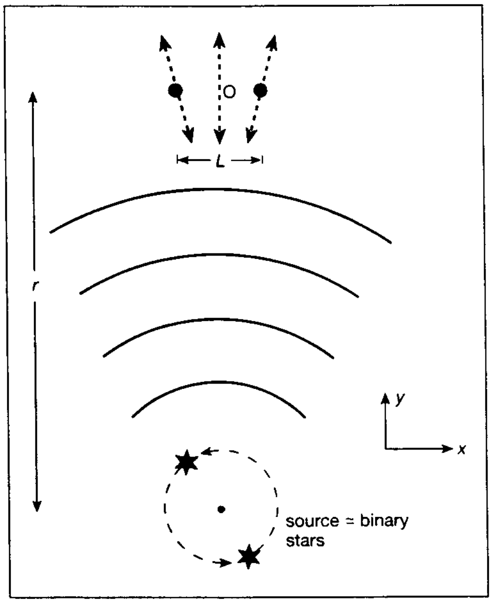
Gravitational waves are generated by the most catastrophic and powerful events in the universe. Such waves could tell us about black holes, supernovae explosions and the big bang – but only if we can detect them

Gravitational physics

GERHARD SCHÄFER AND BERNARD SCHUTZ

GRAVITY is truly universal. It is the force that pulls us to the Earth, that keeps the planets and moons in their orbits, and that causes the tides on the Earth to ebb and flow. It even keeps the Sun shining. Yet on a laboratory scale gravity is extremely weak. The Coulomb force between two protons is 10^{39} times stronger than the gravitational force between them. Moreover, Newton's gravitational constant is the least accurately known of the fundamental constants: it has been measured to 1 part in 10^4, while Planck's constant, which characterizes quantum mechanics, is known to within 1 part in 10^6.



1 A source, in this case a binary star system, emits gravitational waves that affect the positions of two test particles (blue dots) and an observer between them (O). The waves essentially carry the Newtonian gravity field of the source delayed by the travel time of the waves. The force on the particles varies because the field is proportional to $1/r^2$: the force is less when the two stars lie in the x-direction and greater when they lie in the y-direction. The particles thus oscillate about a mean position. However, the observer also experiences this oscillating acceleration. Therefore the change in distance between the observer and the particles is very small and can only be observed in the x-direction.

Gravity only dominates on an astronomical scale – large bodies are usually electrically neutral, and the strong and weak interactions are only important over short distances. Gravity, however, grows with the size of the body. Gravitational forces therefore determine the structure of bodies that are the size of the Moon and larger – such bodies are round because gravity pulls with equal strength in all directions. Astronomy is thus the laboratory for gravitational physics.

Newton developed his theory of gravity in the late 17th century and it is reasonably accurate within our solar system. In 1916 Einstein replaced it with general relativity to make gravitation theory compatible with special relativity. In Newtonian gravity, changes in a gravitational field – caused, for example, by moving stars – are felt instantly everywhere in the universe. This is not allowed in special relativity because no influence can travel faster than light. By crafting a relativistic theory of gravity, Einstein created a gravitational revolution that has had profound consequences for physics.

Perhaps the most basic of these is that changes in a gravitational field must propagate with the speed of light – in other words, any change in the field generates gravitational waves. Less expected, but equally important, is that gravity can create more gravity, an effect that can become so strong that space itself curves up and traps matter inside black holes.

