagne.”

**Einstein in Glasgow**

Even though he couldn’t have known at the time that the University of Glasgow would play such a key role in proving his General Theory of Relativity just over 80 years later, the great theoretical physicist, Albert Einstein, was awarded an Honorary Degree by Glasgow in 1933 – visiting the very same campus where scientists pioneered some of the systems that detected the first gravitational waves, a hundred years after the ground-breaking Theory was published.

*The Scotsman* newspaper reported Einstein saying: “I was very glad to accept the invitation to say something about the history of my own scientific work. Not that I have an unduly high opinion of the importance of my own endeavours... it would be a mistake, from a sense of false modesty, to pass by an opportunity to put the story on record.”

According to *The Scotsman*, “The cheering which greeted his appearance lasted for several seconds, and was acknowledged by a shy smile from the famous savant.”
The real thing?

In September 2015, however, the team soon began to suspect that this was the real thing. The initial data may have seemed “too good to be true,” but they also knew the new detector (Advanced LIGO) had only been running for a very short time and the set-up wasn’t ready to do blind injections. Perhaps this was no accident – perhaps no dress rehearsal, after all. It was tempting to push for a public announcement, but Heng and Hough had been here in the past, and were more aware than most of the need to be cautious. “When something significant happens, it’s easy to jump to conclusions,” says Heng.

Almost two decades earlier, Heng had learned his lesson the hard way, as a PhD student in Australia, writing his Thesis on data analysis for the detection of gravitational waves, using bar detectors (an earlier version, using solid metal cylinders isolated from outside vibrations). “My supervisor and I detected what we thought were gravitational waves,” Heng explains. “It was my first taste of the kind of excitement you get when you make such a discovery – eight tantalising events which together suggested we’d done it.” But the news was released before the final checks were made which showed that it had been a false alarm.

Hough and his research supervisor, Ron Drever, and other younger colleagues, had a similar experience in 1972, soon after building their first prototype detectors in his lab at the Department of Physics and Astronomy in the University of Glasgow. He and his colleagues had already seen the pioneer in the development of gravitational-wave detectors, the American physicist Joseph Weber, discredited for prematurely claiming success, and this meant they were careful before they even started to conduct their experiments. Using what they thought was an improvement on Weber’s design, another type of bar detector, Hough, Drever and colleagues detected a “beautiful signal,” on two separate systems. But even though it looked as if they had detected gravitational waves, this could not be confirmed – all the other detectors in various countries were not operating that day, so no-one else was in a position to confirm or deny the event. Even today, a detection would not be confirmed unless it was confirmed by another detector hundreds or thousands of miles away, to eliminate local effects.

Hough is still convinced it’s highly likely that they did detect gravitational waves, but in their academic paper they avoided such claims, opting instead to describe what had happened in clinical detail – a good example of the scientific method in action. “Weber missed out on the Nobel Prize in Physics,” says Hough, “for his work on the development of the hydrogen maser, so perhaps he was too anxious to announce his results – several other scientists pointed out discrepancies in Weber’s data analysis which later proved fatal, and some of them even accused him of being economical with the truth.”

Fast forward 45 years...

Forty-five years later, Hough and the rest of the team who were working on LIGO were getting ready for the public announcement. The group had lots of work to do to verify the data and write the paper to back up their claim. And everyone was interviewed to find out exactly what happened that day – for example, to determine if there had been any accidents or human errors.

Heng says he was “75% sure” after three or four weeks, then 95% sure after two or three months. The final 5% was writing up the evidence and discussing the details before publication. Hough says he made up his mind by Christmas and when a second, similar, event occurred on December 26, 2015, most of the team were convinced – the signs were unmistakable.

It had taken five decades to do it, but Hough only felt “great relief” when the great moment finally came. At that time, many members of the project team were getting more and more concerned their funding would not carry on if there wasn’t a significant breakthrough soon. “It was a narrow escape,” says Hough. “But now that we have done it, it has opened up an entirely new field of science.”

“It took just three minutes to flag the event,” Heng explains, “and a few weeks to be sure that the data were right.” And when the news finally broke five months later, in February 2016, it was not just another scientific announcement, but a step towards a new kind of science which will change people’s lives – including all the scientists themselves.

“Now we can find out how galaxies formed, and perhaps also find out more about dark matter,” says Rowan. “It is a whole new way of looking at the Universe, and I hope it will also be a great inspiration to children and parents, enthusing the next generation of scientists in Scotland and beyond.”
Not many people spend more than 40 years searching for something that may not exist or may never be found. Albert Einstein had predicted gravitational waves in an addendum (1916) to his General Theory of Relativity (published in 1915), but he doubted we would ever detect them – and even doubted if they existed at all. But in the greater scale of things, a few more decades for a physicist such as Jim Hough in Glasgow are only the blink of an eye, like the first gravitational waves detected by scientists two years ago.

You might expect the Earth to shake, but what started out as a giant explosion arrived not as a bang but as a whimper – changing the distance between two pairs of mirrors “by an infinitesimally small amount” when it hit the detectors, and lasting a few hundred milliseconds before it was gone, a billion years after the waves first set out on their journey.

For Professor Hough, Associate Director of the Institute for Gravitational Research (IGR) and currently Research Professor in Natural Philosophy at the University of Glasgow, that historic moment was in many ways the climax of his scientific career, but for some people also a slight disappointment. In 2004, Hough agreed to place a bet at odds of 500/1 that gravitational waves would be detected before 2010. The odds were later cut to 25/1 when Hough learned how to place his bet, and then were further cut to 6/1 when other punters followed the physicist’s lead; but that was academic by the time of the discovery – five years too late for the pay-out.

Now officially retired, but with a research position at the University, Hough is still as keen as ever to be part of the adventure, and has watched the search for gravitational waves grow from a team of just a few people at the start to over a thousand today. But even though he was a pioneer in the field and things were very different 46 years ago when he was a young research fellow, he got involved in the same way as many others – partly by accident, partly by choice.

For Hough, the story started 46 years ago, and like so many other scientists, serendipity guided events. When he was finishing his PhD in nuclear instrumentation, “the gloss was coming off the nuclear industry,” and he was looking for something more exciting to work on. Several events had taken place which had a huge impact on Hough and many other physicists – including the discovery of pulsars in 1967 by Jocelyn Bell and Antony Hewish at Cambridge. As the Cold War got colder, there was also an increasing need to study gamma ray bursts (some of the most energetic and mysterious events in the Universe), which may or may not have been caused by Soviet testing of nuclear bombs – and all of this required the development of much more sensitive detectors of different types to keep a closer eye on Outer Space.

Hough and Ronald Drever, his research supervisor, also knew about the work of Joseph Weber and his controversial search for gravitational waves, using the first bar detectors – solid metal cylinders which Weber believed were sensitive enough to pick up the vibrations from faraway cosmic events. Even though Weber was “shabbily treated” by some of his colleagues, because of flaws in how he analysed the data, Drever and Hough, and many others, shared his interest in the quest for gravitational waves, and tried to develop new, better detectors and, at the same time, make sure they were getting their sums right.
Using new technology, including very sensitive piezoelectric transducers and ultra-low-noise Field Effect Transistor amplifiers, Drever and Hough designed and built two new detectors which they believed were capable of tuning over a much wider bandwidth. The Glasgow team also kept in close contact with colleagues in the Universities of Bristol and Reading, who were thinking along similar lines. And they also collaborated with groups in Germany and Italy and a number of groups in the USA, who all made “immense contributions,” says Hough, to advancing the science.

“In the early days, the search for gravitational waves was driven by an element of competition between scientists,” Hough told Science Scotland in 2004. But even then, the emphasis was on collaboration, mainly because of the scale of the projects.

There have been several false alarms over the decades. In 1972, Drever, Hough and colleagues detected “a very clear signal” which they were convinced was a gravitational wave. The first signs were characteristic blips on the charts used to record any signals; but to add to the tension, the scientists in Glasgow had to wait for a couple of days – first, they had to develop the film in the camera used to photograph the oscilloscope, then print out the negatives, before they could see the results. While this was going on, the Glasgow team discovered that all the detectors in other locations were not operating at the time of the reported “detection,” thus making it impossible to tell for sure if what they had observed was a local effect or evidence of something more significant. The team of five, including Hough, was confident that they had eliminated most of the “noise” which may have interfered with the beautiful signal, including thermostats, but they knew the source could still be something else. “We were not surprised,” Hough explains, “just excited – we knew we had a better chance than Weber, and also knew the weaknesses in his data analysis.”

No matter what they had detected, the Glasgow team knew that something amazing had happened. “We were lucky – we had probably observed a supernova,” says Hough, “an event which at the time was expected to happen once every 30 years, and was long overdue.” Hough and his team also asked other scientists, keeping a look-out on the upper atmosphere, if they’d seen something unusual. But despite their initial excitement, they could not prove they had seen gravitational waves...

In the end, the Glasgow team published a paper in Nature describing what they had observed, but because they could not prove the signal was a gravitational wave, they were careful not to make any extravagant claims. “We saw exciting shapes in the photo,” says Hough. “On one detector, we could see an increase in the amplitude, and on the other, a phase change. It was a very rare event, but what you would expect to see if this was in fact a gravitational wave.”

In 1972, he thought they had done it and had been disappointed, but Hough knew he “had to keep going,” and was confident they would detect gravitational waves – one day. It was only a matter of time...

The search continues...

