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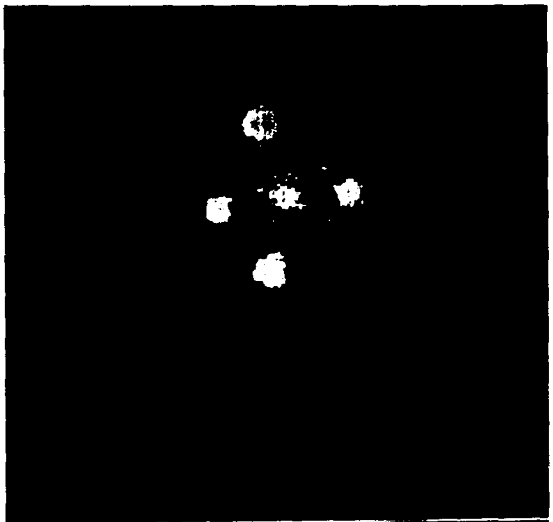

Gravitational Lens G2237+0305

A GUIDED TOUR OF THE UNIVERSE

INAUGURAL LORD HEYCOCK MEMORIAL LECTURE

by

Professor Bernard F Schutz

University of Wales College of Cardiff

September 1994

Foreword

by Professor M Wyn Roberts
Head of the Department of Chemistry
at the University of Wales College of Cardiff

It was with particular pleasure that I agreed to act as Chairman for the first Lord Heycock Memorial Lecture which was given by my colleague, Professor Bernard Schutz, in the Reardon Smith Lecture Theatre at the National Museum of Wales in Cardiff. The lecture was established to mark Lord Heycock's contribution to education in Wales, in schools and in further and higher education. The lecture will be an annual event held in rotation at each of the six constituent institutions of the University and the 1995 lecture will take place at Swansea.

The 1994 lecture, *A Guided Tour of the Universe,* more than fulfilled the hopes of the organisers in the University of Wales that it should be a fitting tribute to Lord Heycock's memory - indeed, given the subject matter, perhaps I will be forgiven for writing that the series started with a (Big) Bang! The lecture was illustrated by slides and video film and by practical experiments of the type which one more usually associates with the televised Christmas Lectures at the Royal Institution of Great Britain. The audience of over 400 - mostly school pupils and students from South Wales - quite clearly enjoyed Professor Schutz's stimulating description of his work. He succeeded in conveying to them his very real enthusiasm for his subject and may even have persuaded some of them to follow his example and to take up a career in astronomy.

The popularisation of science - and of all other subjects - among our young people has a key role in ensuring that we continue to push back the boundaries of knowledge. Undoubtedly, in the years to come the Lord Heycock Memorial Lecture will play an important part in stimulating the young people of Wales to join in the multitude of exciting academic ventures which lies before us, both within the University of Wales and beyond.

Llewellyn Heycock – A Lifetime of Service

Lord Heycock: The boy of 14, the politician and the peer.

Lord Heycock rose from humble origins to become one of the influential shapers of the Welsh education system. Largely self-taught, his passion for education as a means of escape from deprivation is still well-remembered four years after his death at the age of 86 in 1990.

He was born on 12 August 1905 in Port Talbot which was to remain his spiritual and actual home throughout his life. He left school at 14 and found work as a locomotive cleaner on the old Great Western Railway to supplement the meagre family budget. Already his heart was in politics and trade unionism and it was not long before he joined the Labour Party and the National Union of Railwaymen. He was elected to the former Glamorgan County Council in 1937, becoming its Chairman in 1962-63. In 1947 he became the Chairman of the Education Committee, a position he was to hold for the next 28 years. After local government reorganisation in 1974, he became leader of the new West Glamorgan County Council. He was also a founder member and Chairman of the Welsh Joint Education Committee as well as holding other public offices too numerous to mention.