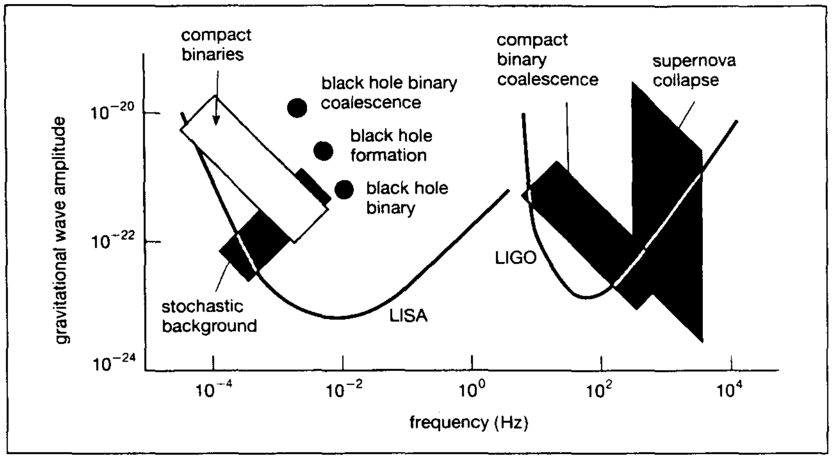
Black holes have had a major impact on our understanding of astronomy in the last 25 years. Massive black holes have been found at the centre of almost every galaxy that has been studied in detail. Black holes are also thought to generate the relativistic jets of gas that power quasars and giant radio galaxies. Smaller black holes are also at the centre of some of the most powerful X-ray sources in our galaxy. In the next 25 years, gravitational waves promise to have an equally profound impact on astronomy.

Black holes and neutron stars

A simple indication of whether the gravitational field in a system needs to be described relativistically is the "escape velocity" of the system. For a spherical body of mass M and radius R, the escape velocity is $v_{esc} = (2GM/R)^{1/2}$. Gravity in the system is relativistic if this speed is comparable to the speed of light; the key ratio is $\phi = v_{esc}^2/c^2 = GM/Rc^2$. Alternatively, ϕ can be thought of as the ratio of the gravitational potential energy of a particle in the system, GmM/R, to its rest mass energy, mc^2, where m is the mass of the particle.

Gravity therefore becomes relativistic when ϕ is close to 1. (It never gets much larger than 1 because the body then forms a black hole.) For the Sun's gravity in the solar system, ϕ never exceeds 10^{-5}. But ϕ approaches unity as R decreases or M gets bigger. Cosmology is a case where mass dominates: as we go further into the universe, M

increases as R^3, so ϕ is proportional to R^2. On the other hand, neutron stars and black holes compress the mass of a normal star inside a very small radius. These objects are at the heart of some of the most impressive phenomena in the universe: quasars, radio galaxies, pulsars, supernovae, gamma-ray bursts and many intense X-ray sources. Black holes and neutron stars also radiate gravitational waves.



2 The sensitivity of interferometers based on the ground and in space. Ground-based detectors can measure gravitational waves of frequencies between 1 Hz and 1 kHz, which are generated by the coalescence of binaries and by supernova explosions. Only a space-based detector such as LISA will be able to detect the low-frequency waves produced by binary systems, the formation of black holes and the big bang.

A black hole can be thought of as a star where the escape velocity equals the speed of light – it appears black because even light is trapped inside the star. The edge of the hole, $R = 2GM/c^2$, is called the event horizon, where R is about 3 km for a black hole with the same mass as the Sun. Anything that falls within the event horizon cannot return.

Michell and Laplace first recognized the special nature of these objects in the 18th century, and in 1917 Karl Schwarzschild theoretically discovered the fully relativistic black hole. However, it was not until the 1960s that John Wheeler of Princeton University coined the name "black hole".

Wheeler also proposed the so-called no-hair theorem, which holds that stable black holes are uniquely described by their mass, angular momentum and electric charge. (In this respect black holes resemble elementary particles. Rotating black holes even have the same ratio of magnetic moment to angular momentum as electrons.) The smooth surface of a black hole also hides any evidence for the number of baryons and leptons that have fallen into it. Gravity therefore violates the conservation laws for baryon and lepton number that are central to the standard model of particle physics. There is also a singularity inside the horizon, where both the density and the gravitational field tend to infinity. A full quantum theory of gravity will be needed to show what happens here, although many speculations have already been made.

The horizon turns a black hole into a perfect black body that absorbs all of the radiation that falls into it. Stephen Hawking of Cambridge University in the UK has shown that a black hole behaves as a thermodynamic object that has entropy and that emits black-body radiation at a specific temperature. Black holes have other macroscopic properties – for example, they have an effective electrical resistivity of 377 Ω when they interact with external electromagnetic fields.