Other scientists were doing a range of experiments which fell by the wayside, but research and development gathered momentum, including the idea of using liquid helium, and SQUID amplifiers (superconducting quantum interference devices) – very sensitive magnetometers used to measure extremely subtle magnetic fields.
The technology took a leap forward when lasers came into the picture. The American physicist and science fiction writer, Bob Forward, then working for the Hughes Aircraft Company in California, had built a small detector using a laser interferometer. Forward owned a small castle in Scotland and, during one of his visits, met the Glasgow team, encouraging them to keep working on their ideas for laser interferometry, particularly on a system with 10-metre arms (the distance between the mirrors), which started in 1979. According to Hough, it was a “technically satisfying” system, but would never have had the sensitivity to detect gravitational waves although it did mark a significant change in direction and was one of the forerunners of today’s much more powerful systems. Despite these exciting advances, this period was “very frustrating” for Hough as he struggled for funding, and the initiative was taken up by Caltech (the California Institute of Technology), where Ron Drever, who had been recruited from the University of Glasgow, built a bigger version of the laser interferometer, with 40-metre arms. Then, in 1986, US researchers started working on the first proposal for LIGO, eventually designing a facility with arms 4km long.

Apart from the huge jump in scale, other aspects of the new design needed improvement. “It became clear that we needed a significant improvement in the sensitivity of the detector,” says Hough, “including better suspension systems and better optical coatings for the mirrors.”

Meanwhile, in Germany, researchers had been going down a similar route, and were thinking of building much bigger detectors, and Hough then got involved in a proposal to construct a large facility in Scotland, with two sites identified – one in Tentsmuir Forest near St Andrews and the other at Buchlyvie near Stirling, using a disused railway junction which had tracks long enough (and straight enough) to have two arms 1km long at close to 90 degrees to each other. “We got planning permission at Tentsmuir,” says Hough, “and I got the impression the local residents thought this was a military project.” The design was never built, however, and UK scientists began to work with colleagues in Germany, making a major contribution to the design of the GEO600 detector in Hanover, Germany. “It was a clever design,” Hough explains, “and the first time we used silica fibres for suspending the mirrors.” It was also a design which formed the basis for the Advanced LIGO detectors, an upgrade which began in 2010 and started operating five years later.

There was another false alarm in 2010 when LIGO (the Laser Interferometer Gravitational-wave Observatory) appeared to detect a very clear signal. The scientists were looking for the merger of two neutron stars or black holes – what’s called “a coalescing binary” – but even though something had triggered the system, it was not what everyone hoped for. “In fact,” says Hough, “it turned out to be a ‘blind’ test injection of signals – deliberately added to test the efficacy of our hardware and signal processing.”

Then finally, in 2015, Hough’s patience was rewarded. Gravitational waves were detected by LIGO. The long wait was over, a theory was proved and a new field of science was born.
For Galileo, it was easy – build a telescope and point it at the sky. You could see the stars and planets with your naked eye and the telescope just made them bigger and let you see much more detail. With gravitational waves, it is different. There is nothing to see, apart from the fleeting effect of them moving two mirrors – apart or together – by an “infinitesimal” distance, inside the most sensitive scientific instrument ever developed. When the project started, the scientists who used the detector did not even know if the thing they were hunting existed – they thought it did, but could not be completely sure until something happened in September 2015 which finally proved it.

For Professor Siong Heng of the Institute for Gravitational Research (IGR), the challenge appears even greater – and more esoteric. He and his colleagues are not gazing up at the sky with a telescope or infrared scanner. They are not looking for an almost imperceptible movement as a ripple in space-time goes by. They are not watching for the signs of an explosion which happened more than one billion years ago far off in space. They are wading through the data generated by LIGO (the Laser Interferometer Gravitational-wave Observatory) to identify the sources of whatever is causing the mirrors to move – looking for a big bang in the midst of big data.

If the detector is the hardware, then Heng and the data analysis group are the software. And as computer power accelerates year after year, and new techniques such as machine learning make data processing quicker and smarter, they play an even more important role in the project – the go-to guys as soon as something happens; which may or may not be gravitational waves. The detector often registers something significant, but the scientists have to be careful not to jump to conclusions. And that is the job of the data analysis group – calming everyone down and then very carefully proving what happened, using the power of maths and statistics.

In addition, says Heng, by creating mathematical models which help to interpret the signals and identify the signatures of different sources of noise (not just from Outer Space but also local noise, including from the detector itself), the data team also help fine-tune the settings and help design future upgrades. There are “multiple ways to analyse the data,” says Heng, and it’s his job to learn from experience so he can do his job better, saving time and making the process much smarter.
Originally from Singapore via Australia, Heng focuses on what is known as “generic transient analysis.” In simple terms, this means identifying statistically-significant correlated signals across multiple gravitational-wave detectors, such as the collision between two black holes – the kind of event which generated the gravitational wave (codenamed GW150914) detected in September 2015 by the LIGO detector – and interpreting the astrophysics behind observed signals. “You see some wiggles in the data from multiple detectors, then check to see if this is consistent with the properties of the detector noise,” says Heng.

As well as being very clever science, however, you could say that it also needs some “educated guesswork” to cut a few corners and process the data as precisely as possible.

For example, when GW150914 arrived, it did not behave 100 per cent as expected. The researchers thought the first detections would be a very small signal buried in a lot of interference or noise, but GW150914 was actually a very loud signal – more a big bang than a whimper. Within three minutes, the data analysis group were already confident the signal was a gravitational wave, but that was just the start of a laborious process to prove it. (Please see story on Page 11.)

What first identified the signal was something called “generic transient analysis.” If both sets of data from the two detectors (one in Louisiana and the other thousands of miles away in Washington) are correlated at a given time, then the scientists know that they have a good candidate for gravitational waves – not proof but probability. “Matched filtering” techniques then compared the data to a range of predicted waveforms, to provide evidence that the signal originated from the coalescence and merger of two black holes.

**Biography**

**Professor Siong Heng** of the Institute for Gravitational Research (IGR) is the chair of the data analysis working group that identified GW150914 as a candidate event – within just a few minutes of the gravitational waves reaching the Earth. Heng works principally on “burst detection and astrophysics,” seeking to identify sources while making minimal assumptions about the precise mathematical form of their waveform, so we are in a position to detect the unexpected and not just sources we’re already confident exist. Heng’s interests also extend into developing powerful algorithms – using methods such as machine learning – to perform automated image processing and characterisation in diverse fields beyond astrophysics.
On the surface, the methods developed by Heng and his team appear bomb-proof, but “nature has its ways of surprising us,” and sometimes data analysts may be surprised by deviations from established theory. The predictions may be way off and the data (or sound) can be very different from what is expected. “The data analysis may be correct,” says Heng, “but the instruments may not be doing their job right.” In addition, it takes time to build up a store of real data to help develop better processing methods and fine-tune the system – no data, no tuning. “The data analysis evolves at the same rate as the detector,” says Heng. “They are interdependent.”

Heng also stresses that it’s not a simple case of building models and comparing the data from signals received, then doing a few sums to come up with answers. “We look for correlative excess,” says Heng. In other words, rather than simply filtering data, the challenge is to find the unexpected in the midst of all the data, by using special algorithms to flag up anomalies, rather than examine every single piece of data all the time. Similar methods are now being used in other applications such as medical imaging, including ophthalmology (please see sidebar), as well as food and drink, security and defence.

“In the search for gravitational waves, data analysis is not just a method to check things but also a discovery engine,” says Heng. And the methods used to find gravitational waves in the depths of the Cosmos may also help to show us what is staring us straight in the eye – and even what is hidden deep inside our eyes.

The methods used to find gravitational waves in the depths of the Cosmos may also help to show us what is staring us straight in the eye – and even what is hidden deep inside our eyes.

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From outer space to inner space

An innovative project which involves collaboration between leading medical technology company Optos and the University of Glasgow’s Institute for Gravitational Research (IGR) promises to help in the detection of retinal defects – using the same kind of Bayesian data analysis methods employed in the search for gravitational waves.

Optos specialises in developing devices which produce high-resolution images of the retina, to provide the information needed for early detection of a wide range of disorders such as retinal detachments and tears, glaucoma, diabetic retinopathy and age-related macular degeneration. The aim is to develop new solutions to automate testing procedures – leading to significant cost savings by improving quality assurance (QA) in the manufacturing process.

Professor Siong Heng

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Scotland has a great science base here at home,” says Professor Sheila Rowan, the Director of the Institute for Gravitational Research (IGR) at the University of Glasgow. “but to stay at the forefront we have to make sure we look outwards.”

And you can’t look much more outwards than towards two black holes colliding in a galaxy a billion light years away... Rowan, who is also the Chief Scientific Adviser to the Scottish Government, played a key role in the first detection of gravitational waves, helping to develop key components used in the detectors, working with her colleagues in Glasgow and elsewhere in the UK, as well as the US and several other countries all around the world. And she sees the LIGO (Laser Interferometer Gravitational-wave Observatory) project as an excellent example of the kind of teamwork required to make such incredible breakthroughs.

“When it comes to big questions like gravitational waves, no country can answer them all on its own,” says Rowan, “and that is why it’s so important to attract talent and exchange ideas with scientists in other countries. Science today is an increasingly international and collaborative activity, operating in a borderless environment.”

In her role as Chief Scientific Adviser, Rowan has to keep in touch with many different scientific disciplines, and for her, public outreach has always been part of the job – in LIGO as well as in her government role. Nowadays, she also has to focus on science for policy (where science can inform government policy in areas such as the environment and energy) and policy for science (how government stewards research), as well as science for society, explaining why it matters to the general public, or as Rowan puts it, “articulating the relevance.”

One of her main roles is to head the drive to make the country more “science literate” in general, and inspire young people to become scientists. "When you make the front page of the papers with a story like that (the first detection of gravitational waves), it helps get the message across," she explains. “It is also a model example of the excellence and leadership of scientists in Scotland, and the part they’re playing in the quest to understand the Universe.”

