The Search for Gravitational Waves

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Einstein's General Theory of Relativity has provided a vision of the galaxy that has been proven correct time and again. Developed between 1913 and 1916 (Curriculum vitae of Albert Einstein), this theory revolutionized the way we viewed and understood the world around us. No field has been affected more by Einstein's theory than that of astrophysics. It is one of only a handful of sciences that routinely deals with the consequences of Einstein's postulates, specifically that of matter bending space-time. This theory continues to offer shocking new insights into the inner workings of the universe. Amidst all of the new applications and interpretations of Einstein's theory, one of the most fascinating and controversial was also one of the first (Ripples in Space-time).

According to Einstein’s theory, just as accelerating charges produce electromagnetic waves, accelerating masses produce gravitational waves, ripples in the space-time continuum that travel at the speed of light (An Introduction to Geometrodynamics). For these waves to be detectible, the event creating the waves must be asymmetrical, otherwise, the waves would almost completely cancel each other out when they superimposed. Specifically, the object generating the waves must produce a quadri-pole or greater multi-pole moment of inertia. Some examples of such an asymmetrical event include some supernovae, binary systems and possibly the Big Bang itself. Unfortunately, “many physicists at the time thought the waves predicted by the theory were simply a mathematical artefact. Nevertheless, others continued to further develop and test the concept” (Ripples in Space-time). However, “because gravitational forces are 40 orders of magnitude weaker than the Coulomb force, the detection of gravitational waves is an huge challenge to instrument builders” (Lewis) and the task proved impossible until the late 1950’s.

Many experimental physicists asked the two obvious questions:

1) How can we prove the existence of gravitational waves beyond the shadow of a doubt?
2) Once we can detect them reliably and analyse the information they carry, how can we use gravitational waves to better our understanding of the universe?

The first of these questions, remarkably, remained unsolved until Joseph Webers, Professor of Physics at the University of Maryland, designed and built the first “resonant-bar detector” in the early 1960’s. This device is essentially a mechanically isolated cylinder of solid aluminium weighing several metric tons that is covered with piezoelectric strain transducers that transform even the smallest of vibrations caused by gravitational waves passing through the bar into a measurable electric signal. Webers configured his detector to detect gravitational waves at the frequency of 1 kHz, the specific frequency theorized to be produced by an asymmetrical supernova, which he believed would be among the strongest sources of gravitational waves. Unfortunately, while his theories were sound, Webers was unable to achieve the sensitivities required to detect gravitational waves and differentiate them from terrestrial sources (Lewis). The famous astrophysicist Kip Thorn once said that a device capable of detecting a gravitational wave would be comparable in sensitivity to a device capable of tracking the movement of Pluto within the diameter of one hydrogen atom. In 1987, scientists at the University of Maryland, in the United States, and the university of Rome, in Italy, claim to have detected gravitational waves originating from a supernova in the Larger Magellanic Cloud, but a number of other detectors around the globe were unable to confirm the readings.

Currently, the most compelling evidence for the existence of gravitational waves is quite indirect. In the 1970’s, astronomers discovered that the Binary Pulsar System PSR1913+16 (a system composed of two neutron stars rapidly and closely orbiting each other) was found to be collapsing at precisely the rate that would be expected if it were losing energy through the emmition of gravitational waves (Lewis). Following this discovery, many other binary systems were examined and the theory was found to hold for most of them.

Now, thanks to advances in laser technology, direct evidence of gravitational waves can finally be found. The Laser Interferometer Gravitational-wave Observatory (LIGO) was constructed in early 1990's. Using pendulums, mirrors and the basic laws of interference patterns, the theory behind the LIGO project is simple:

> In brief, if a gravitational wave passes by, the pendulums holding the mirrors are expected to move a little apart in one leg and a little together in the other leg, in each case by the same tiny fraction of the laser light wavelength. Their movement shifts the relative phase of the two halves of the laser beam, momentarily upsetting the interference patterns that would otherwise cancel out. At that instant, the interference pattern brightens by an amount proportional to the strength of the gravitational wave. The job of monitoring the interference pattern for brightening is handled by electro-optic detectors, which indicate when a passing gravitational wave is detected and which recover its variation over time. (Lewis)

The sensitivity of this new method using lasers is related directly to the distance between the mirrors. The length to be used by the LIGO facilities will be 4000 meters and the laser that is used will be an argon laser emitting light at 500 mm[1]. To improve

[1] I believe that this should be 500 nm as the author of the source referred to as green light, however I am not certain and was unable to find any other document that would decide one way or the other.

the sensitivity, inside the pipes through which the lasers pass, there will exist a near vacuum. All of these measures combine to create a sensitivity of one part in 10^{23}. This is the ultimate limit imposed by the Heisenberg Uncertainty Principle on our ability to measure the position of the mirrors. We should therefore, soon be able to directly detect gravitational waves. To ensure that any measurements are valid, and not the result of seismic activity, two LIGO facilities were set up in the United States, one in Hanford, Wash. and the other in Livingston, La, each mounted on platforms designed to buffer any small vibrations. Finally, the air in the tubes has been removed so that the laser passes through a near vacuum to ensure that the laser is not effected by the air molecules. Any readings measured at either facility can be independently checked at the other facility. More LIGO facilities are being set up around the globe with the hopes that they will provide continuous and fully redundant confirmation of all data received (Lewis).