In addition to his work for schools, Lord Heycock served the University of Wales with distinction for over forty years. He was a member of a number of its senior committees, including Court and Council. He chaired the Estates, Finance, Staffing, Investment and Estimates and Allocations committees at various times. He was awarded an honorary Doctor of Laws by the University in 1963 and took pleasure in being addressed as 'Dr. Heycock'. Further honours were to follow culminating in a life peerage in 1967 as Lord Heycock of Taibach. Typically, he took as his motto 'I always serve my people'.

Professor Bernard Schutz

Bernard Schutz was born (in 1946) and educated in the United States, receiving his PhD in 1972 in California. After a year in Cambridge, he returned to the USA to work in Yale University. He came back to Britain in 1974 as a lecturer in Cardiff, becoming a Professor in 1984.

Even as a teenager, Professor Schutz knew he wanted to learn more about Einstein's theory of relativity, and he feels very fortunate that he has been able to do just that. His research has mainly been in relativity and especially in gravitational waves. He is part of the international collaboration to make the first direct detections of this elusive radiation, and of another one to launch the first space-based detector into orbit around the Sun. Professor Schutz has for many years advised British government agencies that provide money for research in Astronomy, and in 1994 he was appointed Chairman of the Astronomy Committee of the Particle Physics and Astronomy Research Council. This Committee sets the priorities and policy for all research spending in Astronomy and Planetary Science in the UK.

Professor Bernard Schutz

Since the lecture, Professor Schutz has been appointed a Director of the new Max Planck Institute for Gravitational Physics (to be known as the Albert Einstein Institute), which is located in Potsdam in Germany. During the first year of the appointment, he will divide his time equally between Cardiff and Potsdam and will maintain his links with Cardiff for at least a further two years.

In addition to his work at the University in Cardiff and in Potsdam, Professor Schutz frequently gives talks on Astronomy at venues ranging from local astronomical societies to international conferences. His work has taken him to all the continents of the globe. He warmly recommends science in general and Astronomy in particular for an interesting and challenging career.

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A GUIDED TOUR OF THE UNIVERSE[1]

Astronomy in Wales

It is a particular pleasure and honour for me to have been invited to give the first Lord Heycock Memorial Lecture. Lord Heycock was a great friend of education, at all levels, and in all subjects. My wife, who now teaches music at Lewis Girls' School, has often told me about his support for music and in particular for the youth orchestras of South Wales. One subject on which I have no record of his interest is astronomy. It would not surprise me to learn that he paid little attention to astronomy, because astronomy in Wales in the 1950's and 1960's was not a subject that seemed to excite much notice. But this was not always the case.

Wales has in fact a remarkably distinguished history in Astronomy. As early as 1609, in the *same year* that Galileo first observed the heavens through a telescope, two scientists in Wales were also looking through a telescope that had been made by the same Dutch lens grinder who made Galileo's! The pair, Sir William Lower and his friend John Prydderch, made many

[1] *This is an abridged version of the lecture delivered at the Reardon Smith Lecture Theatre, Cardiff, on 28 September 1994.*

observations near Treventy, in Carmarthen, and in 1610 Lower recorded his reaction to seeing the Moon through the telescope (which he called his "cylinder"):

> *According as you wished I have observed the moone in all his changes. ... In the full she appears like a tart that my cooke made me last weeke; here a vaine of bright stuffe, and there of darke, and so confusedlie all over. I must confesse I can see none of this without my cylinder*[2].

The fact that Welshmen were participating in one of the most profound revolutions in scientific thought is something that ought to be taught to all science pupils in Wales, but it is almost unknown. I only learned of it when Rhiannon Williams, a work-experience student who came to me from Llanharry Comprehensive School, did some research for me in some Welsh-language sources.

There were a number of other distinguished Welsh astronomers, but there is one whom I must mention. In the late 1800's, Isaac Roberts was the first to perfect astronomical photography. The use of

Isaac Roberts: a pioneer of astronomical photography

[2] *Seryddiaeth a Seryddwyr,* J S Evans (Wrexham, 1923).

photography truly unlocked the secrets of the Universe, for astronomers could now record the images of objects much too faint to be seen with the eye, just by holding open the shutter of the camera for as long as necessary. Roberts' work was probably the most important technological advance in astronomy since the invention of the telescope itself. He was showered with honours, including the Gold Medal of the Royal Astronomical Society in 1895. Yet he is largely forgotten in Wales. Who ever learns about Isaac Roberts?