Rowan herself has been part of that quest, and has a favourite quote about the nature of discovery and scientific progress: “The reasonable man adapts himself to the world; the unreasonable one persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable man,” wrote George Bernard Shaw in Man and Superman, published just a few years before Albert Einstein’s General Theory of Relativity. “And what we’ve done at LIGO could also be described as an ‘unreasonable’ measurement,” Rowan continues, “because it was such a great challenge, pushing hard to improve the precision of the instruments, and reduce the noise from other sources.”

The scientists in Glasgow have made important contributions to the technologies used in the LIGO detectors. For example, Rowan and her team developed the ultra-low noise suspensions of Advanced LIGO, “without which the detections could not have been made,” says Rowan’s colleague, Professor Martin Hendry – Head of the School of Physics and Astronomy at the University of Glasgow and the co-Chair of the Education and Public Outreach Group in LIGO.
The project has already led to several spin-offs, says Rowan, including new technologies developed in Glasgow, but Scotland’s contribution to LIGO has not just been around designing and developing the instruments themselves, but also the techniques used to analyse the data from the instruments, as well as “worrying about the astrophysics.”

The success of the project will also help to create an “entirely new field of astrophysics,” Rowan continues. Scientists have already developed telescopes to detect various kinds of electromagnetic radiation – the beautiful optical images we see from telescopes or images created from infrared or ultra-violet light – but detecting gravitational waves is not an imaging technique per se, she explains, but more like “feeling the vibrations of space-time” as the distances between mirrors inside the detectors are stretched and squashed. Using an optical telescope, there might be “nothing to see” when you point it at some sources of gravitational waves, but LIGO is a different way of “sensing” or detecting the waves, and getting rich information about them.

“We thought that we would first detect gravitational waves from colliding neutron stars,” says Rowan, “but it happened to be two colliding black holes, and that was a big surprise.”

Also unexpected was the size of the two black holes (29 times and 36 times the mass of the Sun) and the result of their merger – 62 times the mass of the Sun. “This kind of new observation should let us probe currently unanswered questions in astrophysics, including what the properties of the original stars were, from which such massive black holes were born,” says Rowan.

When the black holes collided and merged, they released a huge amount of energy – the equivalent of three times the energy stored in the Sun – in a fraction of a second. On Earth, this may have been a tiny movement, 1.3 billion years later, but it will have enormous implications for the future of science for decades to come.

For Rowan, the discovery came after three decades of specialist research. At school, she found it hard to choose between journalism and science, as a future career, “but science won,” she says, “because it asked the biggest, most interesting questions like where did we come from and where are we going.” She first came across gravitational waves as an undergraduate in Glasgow, doing a summer project on laser interferometry, using the basics of the same techniques as LIGO but in a desktop model; and 30 years later, her passion remains. Her early work involved the development of lasers for gravitational-wave detectors, and more recently her research has been focused on studying the properties of materials used for the mirrors used in the gravitational-wave detectors.

Rowan likes to feel part of “a bigger endeavour,” using state-of-the-art tools to understand the Universe, and working with a team of more than 1,000 people in the LIGO Scientific Collaboration (LSC), a network based in 15 countries all over the globe, involving senior researchers and professors in more than 90 universities and research institutes, plus about 250 contributing students.

Her work on the mirror suspensions is something that Rowan will always be proud of, helping to develop “super-low-noise” solutions for the GEO600 detector in Germany and upgraded versions of these for the more advanced systems in LIGO. But no matter how important these technical advances are, for Rowan there is always another more human dimension.

The challenge in future, she says, will be making sure scientists still have the freedom to work in a borderless world towards common objectives – not just to make important breakthroughs such as detecting gravitational waves and developing exciting new technologies, but also to inspire the next generation of scientists and engineers, and turn on the general public to the wonders of science.
Gravitational Waves

Lateral thinking vs uncertainty

Just when you think you are getting the hang of it – the search for gravitational waves – the science is turned upside down. The most important factor, you learn, is to measure the distances between pairs of very highly polished mirrors, and if the distances change, you’ve detected a force that may turn out to be gravitational waves. To measure the distances, you also have to be able to fix the positions of the mirrors and eliminate the many other sources of “noise” which may cause the mirrors to move.

Professor Ken Strain has spent over 30 years trying to improve the technology used in the detectors, making sure the mirror suspensions are held in position, and now that the technology has finally delivered – by detecting gravitational waves – the next generation could be designed to “ignore” the position and focus on speed or momentum, thus making it much easier to see what lies beyond.

The fundamental physics may be hard to understand, but Strain and most of the other researchers who have worked on the project over the years could be described as “general-purpose scientists,” because they have to do a bit of everything: not just understanding the theories involved, but also designing and building the mechanical and electronic components which enable the detector to function – including the mirror suspensions.

Strain’s first experience was working with the prototypes built in the mid-1980s, with arms only ten metres long, compared to several kilometres in the LIGO (Laser Interferometer Gravitational-wave Observatory) detectors, thousands of miles apart in the US. But despite their modest proportions, the early detectors were “the most sensitive detection instruments in the world at the time,” Strain explains. They were also the progenitors of today’s much more powerful systems, with scientists in the UK and Germany leading the way, pioneering the technology which led in a straight line to LIGO, as well as helping out with other similar projects in Italy and Japan.

“In the early days,” says Strain, “there was a huge exchange of ideas, but only about two dozen experimentalists worldwide involved in the project, including PhDs.”
The Glasgow connection

The main contribution of the Glasgow researchers, says Strain, was the mirror suspensions and the development of the “beautiful silica fibres” which hold them and minimise unwanted noise. Scientists working in Scotland have also helped develop the laser technology used in the latest detectors, improving their stability “by more than a million times.” They have also made a huge contribution to the data analysis which makes sense of the signals and also improves the sensitivity of the detectors by helping them focus on their primary target – the enigmatic and elusive gravitational waves.

Strain explains that one of the critical aspects of the LIGO detectors is the use of hydroxide catalysis bonding, which connects the mirror suspensions to their suspension fibres. Each mirror is at the bottom of a chain of four cascaded pendulum stages to isolate it well from ground vibrations. The technique used for bonding was originally developed by a team at Stanford University to make spacecraft more stable, and involves a chemical reaction between the mirror and an “ear” at the end of the silica fibre, so the materials are “perfectly” joined – as if they are one single object.

The mirrors may all have to hang very still, but the technology never stays static for long. Research into the next generation of detectors has been going on for eight years already, says Strain, since before Advanced LIGO was built and began operations. And this will mean further improvements all round, including possibly scaling up the mirrors from 40kg to as much as 160kg.

Pioneering research

Strain first got involved with gravitational waves in the mid 1980s as a student in a summer project, helping to develop electronics and control systems that improved – by a factor of three – the sensitivity of the ten-metre detector in Glasgow. At that time, he says, almost every part of the equipment used had to be custom made and, because they were using non-standard components to build something never attempted before, they faced enormous challenges in every direction. “If we had used off-the-shelf components,” says Strain, “the detector would never have worked.”

Another breakthrough which enabled the detector to work was a revolutionary technique developed by the late Dr Brian Meers in Glasgow called “signal recycling” – “a method of optimising the response of gravitational-wave detectors to the expected astrophysical signals.”

In 1991, Strain and Meers published a paper describing the first experimental demonstration of “an optical system which should improve considerably the performance of proposed laser-interferometric gravitational-wave detectors,” including an enhancement of the signal-to-noise ratio by a factor of seven.
Sadly, Meers was killed in a climbing accident the following year, but the concept of signal recycling lived on in the Hanover-based GEO600 detector and later in Advanced LIGO, helping to fine-tune the system. Strain explains that signal recycling was a way of boosting or recycling the light beams and changing the resonance, to make the system better at detecting target signals in the midst of the “constructive and destructive interference.”

According to Strain, signal recycling works with other optical techniques at the heart of the detector, and with modern ultra-low-loss mirrors, losing only 50 parts per million of the light from the lasers as the light is bounced from mirror to mirror, and together these form the most sensitive probes to measure “modulation of the refractive index of space due to gravitational waves.” Signal recycling enables you to tune the detector to follow waves of a particular frequency, much as an AM radio can be tuned to a particular channel.

Uncertainty rules

“The chief appeal of working in gravitational-wave research was that it offered just the right amount of uncertainty,” Strain explains. Apart from the challenging science itself, funding is always a headache, and there have always been sceptics who said they would never succeed, but Strain and his colleagues have always believed they could do it, and hope the support will continue. “If the funding stops in this country, that would be our loss – other countries will do it,” he says.

According to Strain, the laser interferometer in Advanced LIGO is so sensitive that it operates close to the limits of the Heisenberg Uncertainty Principle, which states you cannot measure the position and the momentum of an object with unlimited accuracy at the same time – for example, if you shine a light on an object to see it, the object will move, thus making it impossible to know its position exactly. Each of the mirrors inside the detector weighs 40kg, but the photons in the detectors can move them. But the battle to get rid of unwanted noise will continue to make further progress, adds Strain, in the quest to build a new kind of detector in which the Heisenberg Principle does not apply – more sensitive and more efficient.

The future generation of detectors may not even measure position, says Strain. They will most likely focus on measuring speed or momentum. “This will help researchers to look deeper into the data they need to identify signals, rather than fighting against noise to extract subtle details of the signals. To do this, we will need a new configuration of optics,” says Strain.

Time is no object

Thirty years ago, when Strain joined the small band of pioneers trying to find gravitational waves, he didn’t know how long the search would take – and didn’t care. “This was the big challenge in physics,” he explains, “and I thought I could make a contribution.”

