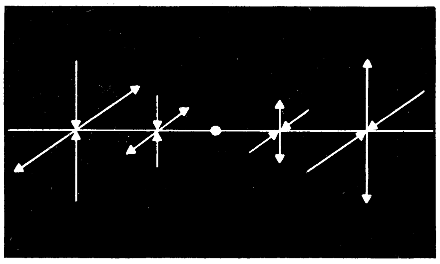
Does Gravity Wave?

Einstein's mathematics says gravity waves exist. Observers have a worldwide search underway while astrophysicists calculate how the waves should be shaped.

BY DIETRICK E. THOMSEN



Gravitational waves are one of the more esoteric predictions of Einstein's general relativity theory. A wave is a cyclic disturbance that propagates itself through space. A gravitational wave is a cyclic disturbance involving gravitational forces. It is the gravitational analogue to an electromagnetic wave, which is a cyclic disturbance involving electric and magnetic forces. Electromagnetic waves — light, radio, X-rays — are common everyday phenomena, and they have been so thoroughly investigated that their detailed conformance to the theory that predicts them is very well certified. The very existence of gravitational waves is yet to be proved.

In fact, for a long time many physicists chose to believe that gravitational waves didn't really exist. Many predictions can be derived from the mathematics of theoretical physics that are either absurd on their face or just don't happen to coincide with a physical reality. The prediction that energy can be carried from place to place by waves, although evidently real in electromagnetism, was widely held to be quite unreal in gravitation. Even those physicists who were willing to admit the reality of gravitational waves were at a loss how to search for them.

Thus, although the theory was published in 1916, it was not until the late 1950s that a serious attempt to detect gravitational waves was begun by Joseph Weber of the University of Maryland. In the last 10 years a number of other physicists have joined the quest, but so far there is no determination that all interested parties can agree is a confirmation of the existence of the waves. So subtle is the phenomenon and so difficult the experimentation that one party can argue that a certain set of data record the passage of gravitational waves while another argues equally plausibly that the data do not. That it will be a long time before there are observatories that routinely record gravitational waves coming to us from astronomical occurrences has been evident for years, and it remains the most evident conclusion after a symposium on the topic at the recent meeting of the American Association for the Advancement of Science.

A physical phenomenon is best observed against a background that is unaffected by it. We measure the motion of one body with respect to another. The passage of an electromagnetic wave will make an electrically charged body move up and down. The motion can be measured against a background of electrically neutral matter. Electric neutrality is possible; gravitational neutrality is not. The passage of a gravitational wave causes all matter in the area to move so there is no background to see it against.

The solution to this problem, as Weber determined it, is to set up a detector that covers enough space to contain a whole wavelength or more. The investigator can then compare the motion of one part of the detector with another part of it. Different parts of the wave make different parts of the detector move differently at a given time. The kind of detector that Weber first chose to make fills a large space with matter. The first Weber detectors are aluminum bars characteristically about a meter in diameter and a few meters long.

The passage of a wave is expected to come across as a vibration in the bar, a very minute vibration. The figure given at the symposium by William O. Hamilton of Louisiana State University at Baton Rouge is five parts in 10^{-19} for the strongest wave we can expect from our galaxy. In a three-meter bar that means a net motion about equal to the diameter of an atomic nucleus or about 1.5 x 10^{-16} centimeter.

Detecting such minute vibrations is no easy trick. Almost anything that shakes can cause problems, including microseisms, passing traffic and lightning bolts striking in the neighborhood. Heat inside the bar is a source of thermal vibrations. It is probably a good thing that Weber brought to the task not only the mathematical capabilities of a general relativist but also the practical experience of an electrical engineer. The detector he designed puts the metal bar in a vacuum chamber and chills it to as near absolute zero as practical. The chamber is supported on a complex system of buffers to damp out environmental vibrations. The vibrations inside the bar are sensed by piezoelectric crystals attached to its surface.

