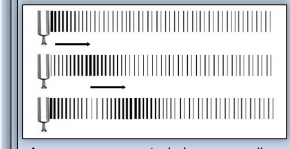
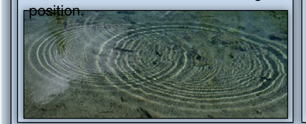
Gravitational Waves

Waves

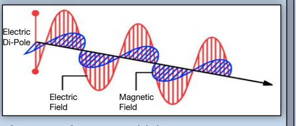
Elastic Waves



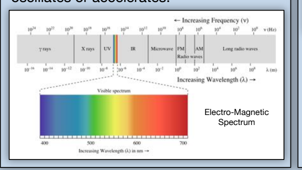
A wave propagated by a medium having inertia and elasticity, in which displaced particles transfer momentum to adjoining particles, and are themselves restored to their original position.



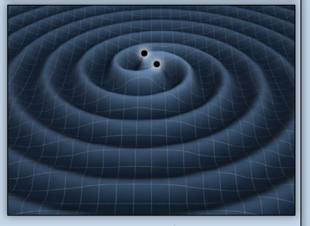
Electromagnetic Waves



A wave of energy which propagates as a periodic disturbance of the electric and magnetic field when an electric charge oscillates or accelerates.



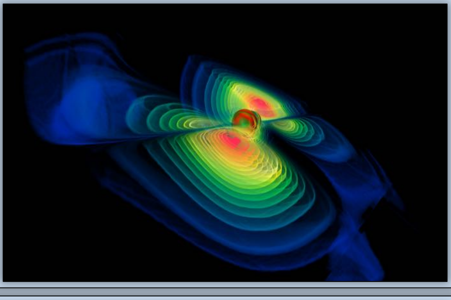
Gravitational Waves



Predicted in Einstein's General Theory of Relativity, gravitational waves are propagating disturbances in the curvature of space-time caused by the motions of matter. Gravitational waves do not travel "through" space-time as such - the fabric of space-time itself is oscillating.

Predicting Gravitational Waves

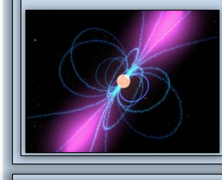
Gravitational waves are created by moving masses (which produce time varying quadrupole moment), much as electromagnetic waves are created by moving charges. But because gravity is the weakest of the four fundamental forces (the others being the electromagnetic, weak nuclear, and strong nuclear), gravitational waves are exceedingly small. For physicists, a strong gravitational wave will produce displacements on the order of 10^{-18} meters - this is 1000 times smaller than the diameter of a proton. Waves of this strength will be produced by very massive systems undergoing large accelerations, like two orbiting black holes that are about to merge into one.
Although Einstein's General Theory of Relativity is adequate to explain gravitational waves, the equations are too complicated to be solved analytically. Today these equations are solved using supercomputers to predict the nature of gravitational waves yet to be observed.



Possible Sources of Gravitational Waves

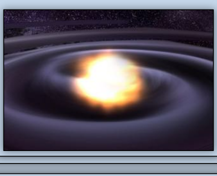
Continuous

Continuous gravitational waves are produced by systems that have a fairly constant and well-defined frequency. Examples of these are binary stars or black holes orbiting each other from far apart or a single star swiftly rotating about its axis with a large mountain or other irregularity on it. These are weak sources.



Inspiral

Inspiral gravitational waves are generated during the end-of-life stage of binary systems where the two objects merge into one. These systems are usually two neutron stars, two black holes, or a neutron star and a black hole whose orbits have degraded to the point that the two masses are about to coalesce. The sound these gravitational waves would produce is a chirp sound.

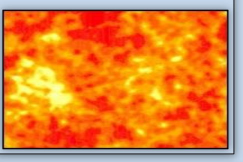


Burst

Scientists predict that explosive events such as supernovae and gamma ray bursts may produce bursts of gravitational waves. The exact form these waves will take, is still unknown. In burst gravitational waves the unexpected is expected. The 'sounds' are expected to be 'pops' and 'crackles'.

Stochastic

Stochastic gravitational waves are the relic gravitational waves from the early evolution of the universe. Much like the Cosmic Micro-wave Background (CMB), which is likely to be the leftover light from the Big Bang, these gravitational waves arise from a large number of random, independent events combining to create a cosmic gravitational wave background.

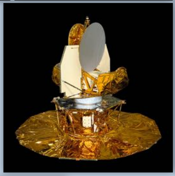


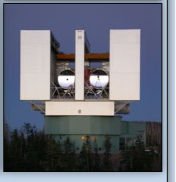
Why study Gravitational Waves

Astronomy is one of the oldest sciences. In ancient times, astronomy only comprised the observation and predictions of the motions of objects visible to the naked eye.

A new age of astronomy began with the invention of telescope by Galileo. This new tool enabled us to observe things never been observed before, allowing new laws of physics being discovered and tested.
Telescopes have changed the way we view ourselves in relation to the Universe.

