Gravity Waves

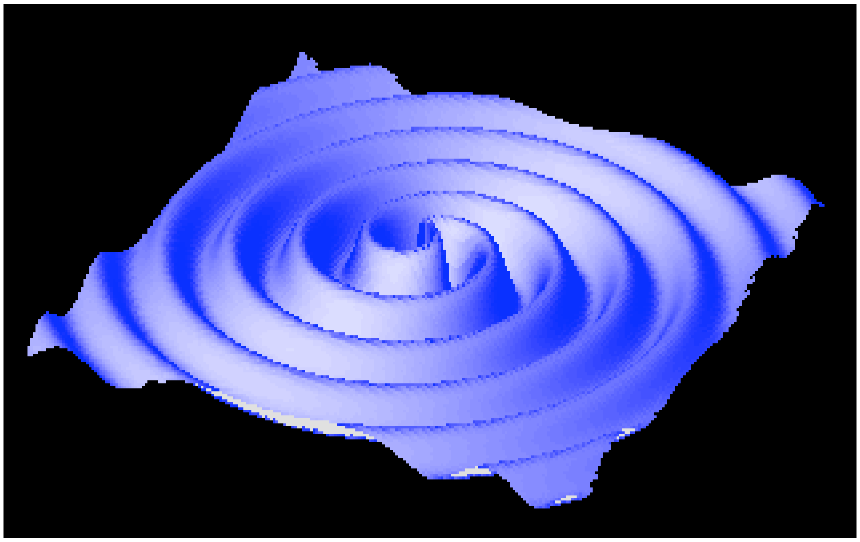
Another new prediction of Einstein's theory of gravity (general relativity) is *gravity waves*, "ripples of spacetime" that travel at the speed of light. Notice that these are ripples *of* spacetime, not ripples *in* spacetime like electromagnetic waves (also called light). Gravity waves are also called *gravitational radiation*. There is no such phenomenon in Newton's theory of gravity.

(Side note: There is a much more ordinary phenomenon also called "gravity waves" in the Earth's oceans and atmosphere: this is simply the fact that if a fluid rises then it will fall again due to gravity. An example is surface waves on the ocean. So when you find an article about gravity waves, check which type they are talking about. From now on, when I say "gravity wave" I mean waves of spacetime as predicted by general relativity)

Gravity waves are generated by the motion of, or changes in, masses in spacetime. For example, if the Sun were to suddenly disappear, the Earth would continue to move in its orbit along the straightest path in the curved spacetime generated by the Sun for eight more minutes. This is because it takes light 8 minutes to get from the Sun to the Earth, so it will take 8 minutes for the change in the spacetime curvature to get from the previous position of the Sun to the Earth. In other words the Earth's orbit would change at the same time that we saw the Sun disappear on Earth, 8 minutes after it actually happened. Don't worry, we're very sure the Sun will not actually disappear.

Actually, the special theory of relativity demands that gravitational changes move no faster than the speed of light, otherwise you could use the gravitational effect of a mass to transmit signals faster than light. This would contradict the understanding of spacetime we have from special relativity.

The detection of gravity waves is an important test of Einstein's general relativity. These waves are very difficult to detect because their effects are very weak for gravity waves generated by most things that happen in the Universe. For example, a rotating spherical mass (like the sun) does not generate any gravity waves at all. Planets orbiting a star generate gravity waves that are far too weak to detect. Normal stars orbiting each other generate gravity waves that stronger, but still too weak to detect from a great distance. Here's a picture of the gravity wave emitted from two stars orbiting each other.



A representation of the gravity waves emitted by two stars orbiting each other.

Only very large masses interacting very close to each other will generate gravity waves that we can hope to detect here on Earth. The strongest gravity waves would be generated by the collision of two black holes. Such collisions are rare, however. More likely is a large mass falling into a black hole such as the one in the center of our Galaxy. This is also rare, but would happen more often than a black hole collision.