The project is an “unusual blend of people and an unusual mix of theory and practical work,” Strain concludes. “To succeed, we needed general-purpose scientists.”

When Advanced LIGO was switched on two years ago, most of the researchers expected it would be at least a couple of years before any success, as they gradually boosted the power. When the breakthrough was made in September that year, it was not only unexpected, but a deserved reward for all those “general-purpose scientists” who made a contribution through the years, including Ken Strain and his colleague, the late Brian Meers.
One day, he is fixing radiators at home. The next day, he is trying to reduce the thermal noise in “the most sensitive scientific instrument ever constructed,” thousands of miles away in the US. When he gets to work at the University of Glasgow, Professor Giles Hammond is not just any other astrophysicist, but a DIY enthusiast, happy to repair the central heating and build garden walls, or “tinker” with some of the most critical components in the Advanced LIGO (Laser Interferometer Gravitational-wave Observatory) detectors.

Even though “do-it-yourself” skills have played a key role in the history of the detectors, the Advanced LIGO project draws on the resources of an international team of over 1,000 leading researchers. The ultimate goal is a big one – the quest to detect gravitational waves – but Hammond has to focus on the tiniest details, at the same time as keeping his eye on the stars.

“We are developing a new field of astronomy,” Hammond explains. “Our eyes can see the stars and we’ve developed ways of seeing electromagnetic radiation (including optical, infrared, gamma ray, etc.), but laser interferometry is a whole new way of looking at the Universe – for example, understanding how a massive star becomes a black hole in the first place.” Einstein’s General Theory of Relativity is a very sophisticated theory, but all the smartest theories in the Universe need evidence to prove they are correct. Gravitational waves are one of the last unproven predictions of the theory, so if the detectors themselves don’t work, or aren’t sensitive enough to detect gravitational waves in the first place, you simply measure noise and not the signals.

To help the group of scientists at LIGO “see through space and time,” Hammond specialises in designing and installing a critical piece of equipment inside the detector – the mirror suspensions. In simple terms, as light reflects from mirror to mirror, inside the detector, the instruments measure the distance between the two mirrors, and if a gravitational wave hits the Earth, it moves the mirrors slightly, thus changing the distance between them. The problem, however, is that thousands of other events also have an effect on the mirrors – for example, an earthquake, a train or even just somebody dropping a spanner. The instruments themselves can create lots of noise, and the challenge is to recognise the signature of different types of noise (including the “jiggling” motion of the atoms that make up the mirrors) so they can be taken out of the equation, using clever mathematics and smart engineering.
The innovative solution was to hang the mirrors using fused silica glass fibres, instead of metal wire, and to suspend four mirrors in a quadruple pendulum – like a vertical necklace – to further dampen the vibrations. One of the biggest contributions of the Glasgow team is the silica fibres themselves, which are made in a special machine in the lab using a process very similar to teasing out wool. First used in the “monolithic stages” of the GEO600 detector in Germany, then later in Advanced LIGO, silica is used for a number of reasons, including the fact that it has a high melting point – 2,000 degrees Centigrade – which means it is one of the most stable forms of glass. Even though the fibres are extremely thin – 400 microns in diameter – they also have to be strong enough to hold up the mirrors, which each weigh 40kg. Part of the new design features new jointing techniques, getting the mirrors to bond to the fibres as if they are a single component, to minimise thermal noise. To illustrate the special properties of the silica fibres, Hammond also explains that thermal vibrations “pluck” the fibres, and it takes several days for the motion to “decay,” unlike the vibration on guitar strings which only lasts one or two seconds.

“We are pushing the limits of technology,” says Hammond. And the net result of meeting this “experimental challenge”, at frequencies around 30Hz, is an improvement of roughly 100 times compared to previous wire-based suspensions in the first LIGO, making it possible to eliminate almost every source of noise they can identify. Even the Earth tides, elastic deformations of the Earth due to the Moon and Sun, which stretch and shrink the Earth by around 400 millionths of a metre along the arms of Advanced LIGO, can be countered by moving the suspensions and seismic isolation systems inside the vacuum chambers. Hammond also stresses that the quest to eliminate noise will continue in future detectors, but says it’s reassuring that they have already had a significant breakthrough with the upgraded version of LIGO, proving that the basic technology works.

According to Professor Martin Hendry, Head of the School of Physics and Astronomy at the University of Glasgow and the Chair of the Education and Public Outreach Group in LIGO, Hammond has made “significant contributions to the development of the monolithic stages of the Advanced LIGO quadruple pendulums, and also pioneered the development of the fused silica suspension for the prototype interferometer in Hanover, as well as new techniques to provide continued fused silica suspension support for future upgrades.”

“

We are pushing the limits of technology

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Biography

Professor Giles Hammond is a Fellow of the Institute of Physics and an alumnus of the RSE Young Academy of Scotland. Together with his colleague, Dr Angus Bell, he led the implementation on site of the silica fibre suspension elements essential to the low-noise operation of the Advanced LIGO detectors. He has also led the application of gravitational-wave technology in other fields – in particular the development of small micro-electro-mechanical system (MEMS) devices that can be used as ultra-sensitive, portable gravimeters suitable for use in applications such as gravity imaging and seismology.
As well as pioneering new technologies, Hammond also helps install the mirror suspensions in the detectors, after several rehearsals in Glasgow. “You can't just turn up with a bunch of components then bolt them together and hope for the best,” says Hammond. “We have to make sure that we get it right every time, first time.” No matter how much they may practice, however, something can always go wrong – for example, minor accidents such as dropping a bolt on the suspensions during installation. “But these are complicated machines,” explains Hammond, “so this is just part of the learning process, and recovering from such incidents is important for developing robust engineering protocols.”

As soon as one problem is solved, Hammond and his colleagues are thinking ahead to the next technological challenge – keeping one eye on the future of the science as a whole. The Advanced LIGO detector has delivered a startling result by being the first to detect gravitational waves, but this is just a step along the way. For example, there are plans to build a new machine called the Cosmic Explorer, with 30-40km arms, compared with LIGO’s current 4km arms, to amplify the signal and improve detection. In Europe, the proposal is to build the Einstein Telescope, several hundred metres underground; while in Japan, the KAGRA detector will operate at around 20 degrees above absolute zero (-253° Centigrade), to eliminate one of the most significant sources of noise – thermal fluctuations. The LIGO infrastructure is 20 years old now, and even though it managed to accommodate the upgrade which led to the breakthrough in September 2015, it needs constant care and attention – an issue in the minds of those designing the next generation of super detectors.

**Spin-offs**

Hammond’s research also includes the development of new techniques to “characterise the mechanical stress in fused silica suspension elements, grow silicon/sapphire crystalline fibres and analyse the performance gains for suspension upgrades to Advanced LIGO and future third-generation detectors.” He has also been closely involved in the development of low-cost, ultra-sensitive gravimeters, which utilise “soft springs” to provide the lowest resonant frequency MEMS (micro-electromechanical system) devices in the world, capable of measuring tiny fluctuations in gravity – for example, to monitor volcanic activity or search for hydrocarbons.
Just one of the spin-offs from gravitational-wave research, these tiny devices, called “Wee-g,” are just a few centimetres across (small enough to be mounted on drones) and will cost only a few hundred pounds, compared to about £80,000 for conventional systems. The new designs are based on MEMS technology, using a sophisticated version of the accelerometers in smartphones which tell up from down, to compensate for tidal fluctuations – i.e., the surface of the Earth goes up and down twice a day by about 40cm because of the pull of the Moon, and this affects the accuracy of subterranean measurements.

Developed in Glasgow by QuantIC, a “quantum technology hub,” which brings together 120 researchers and industry partners, Wee-g “opens up the possibility of making gravity measurement a much more realistic proposition for all kinds of industries,” says Hammond’s colleague, Dr Richard Middlemiss. As well as being used for undersea exploration, the gravimeters will be used in nanosatellites, so they know exactly where they are whilst in orbit – a solution now being developed for Glasgow-based CubeSat developer Clyde Space. Schlumberger is another potential customer, using the gravimeters for oil exploration; while QinetiQ is interested in using the devices in defence aerospace and security systems.

Innovative architecture

Hammond first developed his interest in gravitational waves while doing his PhD at the University of Birmingham, before moving to Colorado, focusing on seismic isolation solutions. He then returned to Birmingham and later moved to Glasgow to develop the mirror suspensions. During this time, he has also been a member of the “thermal noise materials group,” focusing on thermal dynamics and the internal friction caused by thermal noise, which can interfere with the signals. Once you think you’ve got rid of the thermal noise, says Hammond, another problem is discovered – for example, thermal-elastic noise – and a further refinement is needed. That is what makes Hammond’s work so challenging and motivates him and his colleagues.

When he was at school, Hammond wanted to become an architect, but good results in maths, physics and chemistry, combined with an early interest in astronomy, persuaded him to go in a different direction, and now he is the “architect” of very smart components which enable us to look through a new kind of window – and see the Universe as never before. His DIY experience has also been useful, teaching him how he should learn from mistakes – as well as push the boundaries. “Sometimes it’s very frustrating,” he says. But when the boundaries are billions of lights years away, it’s probably worth all the hassle.

“now he is the “architect” of very smart components which enable us to look through a new kind of window – and see the Universe as never before”
Gravitational Waves

At High School in the Netherlands, Marielle van Veggel just “wanted to do something interesting” in her career, maybe something connected with Space. But even though being involved in “one of the most important-ever breakthroughs in astronomy” may look like mission accomplished, she’s now more interested in what will happen next. One of the biggest and most complex scientific experiments in history has finally managed to detect gravitational waves and observe a collision between two black holes – but what lies beyond the horizon? If the research team can develop much more sensitive detectors, what will they tell us in future?