Weber-type detectors are now in use in experiments in various parts of the world from Moscow to Tokyo and from western Australia to eastern New Jersey. One of the developmental aims of the experimenters is to lower the temperature of the bars to as near absolute zero as possible. Hamilton says that the experiment he is involved in at Louisiana State hopes to get the temperature ultimately to 3 millidegrees K. At the moment they're happy to get 4 degrees K. They plan to make use of the supercooling to help increase the isolation of the bar with magnetic levitation. "If you go to low temperatures, you might as well take as much advantage as you can," Hamilton says. The bottom of the bar is coated with a metal that becomes superconducting at these temperatures. An electric current once started in a superconductor will flow on endlessly. So a circular current is started in the superconducting skin of the bar. The circular current generates a magnetic field, and the magnetic force is used to counteract gravity and levitate the bar.

Another desideratum for a Weber bar is a high gain factor. Gain factor, commonly designated by the letter Q, is the ratio of energy stored in the bar to the energy dissipated per cycle of the vibration. Since gravitational wave experimenters are looking for a vibration that is both minute in energy and transient in time, says Hamilton, a material with a high Q is desirable. Weber originally used aluminum, a metal that is readily available, convenient to work with and light in weight. Hamilton cites Weber, David Douglas of the University of Rochester and Vladimir Braginsky

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of the University of Moscow as being particularly involved in efforts to increase the Q. For the future a variety of materials are under consideration, including nonmetallic solids, such as sapphire, silicon and germanium, and exotic metals such as niobium. The numbers are encouraging. Silicon and sapphire have Q's up to a billion. Niobium comes in at 60 million. (The Q of a typical ham radio outfit is 75.) Present-day Weber detectors have Q's up to half a million. The worst, according to Hamilton, is the one at the University of Rochester, which, unloaded, has a Q of 100,000. One of the serious problems in this endeavor is figuring out how to grow crystals of the nonmetallic materials that are big enough to make Weber detectors. A sapphire a meter or two long would be quite a jewel.

A variation on the Weber detector, which uses empty space as its measuring rod, is credited to Braginsky. It is a metal bar or slug with a notch cut in it. The fluctuations in the length of the notch as a gravitational wave passes are what must be measured. The ends of the notch are wired to make an electrical capacitor. As the distance between the ends changes, the capacitance changes. The circuitry to read the capacitance change is straightforward in principle, but difficult in practice because of the minuteness of the effect.

Another empty-space variation is an interferometer. An interferometer takes a beam of light, nowadays usually from a laser, and splits it with a halfsilvered glass plate. The two half beams are sent out at right angles to each other and reflected back by mirrors at some distance. The two half beams are then recombined. If the paths of the two half beams have been equal, they will return in phase with one another and interfere constructively. If the paths are unequal, the returned half beams interfere destructively. Destructive interference results in partial or complete darkness. Because the amount of destructive interference depends on the difference between the two light paths, an interferometer is a very accurate instrument for measuring distance.

A method of using an interferometer to detect gravitational waves was described in detail by Kip S. Thorne of California Institute of Technology. It instruments the path of one half beam with two mirrors attached to sizable masses that the gravitational wave is expected to move. The half beam so instrumented bounces back and forth between the mirrors 600 times before it is recombined with its other half. The passage of a gravitational wave will jiggle the masses attached to the mirrors, and the difference in the two jiggles can be measured by changes in the interference. With changes in the distance between the two mirrors multiplied by 600, it should be a very sensitive device.

For very long gravitational waves, one might imagine the interferometer beam running between mirrors attached to two bodies in the solar system. Something of this kind may, in fact, become a scientific necessity, because certain astrophysical effects are expected to produce gravitational waves up to millions of kilometers long. Terrestrial detectors have a space limitation. They are most sensitive to waves that are twice as long as they are: A two-meter Weber bar is tuned to waves around 4 meters long, and so forth. For million-kilometer waves one might use the earth and a spacecraft as the masses to be jiggled by the passing wave. The difference in the jiggles can be determined by measuring the change in the Doppler shift of the spacecraft's radio signals. A couple of years ago Thorne and Braginsky calculated that the accuracy of space tracking and the frequency control of spacecraft radios was good enough to make the experiment feasible, and they proposed that a future spacecraft of the United States, the Soviet Union, or both should carry such an experiment. They are still hoping.