Today astronomy flourishes again in Wales. Amateur societies abound. The Cardiff Amateur Astronomical Society is one of the largest in Britain. And the University of Wales is very strong in astronomical research. In Cardiff we have one of Britain's largest and most active astronomy research groups. Swansea, theoretical particle physicists study the physics of the Big Bang. And in Aberystwyth, scientists study the way the Sun affects the upper atmosphere of the Earth, leading to auroras, magnetic storms, and other phenomena. Each of these research groups is a world leader in its speciality. Because I am most familiar with the work going on in Cardiff, I will draw on it for some examples later in the lecture.

The science of astronomy

Astronomy is, of course, a science. Like every science, it is a combination of two activities:

Exploration and Explanation.

By and large, scientists love solving problems. They like being able to explore something new, and they get great satisfaction from being able to plain why something happened. Every explanation usually opens up new questions that need further exploration, and further explanation. You will find this pattern – exploring, explaining, exploring some more – in all the sciences. In my youth I had certain prejudices against some branches of science. I loved physics and mathematics, for example, but I didn't much care for chemistry. Now at my advanced age, I have learned that whatever branch of science I have studied has turned out to be fascinating; really, all sciences are interesting, because they all share this problem-solving approach: *first explore, then explain.*

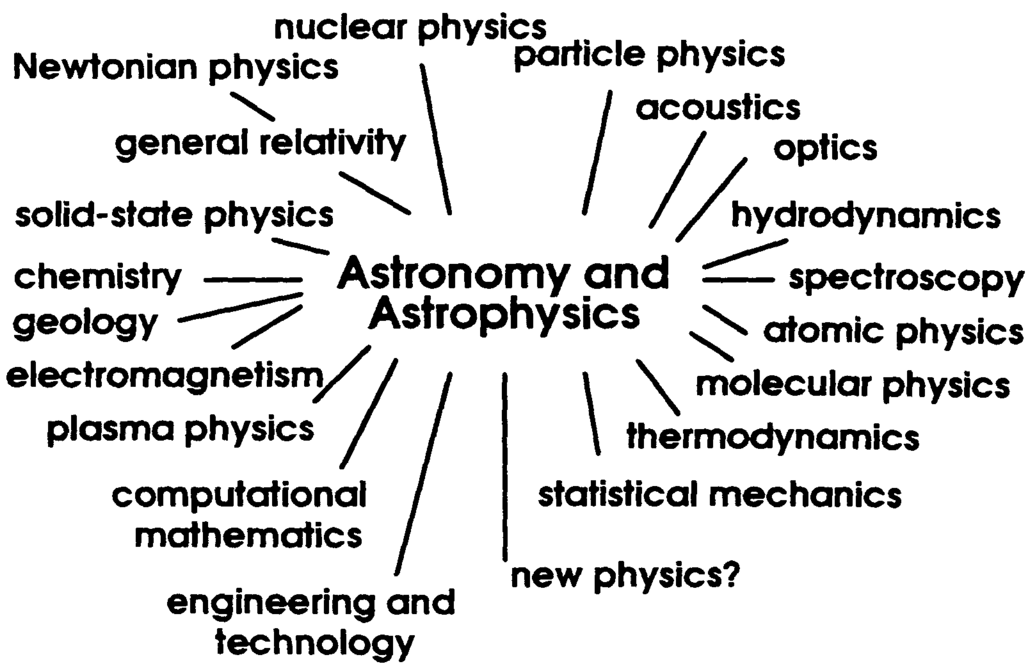
My favourite science, though, is still astronomy. Its special fascination is that it is the science of *everything*.

- Astronomy studies everything except things that happen on that tiny speck of cosmic dust we all call Earth. The Universe is so complicated and has so much variety, that astronomers never run out of new discoveries, new things to explore and explain.