Besides being far more accurate, the LIGO detectors also have the advantage of being able to detect waves from 10Hz to 10 KHz as opposed to the 1Hz-1KHz range of the resonant-bar detectors. The much larger range of the LIGO detectors makes it far more likely that an unexpected wave will be detected.

The specific goals of the LIGO project include:

- Verify directly general relativity's prediction that gravitational waves exist.
- Test general relativity's prediction that these waves propagate at the same speed as light, and that the graviton (the fundamental particle that accompanies these waves) has zero rest mass.
- Test general relativity's prediction that the forces the waves exert on matter are perpendicular to the waves' direction of travel, and stretch matter along one perpendicular direction while squeezing it along the other; and also, thereby, test

general relativity's prediction that the graviton has twice the rate of spin as the photon.

- Firmly verify that black holes exist, and test general relativity's predictions for the violently pulsating space-time curvature accompanying the collision of two black holes. This will be the most stringent test ever of Einstein's general relativity theory (LIGO Fact Sheet).

A third type of gravitational wave detector, called LISA for Laser Interferometer Space Antenna, is based on the Doppler red shifting of signals being transmitted by three probes orbiting outside of the earth's atmosphere. After determining the position of each probe relative to a "proof mass," laser interferometry will be used to determine the distance between the probes to an accuracy of 1 micron (Laser Interferometer Space Antenna). These detectors would specialize on the ultra-low frequencies below 3 mHz (Lewis). Several experiments have been performed, but the results have not yet been published. Like all other methods of detection, this method requires the use of new technologies to eliminate interference from outside sources. In this case, the solar winds will interfere with the probes, accelerating them slightly.

Unlike their detection, uses for gravitational waves were immediately obvious. In theory, although weakened, gravitational waves would remain unchanged when they pass through ordinary matter. This means that, unlike electromagnetic waves, gravitational waves detected here on Earth would be unchanged from when they were generated. This in turn means that the uncertainty produced by unseen interstellar masses could be eliminated from any data taken from the analysis of gravitational waves. Gravitational waves would therefore be very useful in determining the mass, spin, location and existence of such massive objects as black holes and supernovae (Lewis).

Gravitational waves could also be used to determine the nature of some of the universe's missing mass if it took the form of large dark objects. Gravitational waves can also be used to estimate cosmological distances since they also follow an inverse square proportionality between their power and the distance between where they were produced and where they were detected (Lewis).

There are a plethora of other applications for gravitational wave detection. Some of the more exotic uses include determining whether there are black holes in the centre of galaxies and examining the collision of black holes, stars and galaxies in greater detail than was ever possible before. Some physicists also believe that gravitational waves were produced by the Big Bang. If these gravitational waves are detected and analysed, we could finally see the whole picture of the beginning of the universe (LIGO Fact Sheet). These are just some of the many natural phenomena that could be observed for the first time. No one knows what new celestial processes can and will only be discovered by studying the gravitational waves they emit. As the great philosopher Homer said, "There are more things in heaven and Earth than are dreamed of in your philosophy." The analysis of Gravitational waves could expand our knowledge of the cosmos exponentially.

The discovery of gravitational waves would help astrophysicists in two distinct areas. First, it would prove beyond the shadow of a doubt that Einstein's Theory of General Relativity is correct and second; it would enable astrophysicists to gain a greater understanding of the universe in which we live. They would finally be able to create a comprehensive history of the universe all the way back to the Big Bang. Who knows, maybe a full study of gravitational waves could finally provide the insight required to link gravity and electromagnetic radiation into the Unified Theory of Gravitation and Electromagnetism that Einstein himself spent the end of his life trying to perfect.

Works Cited

An Introduction to Geometrodynamics. 01/03/01 <http://www.geo600.uni-hannover.de/shared/gravinfo/geodynamics.html>

Curriculum Vitae of Albert Einstein. 01/03/01<http://www.geo600.uni-hannover.de/shared/gravinfo/einstein.html >

Laser Interferometer Space Antenna. 29/04/01 <http://lisa.jpl.nasa.gov/technology/tech.html>

Lewis, Melvin A. Sleuthing Out Gravitational Waves. IEEE Spectrum May 1995, volume 32, number 5. 01/03/01 <http://solo3.abac.com/gwinstitute/sleuthing.htm>

LIGO Fact Sheet. 11/13/96. 29/4/01 <http://www.ligo.caltech.edu/LIGO_web/about/factsheet.html>

Ripples in Space Time. 11/7/95. 01/03/01 <http://www.ncsa.uiuc.edu/Cyberia/NumRel/GravWaves.html>