Black holes are formed when gravity overwhelms the internal pressure in a star or gas cloud, causing it to collapse. The object's radius decreases during the collapse, causing ϕ to increase. If gravity becomes weakly relativistic ($\phi > 0.001$), the collapse cannot stop unless the total mass is less than about $2M_\odot$, where $M_\odot$ is the mass of the Sun. Below this mass, nuclear forces can halt the collapse once ϕ has reached about 0.4. This creates a neutron star with a density similar to that of a normal atomic nucleus. The matter in a neutron star is so compressed that the electrons combine with protons to form neutrons. Neutron stars are essentially macroscopic nuclei held together by gravity.

Fritz Zwicky and Walter Baade predicted the existence of neutron stars in 1933, shortly after Chadwick discovered the neutron. But observational evidence only came in 1967, when Jocelyn Bell and Anthony Hewish of Cambridge University discovered pulsars – spinning neutron stars with strong magnetic fields. Pulsars emit radio waves and other radiation in beams that sweep across the sky like beams from a lighthouse, and so regular pulses of radiation are observed on Earth. Most pulsars rotate a few times per second, although some spin over 600 times per second. Such speeds are only possible because the objects are held together by ultrastrong gravitational fields.

Neutron stars are often formed in supernova explosions, which happen when a massive star has exhausted its nuclear fuel. The core of the star undergoes gravitational collapse and the energy that is released blows off the outer parts of the star, leaving a neutron star. Striking confirmation of this process came in 1987 with the detection of neutrinos from a supernova in the Large Magellanic Cloud. These neutrinos had energies of about 10 MeV, and were exactly like the neutrinos expected from a hot, newly formed neutron star. However, we still have no direct evidence for a neutron star in this supernova.

Convincing evidence for black holes has also had to wait until recent years. In the 1970s astronomers discovered that certain strong X-ray sources are binary systems: an ordinary star dumps matter onto a companion that is so compact that the gas falling onto it releases huge amounts of energy, including X-rays. Since the energy released must come from gravitational potential energy, the compact object must have $\phi \geq 0.1$ and must be either a neutron star or a black hole. Most systems known today contain neutron stars, but some – such as Cygnus X-1 – contain compact objects with a mass greater than $7M_\odot$ and in some cases $15M_\odot$. These must be black holes.

These findings were not too surprising, but in the 1970s evidence began to grow for the existence of million solar-mass black holes. The stars at the centres of many galaxies have such high random velocities that they can only be held there by concentrations of enormous mass in regions that are so compact that they must be black holes. Masses ranging from $10^6 M_\odot$ to $10^9 M_\odot$ have now been observed in almost every galaxy that has been studied at sufficient resolution to see the stars at its centre: the Andromeda galaxy (M31), its dwarf companion (M32), M87, NGC3115, NGC4258 (or M106), and even the Milky Way (see p20). Such supermassive holes probably form at the same time as the galaxies. At first they appear as quasars and other kinds of active galactic centres, but after a few billion years they seem to settle down and become quieter.

Quasars are the brightest objects in the universe and could be powered by black holes. General relativity predicts that rotating masses and black holes produce swirls in the gravitational field, an effect called gravitomagnetism that was first proposed by Lense and Thirring in 1918. In 1977 Roger Blandford and Roman Znajek, then at Cambridge, predicted that magnetic fields threaded through these swirls could accelerate charged particles. Such an effect could power quasars and galactic nuclei, producing huge jets of relativistic particles that can extend millions of light-years from the central galaxy.

Quasars have also demonstrated gravitational "lensing", another prediction of general relativity (see *Physics World* May 1993 pp26–30). In 1979 Dennis Walsh, Robert Carswell and Ray Weymann used observations made with the Jodrell Bank radio telescopes in the UK to show that the "double quasar" 0957+561 is really two images of the same quasar. Many other examples of gravitational lenses are now known, and this effect is being used to study the distribution of mass in the universe and its expansion rate.