- Astronomy involves *all* the physical sciences. The stars and galaxies that fill the Universe are not choosy about what sorts of science they use to make themselves work. All the branches of physics, chemistry, and geology play a role somewhere in the Universe. Probably the most remarkable fact of all about the Universe is that we can understand it by using only the laws of physics and chemistry that we have discovered with experiments on the Earth. The laws of Nature seem to be just the same *everywhere*.

- Astronomy uses all kinds of observing instruments. There is room in astronomy for people who consider themselves to be radio engineers, television technologists, X-ray specialists, and even – as I will explain later – gravitational wave hunters. Astronomy needs all this variety of information, because each different kind of radiation tells us a different

Astronomy is a Synthesis of Many Fields of Science



piece of the astronomy story. Look at the night sky with your eyes, and you see a picture dominated by relatively nearby stars, collected into a band of stars we call the Milky Way. But if you "look" at the same sky with a radio telescope sensitive to microwaves, you will see the Big Bang, or more specifically a sea of radiation coming at us in all directions, left over from the earliest moments of the Universe. When the COBE satellite detected small irregularities in this microwave radiation, it was such an important scientific event that the major newspapers put it on their front pages.

A tour of the Universe

Let us orient ourselves in this vast Universe. I have assembled a collection of photographs and video sequences that take us out from the Earth to the realm of the galaxies. We leave the Earth, passing the Moon, and head for the Sun. Along the way we pass the mysterious planet Venus, whose surface has now been mapped by the Magellan spacecraft. Venus is similar to the Earth in size and distance from the Sun, and yet it has developed into a very hostile environment. Venus suggests to us that our own existence on the Earth is by no means guaranteed: small changes could wipe us out entirely. After Venus we meet Mercury, a rocky planet that looks like the Moon. And then: the Sun.

There and back again: the star-struck audience guided through the solar system by Professor Schutz

Source of all our energy, the Sun is nevertheless one of the most hostile places one can imagine. X-ray photographs show what a turbulent and dangerous a place it is.

After passing the Sun, we head out into the outer solar system. We pass Mars, a place that probably has no life now, but may have had life earlier: again a lesson on the fragility of our own existence. After Mars, we pass through the asteroid belt, full of pieces of a planet that never was. We reach Jupiter, with its giant spot, its many moons, and its massive girth. Next comes Saturn, whose rings are particles of dust that are shepherded into bands by tiny moons orbiting the planet. And then Uranus, a featureless planet whose rings were only discovered recently. We finally reach Neptune, and then our smallest planet, Pluto, with its moon Charon.

We leave the solar system behind and go out through the Milky Way. One of the most fascinating places is the Orion Nebula, a nursery where stars are being formed by giant clouds of gas. Once through the Milky Way, we head toward our nearest large galaxy, the great galaxy in Andromeda. It looks much like our own does, as if we were seeing the Milky Way from far away. As we approach it, we see more and more detail in its centre. When we finally get near enough, we get a big surprise: it has two centres! The very core of the galaxy is concentrated into two bright regions, each containing millions of stars.

After we pass through the Andromeda galaxy, we head out to look at the Universe as a whole. We see other galaxies, clusters of galaxies, and further surprises. For example, galaxies do not seem to be scattered around the Universe randomly. Rather, they group together into long chains and wide sheets. When we survey the Universe we see a sponge-like arrangement of galaxies, with giant "holes" where there are few or no galaxies, and other regions where galaxies abound. Astronomers have no explanation for this yet, but it must be a clue to the conditions in the very early Universe, when galaxies were first forming, soon after the Big Bang. This is one of the areas of astronomy which are the most active in research, because it is so fundamental.

I have been able to give you only a short glimpse of the great deal of information that we now have about the Universe, but even this information is incomplete. Every day new discoveries are made, and some of them will inevitably change some very basic ideas that we have about our Universe. It is the excitement of continual discovery that keeps Astronomy so interesting to work in.