In the past 400 years, we have studied almost every available window of the electromagnetic spectrum, resulting in a sea-change of our understanding of the universe.

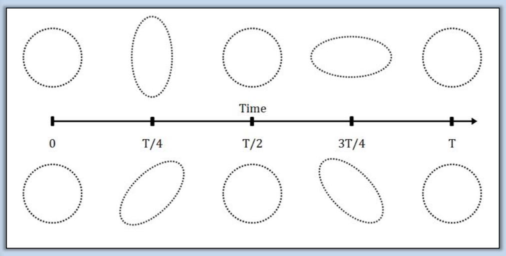




Today, we are on the edge of a new frontier in astronomy: gravitational wave astronomy. Since the universe is more transparent to gravity, this study will explore an unknown aspect of the universe and can be named our attempt to build the first gravitational wave telescope.

Effects of Gravitational Waves

Gravitational waves interact with matter by compressing objects in one direction while stretching them in the perpendicular direction. The plane in which the compressing and stretching happens is perpendicular to the propagation of the wave.
If we have some free particles arranged in circle then if gravitational waves pass through the plane of the circle they move in the following manner. The two sets show the effects of two polarizations + and × separately. T is the time period of the wave.

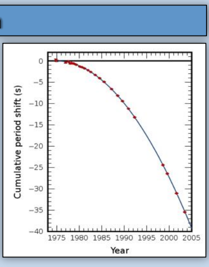


Though gravitational waves pass straight through matter, their strength weakens proportionally to the distance traveled from the source. This alternate stretching and shrinking, happens on an incredibly small scale - by a factor of 10^{-21} for very strong sources. That's roughly equivalent to measuring a change the size of an atom in the distance from the Sun to Earth!

Detecting Gravitational Waves

Indirect Detection

In 1974, Princeton University astronomers Russell A. Hulse and Joseph H. Taylor located PSR 1913+16. This object is a pulsar. It orbits another star, which is likely another neutron star. Four years after first discovering PSR 1913+16 and after some careful timing measurements of the pulsar, Hulse and Taylor found that the two stars were moving closer to each other. That could only happen if something was pulling energy out of the system.
After 18 years of careful measurement, Taylor has now precisely timed PSR 1913+16's orbital periods and found they are within 0.3 percent of general relativity's predictions of energy radiated by gravitational wave.



The Nobel Prize in Physics 1993 was awarded to Hulse and Taylor "*for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation*".

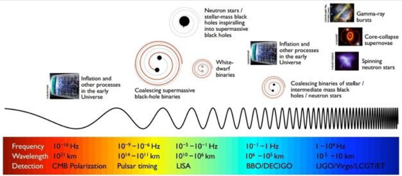
Weber Bar

In 1960s physicist Joseph Weber at the University of Maryland tried to detect gravitational waves by using a device now known as Weber bar which consisted of multiple aluminum cylinders, 2 meters in length and 1 meter in diameter.
These massive aluminum cylinders were designed to be set in motion by gravitational waves of it's resonance frequency. Because these waves were supposed to be so weak, the cylinders had to be massive and the sensors had to be very sensitive, capable of detecting a change in the cylinders' lengths by about 10^{-16} meters.

Unfortunately, despite Weber's claims Weber bar was not sensitive enough to detect any gravitational waves.

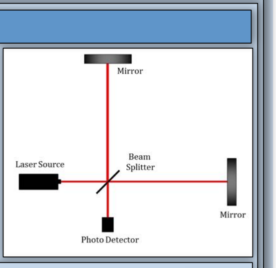
Gravitational Wave Spectrum

Whereas astrophysical electromagnetic waves are incoherent and have wavelengths typically much smaller than their sources, ranging from a few kilometers down to sub-nuclear wavelengths, gravitational waves are coherent and have wavelengths larger than their sources, with wavelengths starting at a few kilometers and ranging up to the size of the Universe. Depending on the wavelength of the wave we can propose different methods like CMB polarization, Pulsar timing study, Laser Interferometers etc. for their detection.

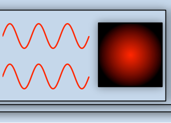


Laser Interferometer

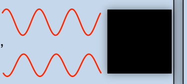
The current state-of-the-art gravitational wave detectors are L-shaped and measure the relative lengths of the arms using interferometry.
A single laser beam is split at the intersection of the two arms. Half of the laser light is transmitted into one arm while the other half is reflected into the second arm. Mirrors are at the end of each arm. Laser light in each arm bounces back, and returns to the intersection, where it interferes with each other.
If the lengths of both arms have remained unchanged, then the two combining light waves should completely subtract each other and there will be no light observed at the output of the detector. However, if a gravitational wave were to slightly (about 1/1000 the diameter of a proton for 4 km arms) stretch one arm and compress the other, the two light beams would no longer subtract each other and produce some light output. This output will tells us about the gravitational waves.



When the beams are in phase, output is maximum.



When the beams are out of phase, output is minimum.



The output can be used to find the phase and the change of length.