Gravitational waves and their sources

Gravitational waves are excitations of a gravitational field. In general relativity the gravitational field is identified with the curvature of space–time, so gravitational waves can also be thought of as ripples in space–time. Gravitational waves travel at the speed of light and are transversally polarized with two polarization states, just like electromagnetic waves, although the polarizations cannot be described by a single direction.

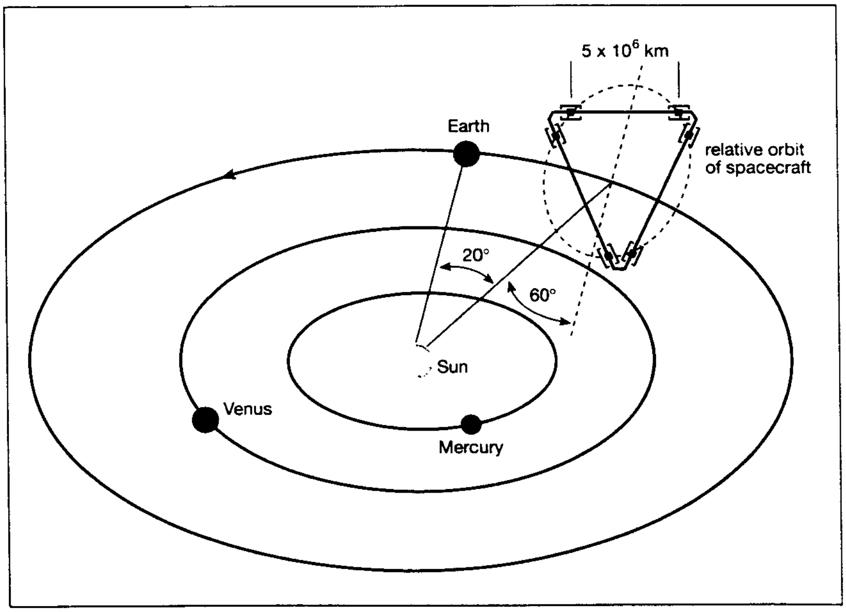
There is a fundamental difficulty in detecting gravitational waves. The equivalence principle states that all particles fall at the same rate in a uniform gravitational field, so the field of a passing wave will affect all parts of an experimental apparatus in the same way. This means that only the non-uniform part of a wave's gravitational field can be measured directly, and this is achieved by measuring the difference in gravitational acceleration across the apparatus. Making the detector larger increases the measured difference and enhances the effect of a passing gravitational wave.

The strength of a gravitational wave is described by the size of the acceleration gradient it produces. Imagine the effect of a gravitational wave on two free particles that are separated by a distance L along a line perpendicular to the direction of the source of the wave (figure 1). The source is far enough away that the wave is essentially a plane wave when it reaches the particles. The wave can move the particles closer together or further apart, but cannot move one particle past the other. Thus the maximum effect a wave can have is to change the particles' separation by L. If the observed change in separation is δL, then the amplitude of the wave is $h = \delta L/L$.

The gravitational waves that we expect on Earth are very weak. An observer located at a distance r from a source of gravitational waves with mass M and typical radius R will see a wave with $h \sim \varepsilon(GM/Rc^2)(GM/rc^2)$, where ε is a dimensionless number. For example, a neutron-star binary system in the Virgo cluster – about 50 million light-years away – with an orbit of radius 50 km and a total mass of $3M_\odot$ would produce wave amplitudes of about 10^{-21}. Such a wave will only move the particles in a detector 4 km long by 4×10^{-18} m, about 1% of the diameter of a proton. And if this movement takes place at the expected frequency of 1 kHz, the relative acceleration of the ends of the detector will only be $4 \times 10^{-15}g$, where g is the acceleration due to gravity on the Earth's surface.

Although these effects are tiny, a periodic source emits gravitational waves with a typical power of $(c^5/G)\varepsilon^2\phi^5$. This power is immense – if an object emitted more power than about $c^5/G = 3.6 \times 10^{52}$ W, it would have so much energy in a given volume that it would collapse into a black hole and not emit anything. This huge intrinsic power means that gravitational waves carry the imprint of the most catastrophic events in astronomy, and that they can propagate through space almost undisturbed. This makes them a valuable source of information, provided that they can be detected (figure 2).