For van Veggel, working on Advanced LIGO (the Laser Interferometer Gravitational-wave Observatory) has already delivered the result the researchers were hoping to find, and future detectors will be much more powerful systems, but she and other scientists have seen that some of their technologies can also be applied to other projects, including launching a gravitational-wave observatory into Space. This ambitious project, called LISA, is a major development sponsored by the European Space Agency with strong contributions from many countries, including scientists from the IGR and other research establishments in the UK (for more details, please see sidebar).

Before she was recruited by the University of Glasgow ten years ago, van Veggel worked on a project called GAIA (please see sidebar). A graduate of the University of Eindhoven in the Netherlands, her experience in this ground-breaking project not only introduced her to the level of teamwork required for such experiments, but also involved interaction with private contractors, using the latest materials science to make the design for the spacecraft more lightweight and stable. Encouraged to accept a position in Glasgow by Professor Jim Hough, who had been one of the external examiners for her PhD Thesis, she “exported” her specialist knowledge to Scotland, helping to develop the silica mirror suspensions, and also developing a new kind of bonding technology which helps to cut noise and vibrations by simplifying how the different parts are connected.

As a member of the Glasgow research team, van Veggel loves to push on every front to develop the technology used in the mirror suspensions, working side by side with data analysts as well as other materials scientists, mechanical engineers and physicists to reduce noise to a minimum and create the “unbelievably accurate” system now operating in Advanced LIGO, while designing future versions which may not be switched on for decades. Van Veggel is comfortable working on such long-term projects – LIGO has only provided a hint of what later detectors may see, and other long-term projects, such as LISA (please see sidebar), will not even go into orbit for another 20 years.
The international dimension

The LIGO Scientific Collaboration (LSC) involves more than one thousand people, and van Veggel loves to feel part of such a large team, with scientists from different countries working on projects in Europe and the US as well as Japan, sharing data and exchanging new ideas. “Some friendly competition is a good thing,” says van Veggel, “but it’s also important to be open-minded, because we are working towards the same ultimate goal.”

Researchers in different countries have also taken slightly different approaches to the mirror suspensions, to improve sensitivity. For example, the configuration in Italy’s Virgo detector uses silica fibres developed in Glasgow, but connects the fibres differently to the mirror and suspension system above, using an inverted pendulum suspension – Advanced LIGO features a quadruple pendulum suspension, connecting four masses (the bottom one being the mirror) in a vertical chain before connecting to a vibration isolation system.

Van Veggel’s major contribution to the mirror suspensions developed in Glasgow is the bonding solution for the mirrors and silica fibres, to enable a low-noise and seamless connection for the “ears” on the sides of the mirrors. As well as installing the mirror suspensions in Washington State, van Veggel also helps to train the team.

According to van Veggel, the detectors of the future will be very different devices, using mirrors and fibres made of silicon or sapphire and including innovative cryogenic systems now being pioneered by KAGRA in Japan (the Kamioka Gravitational-Wave Detector), which will operate at sub-zero temperatures. Using “precious stones” may seem an unlikely solution, but van Veggel says that crystalline materials offer several advantages because they perform better at very low temperatures, helping the detector operate “with less noise disturbance.” Van Veggel has been involved in an exchange programme, working with KAGRA, providing advice on the bonding technology, and also works closely with scientists in the US who are investigating the possibility of Cosmic Explorer (a successor to LIGO) – a new detector with much longer arms and much bigger mirrors, weighing four times as much as the current design. Unlike the Japanese approach, however, this would operate at room temperature, thus “sticking to our trusted fused silica.”

GAIA

GAIA is a Space observatory (launched in December 2013) designed by the European Space Agency (ESA) to catalogue approximately one billion astronomical objects, including stars and planets, comets, asteroids and quasars – to create a precise three-dimensional map of astronomical objects and track their motion through Space. The “stellar census” is also expected to detect “thousands to tens of thousands” of Jupiter-sized exoplanets beyond the Solar System, 500,000 quasars and tens of thousands of new asteroids and comets within the Solar System, and help us understand the origin and evolution of the Milky Way. It will also analyse the physical properties of the stars, including luminosity, temperature, gravity and composition, to provide the basic data we need to answer a wide range of questions about the origin, structure, and history of our galaxy.

LISA

The Laser Interferometer Space Antenna (LISA), is a European Space Agency mission designed to detect and accurately measure gravitational waves (tiny ripples in the fabric of space-time) from astronomical sources, using laser interferometry. The concept is to have three satellites orbiting Earth, arranged in an equilateral triangle 2.5 million kilometres apart, then continuously measure the distance between them to detect a passing gravitational wave – gravitational waves alternately squeeze and stretch objects by a tiny amount, as they travel unhindered through matter and space. The mission was formally selected by the European Space Agency in June 2017 and is currently scheduled to launch in 2034. The Institute for Gravitational Research in Glasgow (IGR) designed and built the optical bench system for a prototype demonstrator satellite for LISA – LISA Pathfinder – in a project directed by Dr Harry Ward. LISA Pathfinder was launched in December 2015 and its performance has been judged to be outstanding, persuading the community and funding agencies that the main LISA project should be pushed forward with all possible speed.
The Einstein Telescope in Europe is another ambitious design, and van Veggel has been working on the project since 2010, when the new design for Advanced LIGO was already completed. “We move on very quickly from project to project,” says van Veggel. The new design will be ten times more sensitive than Advanced LIGO, according to van Veggel, and reveal 1,000 times more sources. “It takes many years to design and construct a detector, and we were very fortunate to witness the detection,” says van Veggel. “But Jim Hough has been waiting even longer!”

So what will be van Veggel’s next career step? Apart from “tinkering” with new designs, to get another glimpse of gravitational waves and understand more about black holes and neutron stars crashing together in galaxies far, far away, she is already working on new applications and spin-offs – including new designs for laser crystal assemblies which utilise the same kind of bonding technologies as those planned for use in future crystalline mirror suspensions, designed to operate at very low temperatures.

But whatever van Veggel may do and wherever she goes, you can be sure it will be “something interesting,” whether she is tinkering in Scotland or Japan, or her mind is on higher things out there in Space.

Biographies

Dr Marielle van Veggel is a Royal Society Dorothy Hodgkin Research Fellow in the Institute for Gravitational Research (IGR) in the University of Glasgow. She has played a key role in developing and applying the bonding techniques used to attach the silica fibres to the silica test masses (mirrors) employed in the Advanced LIGO design – techniques which have significant potential for wider industrial application. In 2016, she shared the Special Breakthrough Prize in Fundamental Physics with the rest of the LIGO team, as well as other international prizes. Her work directly contributed to the Glasgow Herald Research “project of the year” award won by the team based in Scotland.

Dr Harry Ward, a Fellow of the Institute of Physics, leads the research towards the Space-borne gravitational-wave detector LISA in the IGR in Glasgow. Following earlier work towards the design and operation of both GEO600 and LIGO, he more recently directed the Glasgow team who designed and built the optical bench for LISA Pathfinder, a demonstration satellite to test the fundamental concepts behind the interferometry and control for the proposed LISA mission. Pathfinder, launched in December 2015, was highly successful and has provided a high level of confidence that the full LISA mission should be flown by ESA around 2034. For his work with the LISA Pathfinder team, Ward received a 2016 Sir Arthur Clarke Award.
Gravitational Waves

From painting walls and cleaning a laboratory in Germany to being part of the team which detected the first gravitational waves and helping to design the future generation of laser interferometers, Professor Stefan Hild has come a long way on his journey to Glasgow, along the way tackling the effects of “virtual photons” and battling a “mystery noise.”

To describe what he’s doing today at the Institute for Gravitational Research, Hild asks the following questions: “How can you make photons stiffer than diamond? How can we measure space-time without encountering the Heisenberg Uncertainty Principle? What does the Universe sound like?” As an undergraduate student, however, Hild’s experience of gravitational research was not quite as exotic – he was employed for eight euros an hour to fit out the laboratory in Germany, building cleanrooms with simple sheets of acrylic glass and silicone sealant, never dreaming that one day he would be a member of the international team, designing and developing the laser interferometers (detectors) used to discover gravitational waves.

“What first attracted me,” says Hild, “was the spirit of what they were doing. When building a gravitational-waves detector and getting it to work, you need to know a bit of everything.”

Hild was the last student to work on the two Garching Prototype Interferometers, test facilities with arms only 10 and 30 metres long, compared to 4km in the detectors which made the first discovery. At the end of his undergraduate studies, he also had “the sad task” of helping to dismantle the Garching machine, which had provided “a playground” for ground-breaking gravitational waves work for several decades. During his PhD studies, Hild also worked at the core of the British–German Gravitational-wave detector GEO600: “I was lucky to have the opportunity to become one of only a handful people at that time who could operate GEO600, enabling me to watch it grow, subsystem by subsystem, and become more and more sensitive.”

During this period, Professor Ken Strain (now Deputy Director of the Institute of Gravitational Research – IGR) was a regular visitor, spending one week every month at the German facility as part of the team running GEO600 in Hanover. “For three years, there were six of us (I was the most junior and least experienced) sharing a desk in a very small room, with one eye on the monitors, asking questions and sharing ideas with each other, and trying to keep the interferometer ‘happy.’ I don’t think I will ever experience such an environment again,” Hild explains.
There is a lot of “healthy competition” between the different international projects, while at the same time scientific collaboration flourishes, supporting the sharing of new ideas, exchange of hardware, and pooling of the recorded data across LIGO, GEO and Virgo. “Everybody knew that they could not discover gravitational waves on their own – we needed a network of detectors,” says Hild.