Astronomical discovery

Astronomers, like all scientists, love to make discoveries. At Cardiff our observational astronomers - the ones who use telescopes - mostly use observatories or satellites that are open for use by all British astronomers, and which have been paid for by some of the money that the British government allocates to astronomical research every year. Modern telescopes are very expensive and sophisticated, and satellite observatories are even more so. Satellites are necessary because they allow astronomers to observe certain kinds of radiation, particularly X-rays, that are absorbed by the atmosphere before they reach the ground. The most famous satellite observatory, the Hubble Space Telescope, observes light that can also be seen from the ground, but it gets much sharper images than one can get from the ground, because the atmosphere smears out the images. (This is what makes stars twinkle when we look at them with the naked eye.) Among the UK telescopes we use are the ones on the island of La Palma, in the Canary Islands. The largest telescope there, named after the great British astronomer William Herschel, is one of the most powerful in the world.

Cardiff astronomers have built their own camera, called Hitchhiker, that uses the William Herschel Telescope in a unique way. It captures the parts of the image that the astronomer who is using the telescope at the time does not want: he or she may be taking a picture of a particular star or galaxy and may not want the rest of the field of view. Hitchhiker records the rest of the data and astronomers here in Cardiff search through it for random discoveries. They are particularly interested in faint galaxies, which tell us much about the way galaxies formed and what they are made of. Since they are trying to make discoveries, they don't mind having an essentially random selection of images: a faint galaxy might turn up anywhere.

Astronomers in Cardiff have other ways of working, and of making discoveries. One way is to use computers. Computers can simulate real astronomical situations and allow us to experiment with them in a way that we can't do with the real thing. We also use computers to process the astronomical pictures we take and to display in picture form the results of our simulations. And of course we use the computers as word processors: we write our scientific papers on our computers.

Some of the most important discoveries that our computers have helped us to make recently are in the question of how stars form. We know that stars form all over our galaxy, that they shine for a certain amount of time (from about a million years to several billion), and that they eventually die out, either quietly or in a big supernova explosion. The formation of stars is particularly hard to understand, because it usually takes place inside opaque clouds of gas and dust - yes, dust: the Galaxy is full of tiny solid particles, just like soot from a fire, and clouds of them can get so thick that one can't see through them. On top of that, the formation of a star can take millions of years, so we can't exactly watch it happening before our eyes! Instead, we see one stage of the process in one place, another stage in another, and so on. But we don't know which of the stages we see actually comes first! Computers get around this problem. If we can condense the millions of years into a few seconds of simulated star formation on a computer, then we can interpret what we see in photographs more reliably. Cardiff astronomers specialise in the simulation of star formation, and have some of the most important results in that area obtained so far anywhere in the world.

We also use similar programs to explore galaxy formation. Galaxies are thought to have condensed out of large clouds of gas in the early Universe. By simulating their formation, we expect to learn what to look for in pictures taken by the Hubble Space Telescope and other telescopes when they search for early signs of galaxy formation.

Gravitational lensing

Sometimes astronomers make discoveries that they should have expected to make but didn't. An example is gravitational lensing. Albert Einstein predicted that light would not travel in a straight line when it passes a star, but instead be slightly drawn to the star, following a slightly bent path. Indeed, it was the confirmation of this effect during the solar eclipse of 1919 that led to Einstein's enormous fame. Now, the bending of light is just what a lens does, so gravity can act as a lens, a *gravitational lens*.

Although astronomers were aware of this, they did not systematically look for evidence for gravitational lenses until one was discovered by accident in observations with radio telescopes at Jodrell Bank. What they saw was two images of the same quasar. A quasar is a distant galaxy that emits so much visible light and radio radiation that it can be as bright as a nearby star. Many large galaxies seem to have gone through a phase early in their histories where they were quasars. We think quasars are powered by giant black holes in the centres of their galaxies. One of the interests in understanding galaxy formation is to try to understand how black holes formed there and how they made quasars.