Supernovae and binary systems could be the most important sources of detectable gravitational waves. A supernova emits gravitational waves when the collapse of the central core reaches neutron-star densities and the outer parts are blown off, as long as this so-called "bounce" happens asymmetrically. Such gravitational waves would shed light on the dynamics in the core near the point of maximum density. Numerical simulations of axisymmetric collapse processes (i.e. those with rotational symmetry about some axis) have been done in recent years (see *Physics World* July pp43–48). These have produced wave bursts with a frequency range of 100–1000 Hz – essentially because the bounce takes 1–10 ms – and amplitudes of up to 10^{-23} for a source about 50 million light-years away. Simulations of asymmetric collapse with strong rotation will be possible with the next generation of supercomputers, and these models could predict the production of much more radiation.



3 The planned LISA detector will be a space-based interferometer that has three arms to extract two independent gravitational signals. The baseline is five times the Sun's diameter, about 5×10^6 km, and the orbit of the instrument is shown by the dashed lines. LISA will be able to observe waves at mHz frequencies and is due to be launched in 2015.

Binaries consisting of neutron stars and/or black holes lose their orbital energy as gravitational waves before they eventually spiral together and coalesce. The frequency of the waves is twice the orbital frequency of the binary, which gradually increases as the orbit decays. Most detectors start to measure these waves once their frequency is above 10 Hz. By the time the stars coalesce, the frequency is about 1 kHz for neutron stars and a few hundred Hz for the more massive black holes.

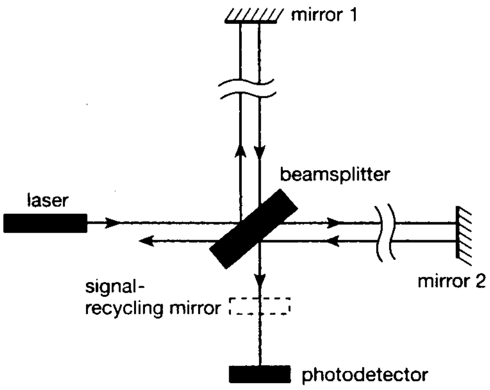
Coalescing binaries happen very rarely – about 10^{-4} times less frequently than supernovae, which occur about once per galaxy per 50 years – but the signal can be detected from a great distance. Indeed, the predicted detection rate of at least one per year is higher than that for supernovae.

Gravitational waves of frequencies between 10^{-4} and 10^{-1} Hz should be picked up by the most sensitive space-based detectors. Many types of binary systems in our galaxy radiate at these frequencies, as will the most spectacular event we expect to see in the universe: the merging of two supermassive black holes in the centre of a very distant galaxy. Rare as such an event may be, a detector in space could see it anywhere in the universe.

Rotating neutron stars could be another important source of gravitational waves. In 1970 the late Subrahmanyan Chandrasekhar of the University of Chicago discovered that gravitational waves emitted by a rotating star can carry away angular momentum so effectively that they amplify themselves, leading to a runaway spin-down of the star. In 1978 John Friedman at the University of Wisconsin at Milwaukee and one of us (BS)

On the lookout for gravitational waves

Albert Michelson invented the interferometer in the 1870s to perform the Michelson–Morley experiment, which showed that the speed of light is the same in all directions. This work laid the experimental foundations of special relativity. Advanced versions of the same instrument are now taking relativity another step forward: these interferometers will be able to detect gravitational waves and will open up an entirely new branch of astronomy.



In an interferometer, light from a coherent source is divided at a beamsplitter and sent down two perpendicular arms (see figure). The light is then reflected back and is again divided by the beamsplitter. One path leads to a photodetector, which measures a coherent superposition of light from both arms. The intensity depends on the relative length of the arms: maximum intensity is measured when they are the same length or differ by a multiple of the wavelength of light, and zero intensity is measured when they differ by an odd number of half-wavelengths. An interferometer can therefore sense changes in the difference in length between the two arms through the change in the intensity at the photodetector.