Therefore gravity waves are difficult to detect. As I'll describe below, there are several experiments underway to detect them. The best evidence to date, however, is indirect, found by examining the orbit of two very massive but close stars around each other. I'll also describe this below.

What Does a Gravity Wave Look Like?

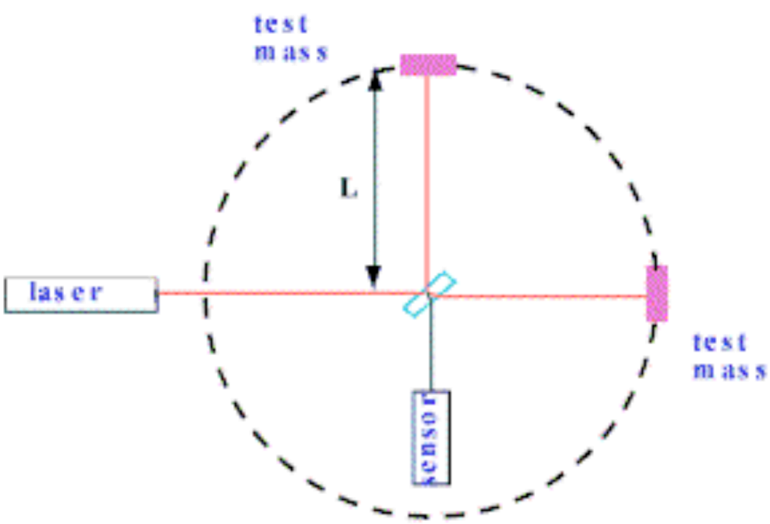
Gravity waves are ripples *of* spacetime, not waves of some material in spacetime. Gravity waves causes space to warp as time passes. Because it is space itself that is warping, everything in that space will warp with it. Therefore you won't see a gravity wave as it passes.

Luckily for physicists, for many gravity waves the warping in one direction will be different from the warping in another direction. We can therefore detect a gravity wave by observing lengths in different directions. If the length changes one way in one direction and a different way in another direction there is a good chance that a gravity wave has passed by.

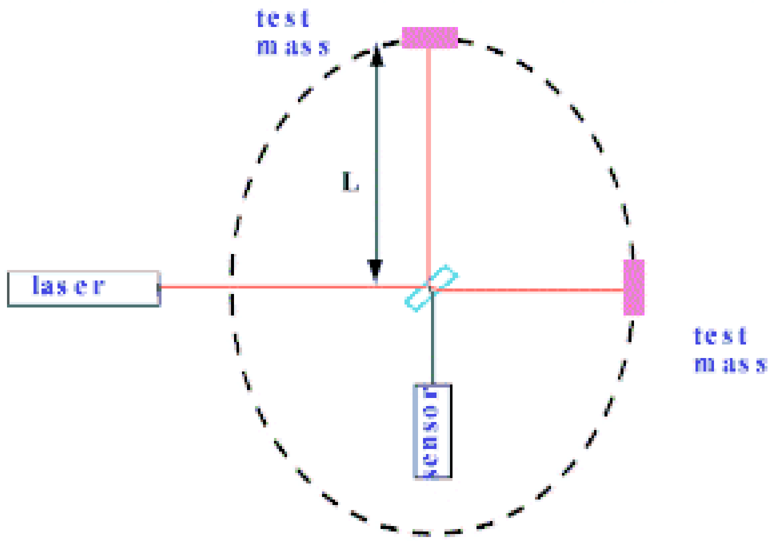
The first attempt to detect gravity waves in this way was by Joseph Webber in the late 60's. He placed very sensitive strain gauges on a large metal bar. If a gravity wave goes by, then the different stretching of the bar in various directions would appear as varying strains. Webber never detected gravity waves, because the bar was not large enough and was subject to too much noise due to changes in temperature and so on.

Joseph Webber and his gravity wave detector.