Now, quasars are so far away that we can't see their structure. We see them only as point-like sources of light. In radio pictures, on the other hand, they do exhibit extended structure, often caused by long jets of gas that seem to be expelled from the central regions in a thin cone. Radio astronomers sometimes see two nearby quasars with almost identical pictures. From this and other evidence (especially by matching the spectra of the two quasars) it is possible to be sure that the two images are really pictures of the *same* quasar, and that the "double vision" is caused by a gravitational lens. Invariably in such cases, we find that there is a large galaxy or a cluster of galaxies between us and the quasar, providing the gravitational field that makes the lens.

Gravitational lenses have many remarkable properties. The images they make can be sharp and point-like, or they can curve like arcs around the lens. They can be magnified or reduced in brightness. And there is a theorem that there is always an odd number of images, although in many observations one is either too faint or too close to a lensing galaxy to be seen. Most remarkably, if there are, say, five images[3], then two of them are actually mirror images, with left and right in the image reversed!

By making detailed studies of gravitational lenses and trying to understand the details of the gravitational field created by the intervening galaxies, astronomers hope to measure the distance to the distant quasars. They would do this by monitoring brightness changes in the quasar images. All quasars are variable in time, and so all the images of a quasar will vary in an identical way, with one exception: since the light forming one image may have to travel a greater distance through the lens than the light forming another image, the variations in the images will not take place at the same time. The delay between images can provide crucial information that allows us to determine just how far away they are, and this in turn tells us the overall size of the Universe and its age, the time since the Big Bang. With such scientific rewards in prospect, it is no wonder that astronomers around the world are searching for new examples of gravitational lensing.

Gravitational waves

Let me now describe to you my own research, which is full of the promise of discovery. My international collaborators, my group here, and I plan to build giant detectors for gravitational waves. Gravitational waves are tiny disturbances in gravity that move through space at the speed of light. They are produced by momentous events, such as supernova explosions and the

[3] As in the Einstein Cross shown on the front cover of this publication.

collisions of black holes. By observing them we expect to detect black holes directly for the first time.

There is a simple way to understand gravitational waves. Gravity is produced by anything that has mass, so in particular it is produced by stars. The strength of gravity produced by a distant star depends on how far away the star is. Now, if two stars are in orbit around one another, the gravity produced by the pair will depend on exactly where they are in their orbits: if one star is slightly nearer to us than the other, the force of gravity from the pair will point a little more towards that one. Then the situation will change, and gravity will change its direction slightly. These changes are minuscule, since the pair of stars is so far away. But it is nevertheless something that can in principle be measured. But why is it called a *wave*? The reason is that Einstein showed that no influences can travel faster than light. Thus, when the stars in the binary pair move, their gravitational influence on the Earth will not be felt instantly, but rather after a delay equal to the time it takes light

A drawing of the first LIGO gravitational wave detector, which is now under construction in the State of Washington, USA.

to travel from the star to us. This is just the same as water waves in a bath: if you disturb the surface of the water, it ripples outwards because the surface tension forces cannot transmit the change in the level of the water instantly across the bath. This takes time, so the disturbance spreads outwards in a wave. So it is with gravity: small changes spread outwards in a wave of gravitational variations.

Gravitational wave detectors are designed to respond to even the tiny changes in a distant gravitational field. Here is how they work. There are 2 detectors being built in the USA, in a project called LIGO. They will be 4 km in length. They will house an *interferometer,* which is a delicate machine for measuring changes in length. It will consist of two perpendicular "arms", whose ends are defined by big mirrors hanging on threads. The hanging mirrors are free to swing in the horizontal plane, so when a gravitational wave passes through, the changing gravity will generally change the length of one arm more than it changes the length of the other. Using powerful laser light bouncing between the mirrors, the interferometer can measure such changes to the incredible accuracy of one part in 10^{22}!! That means that the amount by which one arm might change its 4-km length would be less than 1% of the size of a proton. That this is measurable at all is an indication of how hard scientists have worked to develop this technology.