As a “noise hunter,” Hild tries to track down the hundreds of possible sources of noise in the system – including everything from dust in the laserbeams to earthquakes and tractors in neighbouring fields, misbehaving electronics, lightning strikes or even modulations in the power grid caused by smart electricity meters. “We are trying to put together a super-sensitive system with several hundred control loops, many of which interfere with each other,” says Hild. “You might fix a problem on one end of the system, but if you’re not extremely careful, the same fix might cause some noise at the other end of the interferometer. We had to learn that things don’t always go the way you think they’ll go!”

Hild’s career has taken him from Germany to the University of Birmingham (where he was amused to realise that he was a German researcher being funded by the French and Italians in a British laboratory), to help to develop Advanced Virgo. “I had a lot of freedom then because at that time there were really only two people working full time on the design of Advanced Virgo,” says Hild. Two years later, he was offered a position as a Lecturer at the University of Glasgow, where he found himself supervising five post-doctoral researchers who were all of a similar age to himself, and giving lectures in astronomy, despite the fact that he had never done any undergraduate courses in the subject himself.

According to Hild, the Einstein Telescope will establish a completely new and “fabulously sensitive” class of gravitational-wave detectors, designed to work as a “self-sustained” observatory for at least 30 years. It will also be constructed underground to reduce seismic noise and its influence on interferometer mirrors.
Another new feature of future detectors will be what Hild calls a “xylophone” design – a kind of dual-band microphone to help detect a range of different frequencies. The problem, he says, is that powerful lasers and cooled optics, optimised for certain frequencies at opposite ends of the scale, cannot work well together, so “building two instruments, each optimised for a certain frequency range or tone, will greatly improve our ability to listen to the exotic phenomena in the Universe.” This will allow the team, he adds, “to find gravitational waves from sources we know of, but hopefully – and I am even more excited about this – to find the unexpected.”

As he looks forward to future designs, Hild is reminded of the “mystery noise” once detected by GEO600. No matter how much the researchers looked into the possible source of the noise, they never identified what it was or where it came from. “It’s a curious puzzle,” he says. “The most likely explanation is that it is something completely boring, such as some noise in an electronic circuit, or – less likely – it could be a strange phenomenon from a holographic Universe, as suggested by researchers in Chicago.” But as Hild and his colleagues continue to study the Cosmos with smarter and smarter detectors, the hunt for evidence will never be boring – especially if they discover the source of the mystery noise and other strange phenomena never detected before.

**Biography**

**Professor Stefan Hild**, a Fellow of the Institute of Physics and a member of the RSE Young Academy of Scotland, is a leading authority in laser interferometry and carried out research that led to crucial advances in the sensitivity of both the Advanced LIGO and Virgo detectors. He is also involved in the design of future ground-based interferometers, particularly with regard to developing innovative techniques to exploit some of the weird rules and relationships in quantum physics to further enhance the sensitivity of future detectors. For his outstanding work in physics and astronomy, Hild was awarded the RSE Makdougall Brisbane Medal in 2016.
Gravitational Waves

Astronomy has often been compared to looking for a needle in a haystack, but Dr Chris Messenger makes it sound even harder than that. He has spent a significant part of his career in the quest to detect gravitational waves from “continuously emitting sources” such as neutron stars or pulsars, but 20 years since he first set out on his search at the University of Birmingham, studying theoretical physics, he still hasn’t managed to find them.

Neutron stars are very dense collapsed stars which can rotate at approximately 1,000 times per second. Because they are so dense and exert such a strong gravitational pull from the core, they also have very smooth surfaces, but gravitational waves are only emitted by oscillating or rotating asymmetrical objects – for example, if there is something sticking up from the surface. The tiny imperfections on a neutron star, however, are much more like pimples than mountains – they are only one or two millimetres in height on an object which is roughly the size of a city such as Glasgow, approximately 10km wide with a mass twice as great as the Sun.

This degree of difficulty may explain why Messenger and other leading scientists have not yet detected continuous gravitational waves, despite employing the “most stringent detection methods” ever developed to search “wide area parameter space.” Researchers can simulate the sound of the continuous gravitational waves, and would therefore be able to recognise them if they detected their signature waveform, but so far, there have been no concrete results.

Messenger may have to wait to detect continuous gravitational waves (please see sidebar), but he has played a key role in the first two detections of compact binary gravitational waves (please see sidebar) by LIGO (the Laser Interferometer Gravitational-wave Observatory) in September and December 2015. These two historic events were both caused by collisions between two black holes, which released a huge burst of energy lasting just a split second, rather than the weak harmonic signal you would get from a continuously emitting source such as a pulsar. The team in the LIGO Scientific Collaboration expected that the first thing they’d detect would be a coalescence of two neutron stars, simply because astronomical observations prove their existence, unlike the lack of evidence for merging black holes, but that just goes to prove that probability can be full of surprises.
The search for gravitational waves is an epic endeavour. The sources could be anywhere out there, but according to Messenger, “you would need all the computing power in the world to do an optimal search,” and that is why he and his colleagues in the data analysis groups have focused on novel mathematical methods to improve the sensitivity of the detector – for example, using innovative machine learning techniques (a type of artificial intelligence that enables computers to learn without being programmed to do so).

After gaining his PhD in astrophysics at Birmingham, Messenger then worked at the University of Glasgow, and at the Albert Einstein Institute for Gravitational Research in Hanover, Germany, before spending three years at the University of Cardiff and returning to Glasgow in 2013, to take up a position as a Lord Kelvin Adam Smith Research Fellow. After ten years working as a post-doc in research labs, Messenger was delighted when he was appointed a Lecturer in Gravitational-Wave Astrophysics at the University of Glasgow early this year, but says that most researchers lead precarious lives, without the security of long-term positions.

When he first went back to Cardiff in 2010, Messenger thought he would continue his research into continuous gravitational waves, focusing on candidate stars in the Scorpius constellation, but he shifted his attention to “compact binary coalescence” – looking at black holes and/or neutron stars in compact orbit around each other which are likely to merge because of the energy lost into gravitational waves.

Whilst at Cardiff, and subsequently at Glasgow, Messenger continued to develop new data analysis methods for studying the properties of neutron stars and trying to use them to as cosmological probes. Together with a colleague from the University of Mississippi, he discovered that it was possible to measure how fast these objects were receding from us as the Universe expands. This made the future detection of binary neutron star mergers even more valuable to scientists, since it would enable them to measure this expansion using gravitational waves.

According to Messenger, the mathematics used to study gravitational waves – including Bayesian inference methods* – are already highly advanced, and the next challenge is to develop the next generation of detectors to generate more detailed data. “We can identify and understand the data,” he explains, “and we know the real thing when it comes. The data contains spurious detector noise as well as astrophysical data. We spend a lot of time studying the data to try to disentangle them.”

Messenger says he’s been “lucky” to chair the group tasked with “determining the statistical significance of potential detections” – the probability of candidate events. The data analysts can spend a lot of time dealing with “detector glitches” which may interfere with the signals.

“We get lots of glitches in the noise spectrum,” says Messenger, “and our job is to understand their properties.” Glitches come along which look like signals from Space, and it is possible that both detectors, thousands of miles apart, may detect similar glitches at the same time, but that is statistically very unlikely. To detect false alarms, the researchers use a method called a “time slide” to analyse unusual events dating back over a few days or weeks, and this enables them to see if the event was a coincidence or something more significant.
Neutron stars

A neutron star is the collapsed core of a very large star. With a typical radius of about 10km and a mass of about two times the Sun, they are the smallest and densest stars known to exist. They result from an explosion, combined with gravitational collapse, that compresses the core. If the core is too dense, it continues collapsing to form a black hole. Neutron stars are very hot and so dense that a cubic inch of neutron-star material would have a mass of approximately 13 million tonnes. They also have strong magnetic and gravitational fields. As the core collapses, its rotation rate increases up to several hundred times per second. Some neutron stars emit beams of electromagnetic radiation that make them detectable as pulsars. There are an estimated 100 million neutron stars in the Milky Way.

The checking process involves introducing a series of artificial time shifts to create a much longer data set in which they search for signals as strong as (or stronger than) the candidate event. The time shifts are more than ten milliseconds (the time it takes for light to travel between the detectors) to ensure the artificial data sets don’t contain any real signals, but only coincidences in noise, to see how often a coincidence mimicking the wave would appear. This analysis provides the false alarm rate – how often they expect to measure such a seemingly loud event that was really just a noise fluctuation.

This process doesn’t happen every day, but false alarms must be taken seriously, just in case. Says Messenger: “We generate hundreds of thousands of triggers that can’t possibly be gravitational waves.”

The data analysts have learned from past experience to be very cautious to make any premature claims, but Messenger also believes that even though they may have been “bad science,” the false alarms of the 1960s at least sparked interest in the search for gravitational waves, and alerted future researchers to the need for bullet-proof verification. “You could go and find all sorts of signals out there,” he explains. “That is why we look at populations of sources, and have set up four data analysis groups – focusing on compact binary coalescence, bursts, continuous waves and the stochastic background.

According to Messenger, the current detector will not even reach its “design sensitivity” level for another two years and, meanwhile the researchers are designing much more sensitive detectors which will greatly expand their horizons. Once they have recorded more detections, says Messenger, they will have much more meaningful data on entire populations of black holes – what he calls “ensembles of detection” – and machine learning promises further advances, shedding light on what Messenger calls the “dark fringe” of space. What the team at LIGO has already discovered will lead to the creation of a new field of science, so who knows what they’ll find on the dark fringe of data in future?