Finally, Hamilton mentioned a new type of detector that depends on superconducting magnetics. It is basically a metal ring that is chilled until it becomes superconducting. An electric current induced in the superconducting ring will continue to flow indefinitely, and this persistent current generates a magnetic field that lies perpendicular to the plane of the ring. If the shape of the ring is distorted by the passage of a gravitational wave, the magnetic flux through the ring, that is, the field strength times area, will change. The change can be measured by a device called a SQUID (Superconducting QUantum Interference Device, see SN: 4/9/77, p. 234).

While various types of detector are being developed and observers are waiting for the first detection they can all agree upon, theorists are busy figuring out what kind of astrophysical events might produce gravitational waves and what the shape of the signal should be. Thorne gave three examples.

Electromagnetic waves are generated when an electric charge is accelerated. An example is the movement of charges up and down in a broadcasting antenna. In principle, gravitational waves should be generated every time a mass is accelerated, but, in fact, in Einsteinian theory the simplest form of waves, the dipole configuration that corresponds to the one-dimensional, up-and-down vibration, cannot exist. The equations predict zero amplitude everywhere and at all times for dipole waves. The simplest gravitational wave configuration that Einsteinian theory allows to exist — other, less regarded, theories of gravity differ — is quadrupole waves.

Quadrupole waves correspond to a two-dimensional motion. The ring detector mentioned just above provides a good illustration. The passage of a quadrupole wave would first squeeze the ring vertically into a horizontally oriented cigar shape, second, return it to a circle, third, squeeze it horizontally into a vertically oriented cigar shape and finally, return it to a circle. Quadrupole waves are produced by events that possess what is called a quadrupole moment — that is, generally, collapses or explosions or sometimes rotations involving circular or spherical objects in which the distribution of mass does not have spherical symmetry. The three examples cited by Thorne are: the collapse of the core of a rotationally flattened star, the collapse and coalescence of a binary star system and the collapse of a star to a distorted black hole.

The collapse of the flattened stellar core points out a kind of unusual benefit to be expected from gravitational wave astronomy — if the subject ever gets off the ground. Gravity waves are one of the ways to see into the core of a star. (Neutrinos are another.) Electromagnetic waves from the core of a star would never get out; they would be absorbed on the way by the star's outer layers. The gravitational wave pulse from this collapsing core would have three amplitude peaks. The first would be a low peak due to a bounce in the north-south direction, the second a high peak produced by an equatorial bounce and the third another low peak from a second north-south bounce.

A binary star system, in which two stars rotate around their common center of gravity, can sometimes be subject to orbital decay, in which the two stars spiral toward each other. The wave pulse produced in this case starts out at fairly low amplitude and long wavelength. As the stars spiral together, the amplitude gets stronger and the wavelength shorter until an amplitude peak and wavelength minimum (frequency maximum) are reached as the stars begin to break up under the influence of each other's gravity. After the break-up the amplitude dies down and the wavelength gets longer again.

The collapse to a distorted black hole starts out with a rise to a sudden, sharp amplitude peak that drops instantly to a corresponding sharp amplitude excursion in the opposite direction. The vibrations then die down like a damped oscillator with a fixed period and diminishing amplitude as the black hole settles down. From the actual numbers involved in this wave pattern the mass and angular momentum of the black hole could be determined.

Besides these examples there are lots of other possible sources, says Thorne, and theorists are gradually working on them. But the theoretical work already shows that observers could expect a few events of one sort or another per month. It also shows, Thorne says, that "current detectors are in a regime where, if something is seen and everybody agrees it has been seen, theoreticians have no reason to hide in a corner and say there is no way to explain it." □