A gravitational wave can generate such changes – for example, if it is travelling perpendicular to the plane of the interferometer, one arm is stretched and the other is compressed. The expansion/compression oscillates as the wave passes, so the photodetector measures a time-dependent oscillation in the intensity that can be used to measure the strength of the gravitational wave. However, a single detector cannot determine where a wave has come from. This is one reason why such detectors are being built in the US, Europe and Japan.

It has taken decades of development to convert these principles into practical instruments. Even if the arms are 4 km long, the relative change in length between the arms will only be about 4×10^{-18} m, so it is crucial to prevent any disturbance. Ground vibration is eliminated by suspending the mirrors on wires hanging from vibration-absorbing stacks. This mirror "pendulum" typically has a natural period of about 1 s, which prevents ground vibrations above a frequency of about 1 Hz from moving the mirror. The pendulum also allows the mirrors to move freely when a gravitational wave passes through. This effectiveness of this isolation system sets a lower limit on the observing frequency – the first instruments will go down to about 100 Hz and we hope to see 10 Hz in a few years' time.

Detectors must operate in high vacuum, about 10^{-8} Torr, to prevent pressure fluctuations that could affect the speed of light in one part of the instrument. Observations must also be made away from the resonant frequencies in the detector – the natural frequency of the suspension is typically about 1 Hz, and the mirrors have fundamental vibration modes above 10 kHz. But the upper frequency limit for observations is likely to be about 100–200 Hz because of thermal vibrations. These can be minimized by choosing suitable materials and mirror sizes and shapes, but the behaviour of thermal noise as a function of frequency is not yet well understood.

However, an intrinsic source of noise – a quantum effect called photon shot noise – is likely to set the sensitivity limit over most of the observing range. A light intensity of up to a megawatt would be needed for the signal from a gravitational wave to overcome quantum fluctuations, but lasers cannot produce this kind of power continuously. A number of clever tricks have been developed to overcome this problem. For example, the power requirement could be reduced to 20 W by bouncing the light up and down the arms about 500 times, which would accumulate the effect of the wave on the light.

Even better is an idea called power recycling, which was invented in 1983 by Ron Drever at Glasgow University, and independently by Roland Schilling of the Max Planck Institute for Quantum Optics in Munich. This trick basically involves reflecting the light that exits the interferometer

showed that this could affect all neutron stars, no matter how slowly they are rotating. This so-called CFS instability is a gravitational version of the Kelvin–Helmholz instability, which describes how the wind excites waves on the surface of the ocean. This effect could be observed in gravitational waves from neutron stars, particularly those that are accreting mass and angular momentum from a companion in a binary system.

Gravitational waves were also generated in the big bang. These now form a random sea of radiation called the stochastic background that, like the cosmic microwave radiation, carries information about the very early universe. But while the microwave background was created when the universe was about 3×10^5 years old, primordial gravitational waves were generated in the first microsecond after the big bang. Unfortunately, we cannot predict how much of this radiation exists because we do not yet understand the physics of the very early universe. But the detection of these waves would provide fundamental insights into how the forces of nature might unify at high energies.

towards the laser back into the instrument with the same phase as the incoming laser light. This technique reduces the laser power requirement to 0.2 W, and means that detector builders are optimistic about measuring amplitudes of 10^{-21}.

However, astrophysicists want to measure amplitudes of 10^{-22}, which raises the power requirement by about 100. Continuous solid-state Nd–YAG lasers, now being developed, should deliver the extra power. But with this much power in the system other things can go wrong. For example, the beamsplitter could absorb enough light to heat up, which would change its refractive index and destroy the interference effect. This thermal lensing problem could be solved by a technique called signal recycling, which was devised by the late Brian Meers of Glasgow University.

In signal recycling, a partly silvered mirror is placed between the beamsplitter and the photodetector, which creates a cavity for the light beam between the mirrors at the ends of the arms and the extra mirror (see figure). If the light has the right wavelength to fit inside the cavity, it will form a standing wave pattern that becomes stronger with time. Any motion of the mirrors alters the frequency of the light supported by the cavity, so a gravitational wave splits the single-frequency input light into two frequencies that are equal to the laser frequency plus or minus the frequency of the gravitational wave. The aim is to place the mirror such that a standing-wave pattern will form for one of these frequencies.