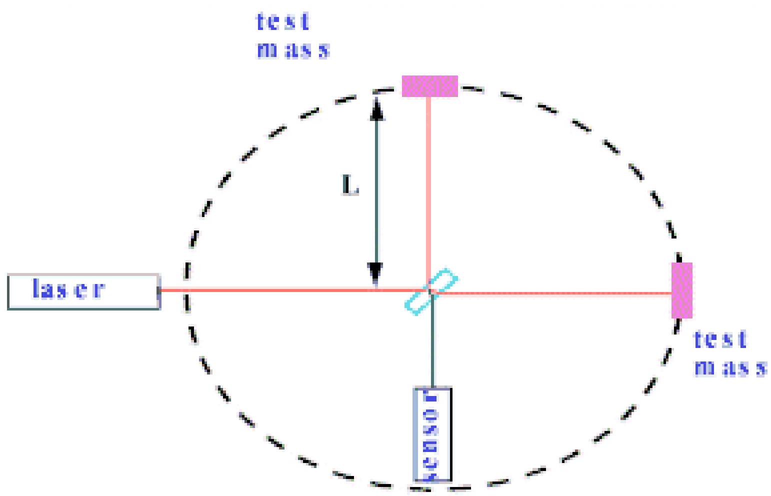
A number of experiments are now coming into operation that try to measure differences in length in various directions by using the interference of light: a laser beam is split in two, sending the two beams along perpendicular paths, then reflecting them back so they can be recombined. The *interference* of the recombined beams will show a length difference as variation in the brightness of the recombined beams. Here's some pictures showing such an experiment in operation:



An interference-based gravity wave detector. The line is the path of the laser beam. This is the picture when no gravity wave is passing.



Here is the situation when a gravity wave is passing: first the beams are stretched in one direction…

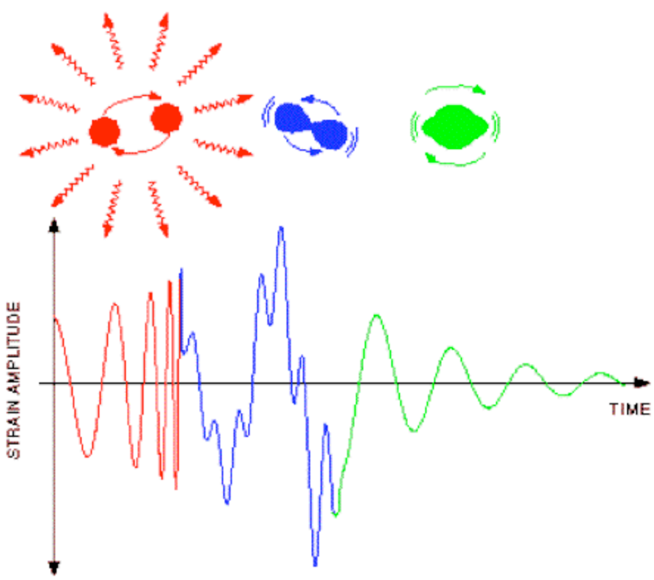


then they are stretched in the other. The sensor will change in brightness in a characteristic way.

Two large interference-based experiments are now operating in the US, one in Livingston, Louisiana and the other in Hanford, Washington. Both are part of the Laser Interferometer Gravity-Wave Observatory (LIGO), run by Cal Tech and MIT. These devices are quite large, with the arm of each laser path (L in the above diagrams) being 2.5 miles. The reason there are two of them far apart is to make sure any signals detected at one is not due to some local noise. A real gravitational wave would be detected at both experiments. LIGO has been taking data since April of this year, with increasing sensitivity over time. Hopefully we'll see an announcement of gravity wave detection soon, though LIGO is just barely at the required sensitivity to detect gravity waves from very large sources.

The LIGO facility in Hanford, Washington, showing one 2.5 mile arm, with the other arm going out of the picture to the left.