* Bayes’ theorem is used to “update the probability for a hypothesis as more evidence or information becomes available”

Biography

Dr Chris Messenger was, until recently, a Lord Kelvin Adam Smith Research Fellow in the Institute of Gravitational Research (IGR), and was appointed a Lecturer in Gravitational-Wave Astrophysics in early 2017. He is a leading authority in Bayesian inference methods, which allow us to probe and constrain the properties of individual sources of gravitational waves and also the properties of their underlying population – i.e., understand the properties of that population from the few sources we have detected by taking into account the sources that we haven’t detected. For several years, Messenger chaired the working group charged with developing methods for estimating the rate of gravitational-wave events to be expected, and determining the significance of the source candidates.
When Professor Graham Woan joined the team hunting gravitational waves, he estimates that 75% of the LIGO Scientific Collaboration (LSC) could have been classified as “instrumental scientists” – designing, building and operating the detectors – while only 25% were data analysts, developing novel computer-based methods to identify the signals in the midst of the noise. Seventeen years later, he says, the proportions are reversed, and most of the researchers now focus on the use of computers and advanced mathematical methods to interpret the data. At the same time, the roles of the different researchers have also evolved, overlapping in virtually every activity, including the design of the next generation of detectors.

Unlike most other members of the team, Woan started as a radio astronomer who did his first degree in Natural Sciences and his PhD in radio astronomy at Clare College, Cambridge and served his “apprenticeship” at the Mullard Radio Astronomy Observatory and the Cavendish Laboratory. Woan therefore brought a different set of skills to the table when he joined the team in 2000, but since then, the project has changed out of all recognition, not just using bigger and better detectors, but also much more powerful computers, taking advantage of tools such as Bayesian inference methods – which update probability as more data becomes available.

In the early days, Woan’s contribution was not only his theoretical background, but also his practical knowledge of computers, electronics and astronomy. “Radio astronomy attracts people with a broad range of skills,” he says, “and statistics is particularly important for radio imaging.” The pictures of radio sources were fairly crude in the early days of radio astronomy, but clever techniques helped radio astronomers make improvements by using incomplete information on the overall structure of the image to infer the brightness of individual pixels, and build a more complete and detailed image. And similar techniques, says Woan, are used to interpret the signals generated by the LIGO detectors – a kind of “educated guesswork” based on data and experience.

Convergence
Computing and astronomy have gradually come closer and closer together, and Woan believes that Bayesian methods have also become much more relevant because of technological advances, and the vast amounts of data that result.
Woan came to Glasgow in 1996 to join his wife, who already had a job in the English Language department, and he was offered a Lectureship in astronomy and astrophysics, doing research in solar winds, pulsars and interplanetary scintillation (IPS). He was already aware of the work being done in gravitational research, in Glasgow and beyond, and realised he had a contribution to make, providing “astronomical input” to a group populated at that time by specialists in optics and quantum optics, as well as delicate mechanical systems. Gradually, however, Woan expanded his role within LIGO (the Laser Interferometer Gravitational-wave Observatory) as the different groups came closer together to collaborate on Advanced LIGO.

Like most other scientists, Woan believed binary neutron stars would be the first source of gravitational waves to be detected, and they are still a “beguiling source,” he says. Black hole coalescence was also a promising candidate, but a big surprise when that was the first source detected by LIGO.

Woan maintains his interest in continuous gravitational waves, emitted by rotating neutron stars, because these will also provide very valuable data. For example, he keeps a close eye on the Crab Nebula, a supernova remnant in the Taurus constellation which exploded about 1,000 years ago, with a neutron star right in the centre, about 20km across and rotating 30 times a second. “It’s a like a huge flywheel,” says Woan, “and as it throws off lots of energy as electromagnetic radiation, it slows down at a rate of one less rotation in each consecutive 14-hour interval.” If all that energy was released instead as a gravitational wave, Woan explains, we would have detected it several years ago, but we now know that less than one per cent of this energy is emitted in gravitational waves, so the hunt for more data continues. “There are many other good candidates,” Woan says, “including other young pulsars, but also many neutron stars that are not seen as radio pulsars.”

Two black holes colliding and merging is a very dramatic event, but if we saw two neutron stars colliding, we would also learn a lot about what these stars are made of, and answer lots of questions in particle physics. The sensitivity of the detectors is steadily increasing, and the team reduce the noise floor every year, but it may be some time before Woan and his colleagues detect continuous waves.

The ratio of instrumental physicists to data analysts and astronomers may have been turned on its head, but Woan also feels very strongly that data analysts will always have a big role to play in designing the detectors of the future, and that instrumental physicists will always play a big role in data analysis. But no matter where they come from, they all speak the same astronomical language – even if the vocabulary still has words missing.

**Biography**

**Professor Graham Woan** leads the data analysis section in the Institute for Gravitational Research (IGR) and has held key leadership roles within the LIGO data analysis working groups for more than ten years, including co-Chair of the LSC/Virgo "pulsar group" (or Continuous Waves Investigations Group). He pioneered the development of Bayesian inference methods in the project and is also a leading authority in gravitational-wave data analysis and astrophysics, leading the efforts to detect gravitational waves from isolated rotating neutron stars known as pulsars – which may be the next type of source that Advanced LIGO detects.
The Scottish connection

The search for gravitational waves has taken decades to produce its first results, involving hundreds of scientists from countries all over the world. There are currently four people with PhDs from the University of Glasgow working in LIGO at the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT) and Professor Norna Robertson is one of that select group who has worked on the project in both Scotland and the US – not just bridging the Atlantic but also generations of researchers.

Q: How long have you been doing research into gravitational waves, and how long have you been part of LIGO at Caltech? Who have been the major influences on your career?

A: I started doing research into gravitational-wave detection as a PhD student in 1977 in Glasgow. Apart from two years as a post-doc in infrared astronomy, I have worked in the field of gravitational waves throughout my career. I joined LIGO at Caltech ten years ago, in 2007.

My PhD supervisors were Ron Drever and Jim Hough. However, Ron started his visits to Caltech (spending six months a year there) just a few days after I started my PhD, so de facto Jim was my supervisor – and a major influence in my career. Also, both my parents were scientists at the University of Glasgow (though neither were physicists) and they were definitely strong role models for me.

Q: Why is the search for gravitational waves so important? Why does it matter? What excites you most about it?

A: I guess one of the things which has excited me most about working in this field was the fundamental nature of what we were trying to achieve – verifying one of Einstein’s predictions, and opening a new field of astronomy. And I enjoyed the challenge of making such incredibly sensitive measurements, where we were pushing the bounds of physics and technology in every aspect of our work.

Q: What do you think the project will lead to in future – ten years from now and 100 years from now?

A: In the next ten years, I look forward to seeing what new astronomy comes out of our detections. We will certainly see more black hole binary mergers and learn about their likely evolution, but we should also be detecting other sources, including some we haven’t yet conceived of. Just think what a field day that will provide for our theorists! In the 15-to-20- year timescale, the Space-based LISA project, working at much lower frequencies, should complement the work of ground-based detectors by detecting different sources and giving us new insights into the Cosmos. As for 100 years from now – who knows?
Q: Can you describe the role of the suspension systems in LIGO? How important are the suspension systems? Would LIGO have succeeded without the current design/with a different design?

A: Each suspension system, nicknamed the quad, consists of four cascaded stages of pendulums whose bottom mass is the test mass – the mirror whose motions we monitor when looking for gravitational waves. The quad provides more than a factor of a million isolation for the mirror from residual seismic noise, and is designed to minimise another fundamental source of noise – thermal vibrations in the suspension itself. Thermal noise reduction is achieved using very delicate, ultra-low-noise, silica fibres to support the silica mirror, and hence the lowest stage of the assembly is described as a monolithic silica suspension. The original LIGO suspensions consisted of a single stage pendulum, with the mirror hanging on steel wires. With that suspension we could not have achieved the noise performance that was needed to make our first detection.

Q: What are you most proud of in your own work – your own contribution to LIGO?

A: It is has been a long, long road since I started as a young research student 40 years ago. There have been many challenges, and not just the formidable scientific and technological ones. Support for our work has ebbed and flowed over the years, but we kept going. Perhaps perseverance is one of my biggest contributions to the field!

Q: You headed a large team as both manager and scientific researcher. How did you combine these roles? Which role do you prefer?

A: I did manage a large team when I headed the Suspensions team for the Advanced LIGO project. In that position I was responsible for overseeing the design, fabrication, assembly and installation of the multistage suspensions supporting all the major optics in both Advanced LIGO detectors, including the quads described above. The work involved coordinating and managing a team of approximately 40 scientists, engineers and technicians from eight institutions within the USA and the UK. Given the UK involvement and the eight-hour time difference, this led to many early morning telecons, and a lot of travel! During that time I did not do much research, but I enjoyed the challenge of keeping the team working together, and felt a great sense of satisfaction when the final suspension was installed into the detector. It is fair to say I have enjoyed both aspects of my work over the years.
Biography

Professor Norna Robertson, a Fellow of the RSE, the Institute of Physics and the American Physical Society, is a lead scientist at the California Institute of Technology (Caltech), working in the LIGO project. She also spends a few weeks every year working at the University of Glasgow, where she is a Professor of Experimental Physics. She gained her PhD at Glasgow in 1981, focusing on “experiments relating to the detection of gravitational radiation and to the suppression of seismic noise in sensitive measurements.” After a post-doc position at Imperial College in infrared astronomy, she returned to gravitational-waves research in 1983 as a Lecturer at Glasgow, where she was appointed Professor in 1999. In 2003, she moved to the USA to work at Stanford University, and in 2007 she moved to Caltech to head the Suspensions team for the Advanced LIGO project. Currently, she works on suspension-related research for possible improvements and upgrades for Advanced LIGO.
What connects a purring cat with Einstein and black holes colliding in deep outer space?