The technology will be expensive, however. This is principally because the laser light in the "arms" needs to run in vacuum; small pressure fluctuations in any air inside the system might disturb the light beams. Such a detector will be a huge vacuum chamber, the largest ever constructed. And one of the most expensive: the Americans expect to pay about £150 million in total for their two detectors.

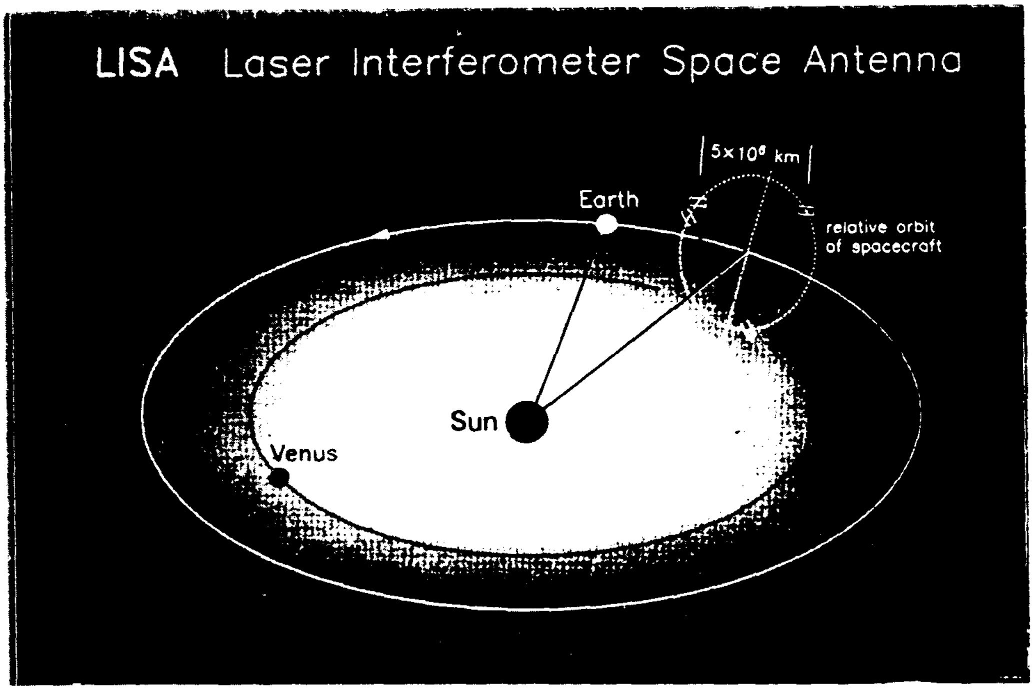
A similar detector with size of 3 km is also planned for Italy, in a collaboration between France and Italy, called VIRGO. Britain and Germany once had plans for a similar joint detector (GEO), but financial constraints in both countries forced those plans to be shelved, and scientists in those countries, including my group in Cardiff, are planning a more modest 600 m instrument based on the very highest technology (GEO600).

The world of astronomy can therefore look forward to a network of at least 3 and possibly more highly sensitive detectors that should operate by the turn of the century. This is not needless duplication. Gravitational wave signals are very weak, and we need the confidence that they have been detected by at least 2 detectors independently before we will believe a detection. Moreover, detectors are not telescopes; they cannot point in only one direction. Gravitational waves from almost all directions excite them. Only by recording the differences in arrival time of a wave at different detectors can one triangulate the direction of the wave. This requires at least 3 and preferably 4 detectors.