Here's a picture of the signal the LIGO experiment may detect from two massive stars coalescing after orbiting each other very closely:

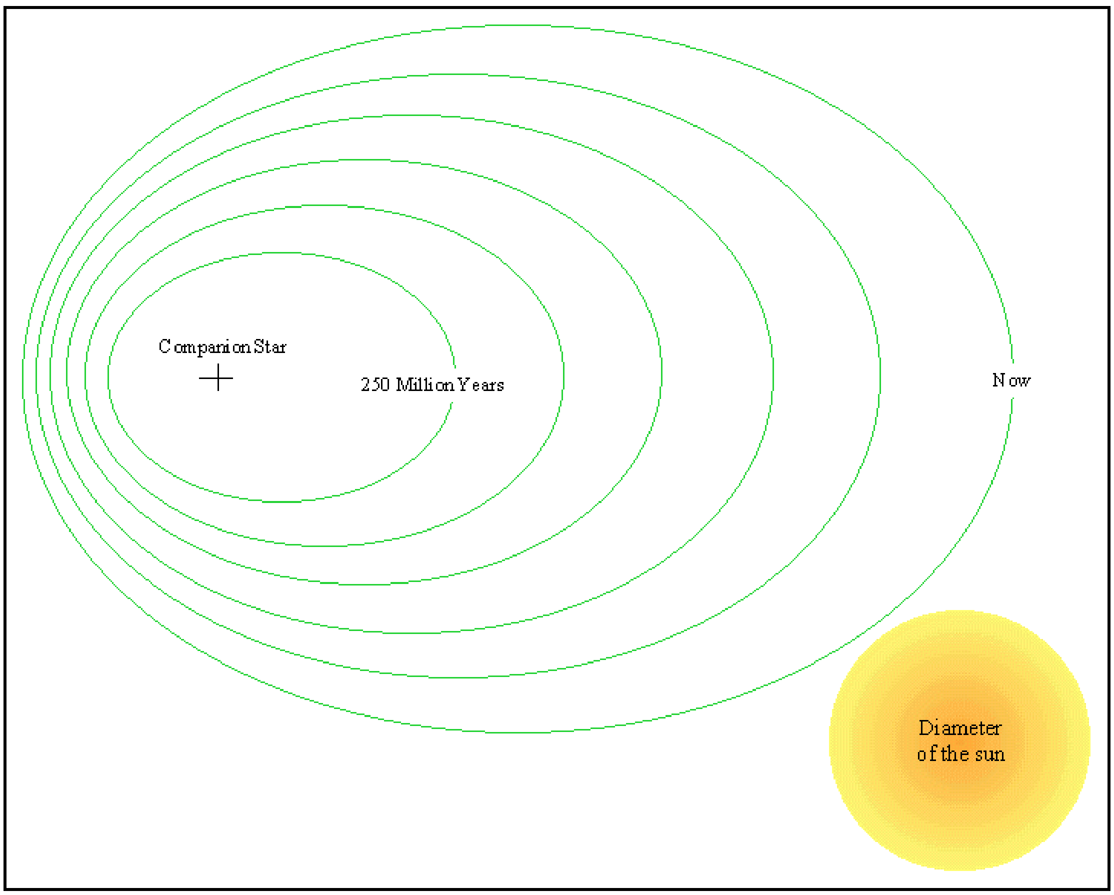


The top of the figure shows two very massive stars coalescing after being in a close orbit. The bottom shows the gravity wave signal that LIGO would detect from this event.

Several other interferometer-based experiments are being built in France, Germany, Japan and one is proposed in Australia. The most ambitious and sensitive proposed interferometer-based experiment is the Laser Interferometer Space Antenna (LISA), a fleet of three spacecraft that would form an equilateral triangle in space, measuring the changes in the length of the triangle with laser beams between the satellites. The sides of the triangle would be about 3 million miles.