Signal recycling therefore tunes the detector to a narrow signal bandwidth. The more reflective the mirror is, the narrower the bandwidth and the greater the gain at the selected frequency. The selected frequency can be altered by moving the signal-recycling mirror – this movement is only about 0.004 μm for a detector with 4 km arms, which is quite easy to achieve. Alternatively, a wide bandwidth can be achieved by choosing a mirror with high transmissivity, which can be useful for "cleaning" the beam and removing some of the effects of thermal lensing.

The GEO600 detector will be the first to implement signal recycling. The initial aim is to clean the beam and to produce good sensitivity over a fairly wide bandwidth. But later observations will use a narrow-band mode to look for specific sources, including rotating neutron stars. □

Wave detectors

Many gravitational-wave detectors are now being developed, particularly resonant-mass detectors and laser interferometers on the ground and in space. Waves can also be detected by precisely timing ultrastable pulsars and by tracking the position of interplanetary spacecraft.

Resonant-mass, or cylindrical bar, detectors were first built in the 1960s by Joseph Weber at the University of Maryland, and many groups are now building and improving these detectors. Modern instruments can detect waves with amplitudes down to 10^{-19}, but they are sensitive only to frequencies over a range of about 1 Hz near 1 kHz; at other frequencies they are "blind". New technology is being developed to cool the bars to below 100 mK and to build massive spherical solid detectors, and should allow amplitudes of 10^{-21} to be measured over bandwidths of 100 Hz.

However, the most promising detectors are the interferometers, which measure the effect of a gravitational wave on light travelling in two perpendicular arms (see box). Several prototype interferometers with arm-lengths of tens of metres have been shown to detect waves of amplitude 10^{-19} at bandwidths above 100 Hz, and the very large interferometers needed for realistic detection are now being built. The Laser Interferometer Gravitational-wave Observatory (LIGO) in the US is a pair of 4 km interferometer systems, one in Hanford, Washington and the other in Livingston County, Louisiana; the French–Italian detector VIRGO has 3 km arms and is being built near Pisa in Italy; and the British–German detector GEO600 is a 600 m instrument that is under construction near Hannover in Germany. All of these instruments should be able to detect amplitudes of 10^{-21} over bandwidths of a few hundred Hz by the end of this century, and the sensitivities of the longer instruments could be improved further.

The most ambitious project is the Laser Interferometer Space Antenna (LISA), a space-based laser interferometer that is planned as a cornerstone mission by the European Space Agency. Consisting of free-flying spacecraft that communicate by lasers over distances of a few million kilometres, LISA comes close to the ideal gravitational wave sensor (figure 3). It will be able to detect the gravitational waves from ordinary binaries and from supermassive black-hole systems that have frequencies of 10^{-4}–10^{-1} Hz and amplitudes of as low as 10^{-23}. This is a long-term project that might not be launched until after 2015, but such timescales do not discourage scientists in this field. After all, they have been developing ground-based techniques for the last 35 years and expect to wait another 3–5 years to see the first detection.

Binary pulsars

The motion of astronomical binary systems has been the test bed for gravity from Newton's time. The nearby solar-system binaries — Moon–Earth, Mercury–Sun and others — first helped to establish Newton's laws, and later revealed the anomalous perihelion advance of Mercury.

This was a crucial test of general relativity, which has been tested further by studies of the equivalence principle in the Moon–Earth system, the relativistic precession of the Moon–Earth system, and time dilation effects in the solar system. These tests have all confirmed that general relativity is highly accurate, but they only explored the weak gravitational fields of non-relativistic bodies that move slowly enough for the fields to be independent of time.

The main problem with general relativity is that it is incompatible with quantum mechanics. Tensor-scalar theories of gravity take account of the effects that arise from a quantum theory that unifies gravity with other interactions, but they only deviate from general relativity when the bodies have strong internal gravitational fields.