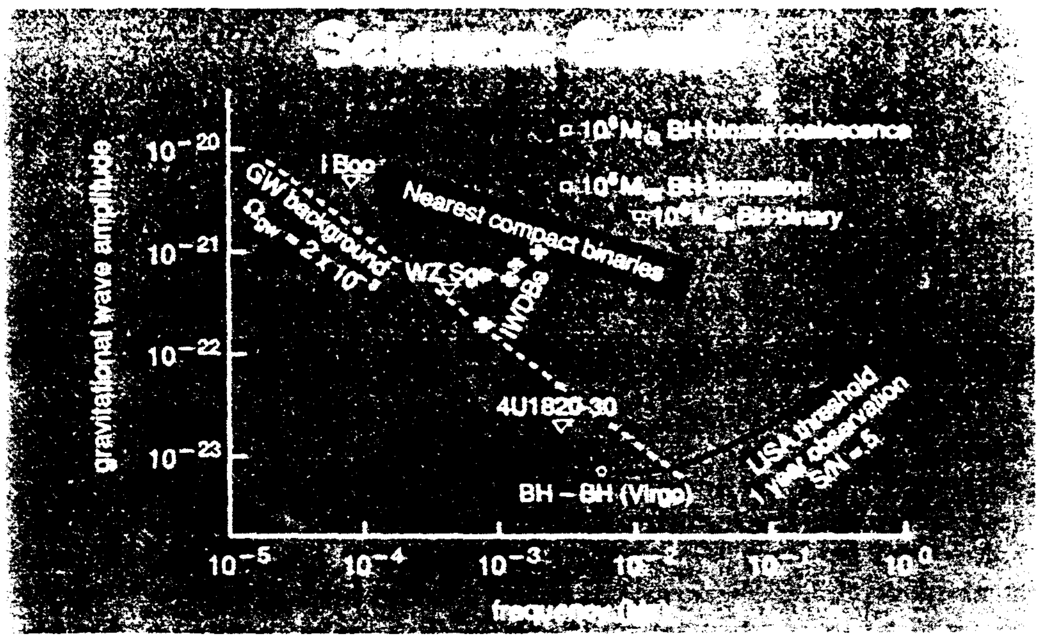
I have mentioned the weakness of the effect we are looking for. How could we possibly expect to see this against a background of mechanical vibrations, such as those caused by thermal effects, and so on? The is key pattern matching. Think of how the ear hears pure notes. It can hear the tiny sound of an oboe playing against a background of notes from an entire orchestra. It can hear the ringing of a telephone against the background noise of people talking in a crowded room. This is because it is specially designed to be sensitive to pure notes. Similarly, the eye is good at picking out straight lines in pictures, but not good at telling whether a curve is exactly an ellipse or not. The eye and brain have special circuits designed to respond to straight-line patterns. Scientists understand now how to teach computers to do the same thing, for any desired pattern. A computer could be taught to pick out ellipses in pictures. It could be taught to recognise pure notes. (In fact we have one in my department that does just that.) Similarly, we can teach a computer to look for exactly the pattern we expect from a gravitational wave when it reaches our detectors. This is what we specialise in at Cardiff: my group is the only one in the world which studies the astrophysics of possible sources of gravitational waves, calculates the wave patterns we expect to receive, and designs computer programs to look for them. Because our work is applicable to all detectors, we collaborate with all the groups around the world. In the British-German GEO600 project, we will be the principal site for data analysis.

A space project for gravitational waves

Proposals for gravitational wave detectors are getting ever more ambitious. Currently there is a proposal before the European Space Agency (ESA) to launch a detector into orbit around the Sun. This is called the Laser Interferometer Space Antenna (LISA) and it would be a giant version of the interferometers I have described. Its "arms" would be millions of kilometres in length, but fortunately outer space provides the vacuum, so we do not need solid pipes that length! The reason for going into space is to get away from the noisy Earth. No matter how well we isolate our detectors from vibrations on Earth, there are some disturbances we can't escape. For example,



The LISA detector's orbit around the Sun



The likely sources of gravitational waves that LISA could see are plotted here, against the sensitivity limit (solid curve)

The University of Wales

Founded in 1893, the University of Wales is now second in size only to London in the UK. Well over 30,000 students are studying in almost every subject in its six constituent institutions, Aberystwyth, Bangor, Cardiff, Swansea, Lampeter and the College of Medicine in Cardiff. The various campuses occupy some of the most beautiful locations in Britain and maintain a friendly, accessible atmosphere. If you would like any further information about any of the Constituent Institutions, please get in touch direct with the institution concerned. Their addresses are as follows:

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