The Royal Society of Edinburgh

Gunning Victoria Jubilee Prize Lecture

Ripples from the Dark side of the Universe – the Search for Gravitational Waves

Professor James Hough FRS FRSE

15 June 2009

Report by: Bryan Christie

The evolving field of Gravitational Wave Astronomy

Gravitational waves are ‘ripples in space-time’ caused by the acceleration of large masses in the universe. They carry information about what is happening deep in the heart of some of the most violent events in space. It was Einstein who first postulated that they exist in his General Theory of Relativity in the early part of the last century. Almost 100 years on, they have never been directly detected by scientists, although there is indirect evidence of their existence. Professor Hough explained the nature of gravitational waves and the research being carried out around the world to detect these elusive signals. He said that establishing proof of their existence would confirm Einstein’s theory and, more importantly, would open up a new kind of astronomy that would add to our understanding of the universe.

According to the theory of relativity, gravity is the result of the curvature of space-time. As two objects orbit each other, their acceleration causes disturbances in space-time which move outwards like ripples across a pond. However, these strains, as they are known, are at extremely low levels of the order of one part in a thousand billion billion. That is equivalent to a change in the separation of the Earth and the sun by less than the diameter of an atom. Detecting them has proved to be one of the most challenging problems in experimental astrophysics.

Little interest was shown in carrying out experiments in this field until the work of Joseph Weber in the 1960s. That encouraged other research teams to become involved, leading on to the developments of recent years. Professor Hough said this work was designed to answer some important scientific questions including:

- What are the properties of gravitational waves?
- Is Einstein’s theory of general relativity the correct theory of gravity?
- How does matter behave under extremes of density and pressure?
- What is the history of the accelerating expansion in the Universe?
- Where and when do massive black holes form and how are they connected to the formation of galaxies?
- What happens when a massive star collapses?
- What is the history of star formation in the Universe?

Professor Hough said that up to about ten years ago scientists thought they were close to understanding everything about the universe. However, it was then discovered that the universe is expanding, with its outer part accelerating away as if gravity was acting as a repulsive force. No one could understand what was causing this to happen. It is believed to be due to something called dark energy, but that is another phenomenon that is not understood. Professor Hough said that detecting gravitational waves will help scientists measure what the universe is doing in a totally different way and begin to get an understanding about what is causing this acceleration.

A large part of Professor Hough's lecture was devoted to the technical challenge of detecting these minute signals from faraway in space. It will need huge masses accelerating very strongly to produce waves that are capable of being detected from Earth. This will come from events such as black hole formation; neutron stars coalescing; rotating neutron stars such as pulsars; and from general noise background from sources such as cosmic strings which are thought to be like elongated black holes. To a non-specialist, the challenge seemed not dissimilar to designing and deploying equipment in Edinburgh that could detect a leaf dropping from a tree in Ecuador.

The technology being used to detect gravitational waves is the laser interferometer. The interferometers used for this work have two arms down which the laser light is fired, with reflecting mirrors at the ends of the arms. The light travels inside stainless steel tubes which are kept evacuated. The arms need to be up to four kilometres long and built on the surface of the earth (with the mirrors isolated from seismic disturbances by being hung as pendulums), to make them sensitive enough to pick up the wave signals. The laser light inside the tubes is the measuring tool. The laser light is first split into two beams by a beam-splitter, and after travelling to the ends of the arms and being reflected back, the two beams then combined to interfere with each other. This creates a form of 'telescope' that can 'see' these signals from space.

This system is incredibly sensitive and can be affected by the smallest vibration, sound or Brownian Fluctuations of its mirrors. Professor Hough said a great deal of experimental care is needed to isolate the equipment from all these influences to ensure that pure measurements are obtained. Animals living in the surrounding area can exert a gravitational pull that can affect equipment and even passing clouds have a gravitational influence. All this has to be taken into account in designing and operating the interferometers.

A network of interferometers is currently in operation around the world. Professor Hough's team is involved with colleagues in Germany on GEO 600. This uses a novel technology known as Signal Recycling, which feeds the signals that try to come out of the interferometer back into the system to make them bigger and more measureable. It also suspends mirrors with pure glass fibre to reduce fluctuations in movement (Brownian Fluctuations) caused by the system being at room temperature. Other detectors exist in the United States (the LIGO experiment), Italy (the Virgo experiment) and Japan (the TAMA experiment) and there are plans for an additional interferometer in Australia. The Scottish and German research teams have joined together with their US colleagues in the LIGO scientific collaboration to pool their knowledge and work together. This involves some 500 scientists from 55 institutions. Five science runs have now been completed with the detectors in this collaboration but, so far, nothing has been found. Professor Hough said this is not surprising given the current limitations of the existing instrumentation, which cannot reach far enough out into the universe to pick up potential measurable events. The LIGO system is currently being enhanced by a factor of two and there are plans to run the systems again this summer. At this improved level, LIGO might be able to detect two events a year.

The real promise for the future lies in developing advanced detectors that will have 10–15 times the sensitivity or range of current interferometers. This will allow scientists to reach further out into space and increase the number of large-scale events that potentially can be detected to 500 a year. An advanced version of the LIGO detector, based on the British and German technology, is expected to be fully installed and operating by 2014. The Italian-based detector is to have a similar upgrade. In Japan, an interferometer – called the Large Cryogenic Gravitational Telescope – is planned to be built underground in a disused mine to reduce seismic and gravitational fluctuations. It will also be cooled to cryogenic temperatures to reduce Brownian Fluctuations. Professor Hough described this as quite an undertaking, but predicted this would be the first phase of the next generation of experiments where cold systems are built underground.

Scientists are also looking beyond advanced detectors to build the third generation of instrumentation. This would have ten times the sensitivity of the advanced detectors and a design study, funded by the EC, has already begun to assess the building of such a detector, which has been given the name of the Einstein Telescope. Professor Hough said the technological challenges involved will be significant, but the spin-offs from this work will have benefits for industry around the world. The timescale for starting building is around 2020.

There are also proposals from an American and European team to take experiments into space. This is known as LISA and would involve creating a space-based laser interferometer, consisting of three spacecraft orbiting the earth connected in a triangle by laser light. A demonstrator mission LISA Pathfinder is being prepared for launch in late 2011 to test the potential of this proposal.

Professor Hough said there is a whole network underway which he is confident will be able to guarantee detection of gravitational waves sometime after 2014, although it is possible that something will be seen before then. It offers nothing less than the prospect of a whole new astronomy, leading to a host of new and totally unexpected events and phenomena to be observed in the future. Astronomy, he said, has been exciting since man first looked up at the stars. More recently, Infra-red and gamma-ray astronomy, together with cosmic microwave background scanning, have increased our understanding of the universe. He is confident that with the detection of gravitational waves, another new chapter is about to begin.