It may seem like a silly joke, but Professor Stuart Reid of the University of the West of Scotland (UWS) has an interesting answer – because he has not only played a key role in developing the technology used to confirm one of Einstein’s most challenging theories (general relativity), but is also applying it to ground-breaking medical research which may enable scientists to grow human tissue by mechanically vibrating mesenchymal stem cells (MSC) at the nanoscale. And it’s all about vibration, whether it’s from purring cats or being applied to stem cells, or a giant explosion which sends gravitational waves through the Cosmos, distorting space and time.

Using “nanokicking” to stimulate stem cells is a radical method to grow bone in the lab – a technology which could potentially change the lives of millions of people. But even though it is a brand new technique in medical science, it is based on well-known scientific concepts.

According to one theory, the first sense developed by living cells was the ability to sense mechanical pressure – which is closely related to hearing and touch, and helped these organisms to survive. According to a second theory, cats purr because the vibrations are good for their bodies by helping to heal damaged tissues. And although this

may seem rather wacky, “whole body vibration” is already used to help increase bone density and build muscle tone in people who have suffered spinal injuries, as well as to improve the fitness of athletes and speed up recovery from injury. Quite simply, vibration encourages cells to repair damaged bone.

What Reid is working on is not a million miles away from whole body vibration, but what makes his research so different is that he is concerned with vibrating and activating individual cells, the tiny building blocks of the body, at the same time as working as part of the team developing equipment for Advanced LIGO, measuring the largest, most powerful vibrations ever observed in the Cosmos, applying the same technique used in the hunt for gravitational waves to measure and calibrate the tiny vibrations used to nanokick cells.

“In fact,” says Reid, “the tiny signal we send to each stem cell is astronomical compared to the very faint sound from gravitational waves, partly due to the billions of years gravitational waves take to reach us.” And because the laser interferometry technique is so sensitive, it is “relatively easy” to measure what is happening to the stem cells.
This focus on the tiniest and largest of phenomena explains why Reid begins his presentations with an opening slide which shows black holes on one side and stem cells on the other side, to illustrate the different extremes of his work and the fact they’re so closely connected.

What connects the black holes and the stem cells is that both emit pressure or waves that detectors are able to sense. Vibrating stem cells encourages them to grow bone, but the key to success is to make sure that the frequency and amplitude of the vibrations are exactly in tune with the stem cells so they can get on with their job, and this requires an instrument to measure and control the vibration – at the nanoscale level.

Reid said in an earlier interview: “If you take one cell and blow it up to the size of a football, then the amount we’re shaking the cells is the same as sliding one sheet of paper in and out from the bottom.” And according to co-inventor Professor Adam Curtis, the so-called nanokicking is more like “the tiniest tickle.”

The solution developed in UWS and the University of Glasgow has since been used successfully by scientists in Nottingham and Galway, without the original team members even needing to be there – proving that the innovative kit can be used “knockdown-style” in other labs with minimal training. Another big attraction, says Reid, is that this new approach needs no fancy chemical “cocktails” or complex and expensive engineering techniques.

In a different area, some of the mirror coating technology developed for the gravitational-wave detectors is also being used for several other applications, including equipment which monitors hospital patients to check if they’re dead or alive, by measuring the carbon dioxide exhaled during anaesthesia. The monitors in use today can be confused by nitrous oxide (laughing gas), because it is similar to carbon dioxide, which means it takes longer to check readings and can cause errors. By using special optical filters, however, the new sensor is more accurate and faster. Reid is working in partnership with Cumbernauld-based company Gas Sensing Solutions (GSS) to develop this novel device, and GSS, in turn, will help Reid and his team develop new coatings for the mirrors used in interferometers – the detectors used by LIGO – by growing single-crystal layers which are “structurally perfect” at the atomic level, and thus more sensitive. Reid explains that these “lattice-matched” materials could greatly improve the performance of the next generation of interferometers, and also win new customers for GSS, to make the new production facility more economic to run for everyone involved. The partnership is all about mutual success – Reid and his fellow researchers (including the Institute for Thin Films, Sensors & Imaging at UWS) will help to develop new sensors and upgrade production, while GSS develops a potentially “magic solution,” for astrophysicists and medical researchers.

If at first...

Reid first got involved with stem cell research when Professor Jim Hough, from the Department of Physics and Astronomy at the University of Glasgow, was asked for help by Professor Adam Curtis of the Institute of Molecular Cell and Systems Biology. One of Reid’s colleagues was on holiday that week, so Reid got involved from the start and has not looked back since. In fact, his career has been turned upside down, and he is soon to join the Department of Biomedical Engineering at the University of Strathclyde, focusing on new applications for translational medicine emerging from technology developed for gravitational-wave detection.
The early experiments were not an unqualified success, however, looking at the laser interference patterns projected across petri dishes to measure the effects of different rates and amplitudes of vibration. The technology was not always state-of-the-art – including sticky tape and rulers on computer screens – but the key to success was the combination of expertise used by the team, including physicists such as Reid, who was experienced in similar precision measurement experiments within gravitational-wave research, including computer simulation techniques, and also had a good understanding of mechanical and resonant systems.

The basic idea was that if they could vibrate cell membranes, the cells would respond in particular ways – e.g., secreting minerals. Researchers had already done experiments with cells extracted from mice, but even though the scientific principles appeared well established, in an attempt to “mimic nature,” progress was slow.

“We didn’t see any response in the stem cells until we reached about 1,000 Hertz (1,000 vibrations per second),” says Reid. “We were confused at first by this result, because we were initially focused on slower vibration rates similar to that associated with the heartbeat or with walking. We later discovered that bone was optimally piezoelectric (capable of generating voltage), at 971 Hertz, which might explain why we saw the strongest result at 1,000 Hertz.”

The original equipment used was relatively simple, says Reid – with petri dishes (containing cells dispersed in gel) glued to rigid aluminium support disks which were vibrated at different frequencies. Reid’s job is to verify the vibrations by quantifying the frequency and amplitude in order to calculate the forces involved, and enable the researchers to control the vibrations in the bioreactor, so the process can be reproduced precisely again and again.

The project has been so successful that it recently attracted £2.8 million in funding from a charity called “Find a Better Way,” founded by the Manchester United football legend Sir Bobby Charlton to provide help to victims of landmines. Reid says it is already possible “to produce three-dimensional volumes of bone,” but there’s still a long way to go before we can regenerate limbs – and that is the ultimate aim of a new branch of science called “tissue engineering.”

The Find a Better Way project is led by Professor Manuel Salmeron-Sanchez and Professor Matthew Dalby, and includes partners at the Scottish National Blood Transfusion Service (SNBTS). It will develop a novel bone scaffold material, called “HealiOst,” alongside nanokicked bone graft, and will also fund the first in-man trial of nanokicked stem cells within the next 3–4 years.

“Bone is the second most transplanted tissue,” he adds, “and tissue engineering is one of the biggest challenges currently faced within regenerative medicine.”
Turning the tables

According to Reid, “people don’t often think of mechanical transduction” in relation to medical science. Perhaps we’ve missed a trick, he says, by not using more mechanical engineering techniques in biotechnology, and now it’s time to change this. “We have under-explored and under-investigated the role of mechanical influences in other areas of science,” he adds.

What Reid will focus on in future research is the use of “highly controlled, reproducible cues to control the behaviour of cells at the nanoscale level,” but Reid is not forgetting astrophysics – this will also lead to the development of innovative solutions which are equally useful in the ongoing quest for gravitational waves.

The major challenge for the astrophysicists is to make sure their detectors can unscramble the signal from gravitational waves from the other noises in the environment (such as earthquakes) and the equipment itself, including the thermally-driven motion of the atoms within the 30 layers of materials, 4.5 microns thick, that form the front surface of the mirrors. Atoms and molecules “jiggle” around at specific temperatures, and the ultimate aim is to eliminate this “thermal noise.” Another major challenge is the way the light is absorbed and scattered by the mirrors, which can also interfere with the signals.

Reid and his research team, along with colleagues at Glasgow, are developing a new kind of dielectric laser mirror coating for the mirrors which involves using microwaves to help deposit silicon atoms on the surface to reduce thermal noise. The ultimate challenge is to make sure the atoms do not land in completely random positions, but arrange themselves in patterns, close to that of a crystal – or what is called an “ideal glass.” The alternative is growing absolutely “perfect” crystals, but Reid says that this is a long-term solution which may require another 10–15 years of research. Meanwhile, the next generation of detectors is being designed and developed, so short-term solutions are also essential to deal with the internal friction which gives rise to the thermal noise observed in the detectors.

“Almost everything wants to move the mirrors more than gravitational waves,” says Reid. The waves may come from a giant explosion 1.3 billion light years away, but even a vibrating stem cell at nanoscale level is louder. And Reid’s future research appears to be heading in both directions at once – Inner Space and Outer Space. “My work in stem cells used to be a spin-off of my work in gravitational waves,” he concludes. “But the tables have turned, and now gravitational-wave research is also, in part, a spin-off of my work in biomedical engineering.”

Biography

Professor Stuart Reid, co-Chair of the RSE Young Academy of Scotland, is a Professor of Experimental Physics and Royal Society Industry Fellow working in the Institute of Thin Films, Sensors & Imaging in the School of Engineering and Computing at the University of the West of Scotland. He leads a research team of staff and students who are investigating novel laser mirror coatings for use in future gravitational-waves observatories, focusing on the development of ion-beam sputtering (IBS) and molecular beam epitaxy (MBE), “nanokicking” stem cells in collaboration with Professor Matthew Dalby and Dr Peter Childs of the University of Glasgow, and breath analysis for patient safety during anaesthetic procedures in collaboration with Professor Des Gibson (UWS) and Gas Sensing Solutions Ltd.
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