A means of testing strong, dynamical gravity was provided by the discovery of a binary pulsar in 1974 by Russell Hulse and Joseph Taylor, then at the University of Massachusetts. This pulsar, PSR 1913+16, and its companion are neutron stars with strong internal fields ($\phi \approx 0.2$), and they reach a maximum speed of about 400 km s^{-1} in their highly eccentric $7\frac{1}{4}$ hour orbits. The arrival times of the radio pulses at the Earth vary according to the position of the pulsar in its orbit, and their regularity makes them ideal for tracking the star. The arrival times are influenced by several relativistic effects: the precessional motion of the pulsar's orbit, known as the periastron advance; the variable speed of the pulsar as it moves through the companion's gravitational field, which leads to time dilation and gravitational red shift; and the loss of gravitational waves that causes the orbital period to shrink.

All of these effects can be isolated in the measured arrival times. The first two have been used to determine the orbital parameters and the masses with unprecedented accuracy – the pulsar's mass is 1.4411$M_\odot$ and the companion's mass is 1.3874$M_\odot$. These values can be used in general relativity to predict the change in orbital period, and the prediction agrees with the observed value to within measurement errors, about 0.35%. This is the best test we have of general relativity for strong gravitational fields, and it earned Hulse and Taylor the Nobel Prize for Physics in 1993.

Of the 700 or so pulsars known today, only 44 are in binary systems. Most of these have white dwarf companions, but five appear to be in a binary system with a neutron star. All of these show relativistic effects, and an important binary for general relativity is PSR 1534+12, which was discovered in 1990 by Alexander Wolszczan, then at Cornell University. Although the orbital period is still fairly stable, this system allows an effect that is too small to be observed in the Hulse–Taylor system to be measured. This Shapiro time-delay is caused when the radio signals from the pulsar pass so close to the companion that gravitational lensing introduces an extra delay into their arrival times. This independent strong-field test of gravitation theory is not dynamical, but it agrees with general relativity to within 1.5%.

Binary pulsars with white-dwarf companions also play an important role in testing gravity theories. For example, tensor-scalar theories predict that the binary system of PSR 0655+64 should radiate dipolar scalar waves and that other binaries should experience dipolar forces in the direction of the galactic centre. This would be a violation of the equivalence principle that would effectively polarize the orbits. None of these effects have been detected so far, which constrains possible scalar gravitational fields.

Apart from binary pulsars, spacecraft and artificial satellites are useful tools for testing gravity theories. The first such test was in 1976, when a Scout rocket took a maser clock to an altitude of 10 000 km. Robert Vessot and collaborators from Harvard University compared the rate of the clock with that of an identical clock on Earth, and measured the gravitational red shift to a precision of 0.02%. The test is now known as the Gravity Probe A experiment.

Gravity Probe B, also known as the Relativity Gyroscope Experiment, is now being built at Stanford University by a team led by Francis Everitt, and it is due to be launched in 1999. This probe will provide the first direct observation of gravitomagnetism – the eddies in a gravitational field generated by rotating masses – by measuring the gravitomagnetic field of the Earth from a low polar orbit.

The STEP (Satellite Test of the Equivalence Principle) experiment is another idea from Stanford, which is currently being considered by space agencies in Europe and the US. This space-based experiment will test the idea that gravity has the same effect on identical particles to a precision that is some 10^5 times greater than can be achieved with Earth-based techniques. The plan is to measure the difference in acceleration between two bodies of different composition to an accuracy of one part in 10^{17}. This could unveil a composition-dependent force that could prove important for theories attempting to quantize gravity.

A gravitational revolution

In the long term, LISA is likely to provide the most fundamental tests of strong-field general relativity. This space-based interferometer will measure the radiation emitted by merging black holes and by neutron stars falling into massive black holes. It will thus explore the strongest possible gravitational fields and will test many aspects of gravity, including the no-hair theorem, gravitomagnetism and the equivalence principle. It might also provide measurements of the cosmological deceleration, and hence of the total mass of the universe, to an accuracy of better than 1%. The use of gravity to test gravity – by using gravitational waves to tell us about the strongest gravitational fields in the universe – will mark the maturity of general relativity and the fulfilment of Einstein's gravitational revolution.

Further reading

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