The Indirect Detection of Gravity Waves

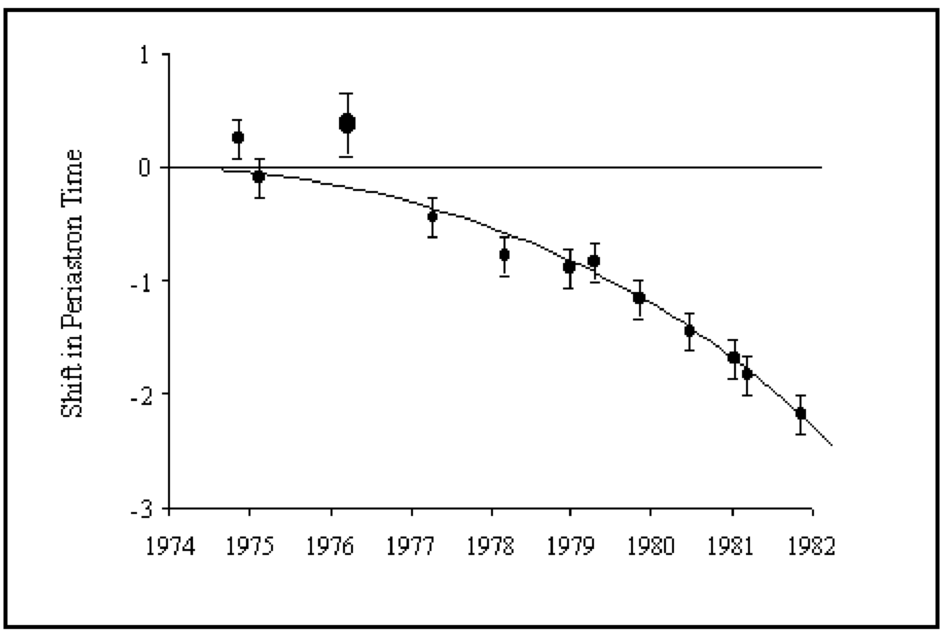
The best evidence for gravity waves to date is indirect, based on observations of the binary star system PSR1913+16. One of the stars in this system is a pulsar, which is a massive star in the last stages of life that has collapsed to a very small size, on the order of 10 miles in diameter. Both stars in PSR1913+16 are about 1.4 times the mass of the sun, and are orbiting very close together. Their orbits are very elliptic, with a closest approach of only 776,000 miles (a little more than the radius of the sun) and a furthest distance of 2 million miles (for comparison, the average distance between the Earth and the sun is about 93 million miles). The orbital period is only 7.75 *hours*.



The orbits of PSR1913+16 (from the point of view of one of the stars) compared with the size of the sun. The ellipse marked “now” is the current orbit. The other ellipses show the future orbits as the stars lose energy by emitting gravity waves, which cause them to slow down and fall into smaller orbits.

Because each star in PSR1913+16 is so massive and they get so close together, their gravitational field is very strong (in other words the spacetime between the pulsars is highly curved). Therefore they emit stronger gravity waves than most objects in the sky. These gravity waves are still too weak to detect even with LIGO, but they carry energy away from PSR1913+16. This energy loss causes the stars in PSR1913+16 to slow down, which causes a change in their orbit that we can detect from Earth. From these observations we can reconstruct the energy loss, and it exactly matches the energy of the gravity waves predicted by general relativity!

If you want a little more detail, here it is. The energy loss is measured by observing the time of closest approach between the stars (which is observed via the very fast pulses of the pulsar). If there were no energy loss then the time between closest approaches would be constant. If energy were being lost due to gravity waves, then the time between closest approaches would become shorter as the stars moved closer together. The closer the stars are together, the larger the gravity waves so the greater the energy loss, which moves the stars closer together still. Detailed calculations from general relativity predict that the time between closest approaches would decrease at an ever increasing rate. When the observations of the closest approach times are plotted over several years, they dramatically match the prediction of general relativity.



The change in time of closest approach of the stars observed over several years (dots with error bars) compared to the prediction of general relativity (curved line). The horizontal straight line (at 0) is the prediction if there were no gravity waves.

Though indirect, this observation is a dramatic vindication of general relativity.