Gravitational waves:

Understanding and Detection

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Abstract

Gravitational waves carry information about catastrophic events in the universe. We give a brief description of gravitational waves with an overview of the current projects underway to detect them. We begin by discussing the theoretical prediction of gravitational waves from Einstein's General Theory of Relativity. We list several possible sources of these waves and describe how they produce gravitational waves. We also discuss the characteristic signals each source sends to Earth. We outline advantages and challenges for several detection methods now being implemented. These include resonant mass detectors and laser interferometry. We also discuss improvements being made to each system and how these improvements further our progress towards detection of the waves. Finally, we conclude with a prediction that laser interferometry will first detect these waves within the next few years.

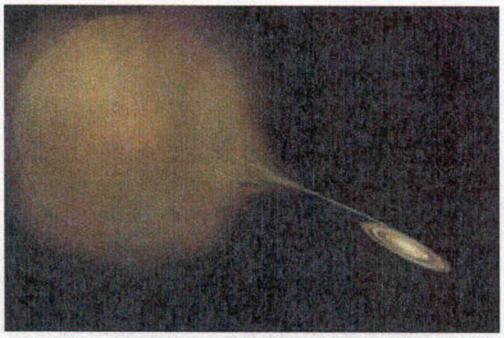
In 1905 Albert Einstein presented his Theory of Special Relativity with two postulates that led to a new realm of reasoning and observing the universe. Eleven years later Einstein extended these postulates to form the General Theory of Relativity. This theory predicts the existence of gravitational waves and describes properties these waves must have. If such gravitational waves could be detected, they could reveal much about the physics and history of the universe. In the years since their prediction, many attempts have been made to detect these elusive waves. As of yet we have failed to do so in any reproducible manner. In recent years renewed effort and the aid of technological advances have rekindled excitement to detect Einstein's gravitational waves.

Gravitational waves are disturbances in the curvature of spacetime caused by accelerating matter. The wave is an oscillation or ripple traveling at, or near, the speed of light through the fabric of spacetime. This propagation can be compared to the ripples on the surface of a pond caused by dropping a stone. Gravitational waves also ripple away from their source. As the gravitational waves travel through intervening matter in space, they lose strength proportional to the square of the distance from their source.[1] Gravitational waves are produced by large-scale and non-spherical vibrations of spacetime caused by accelerating matter.[2] Sources of gravitational waves can be found in various forms throughout the universe.

We will describe five such sources of gravitational waves. The first source we discuss is that of orbiting masses. One such source is a binary star system. General relativity predicts that some of the star's orbital energy dissipates as gravitational radiation.[3] As the binary system emits gravitational waves its orbital period decreases. For example, Hulse and Taylor observed the decelerating orbital motions of the neutron binary star system, PSR 1913+16. They showed that this predicted loss of energy was precisely that observed in the two neutron stars. In 1983, they received the Nobel Prize in Physics for their work.[4]

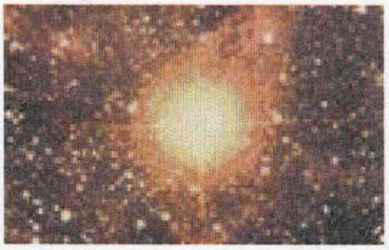
At the end of a binary systems life the two stars will become one as their cores come together and merge. The collision, or coalescence, between two massive objects produces a “shock wave that ejects matter outward and back into the stars' cores, causing them to expand and contract in powerful oscillations.”[5] As the stars spiral inward and collide they should generate a large burst of gravitational waves. Similar sources include coalescence of galaxies, black holes and other massive systems. These collisions between galaxies may form massive central black holes. These short lived events, could produce extremely powerful gravitational wave bursts.[6]

Another physical system that produces gravitational waves is mass transfer. When two massive bodies orbit each other at a critical distance the more compact object acquires matter from the other, due to its stronger gravitational pull. One could imagine that in spacetime each mass creates a well. The denser object produces a deeper and sharper well. Mass transfer occurs when the two wells are close enough that matter from the broader well spills into the sharper well. The material spirals toward the surface of its denser counterpart emitting some of its energy in the form of gravitational waves. The following diagram illustrates mass transfer that may occur in a binary system.[7]



Mass Transfer[8]

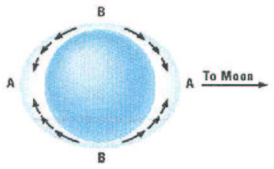
The collapse and explosion of a star may also emit gravitational waves. A collapse occurs near the end of a star's life when the inward gravitational pull becomes greater than the outward forces from its thermal activity. If the implosion of a star is non-spherical, it will radiate gravitational energy.[9] After the collapse of a star, renewed fusion and gravitational contraction are capable of producing a catastrophic explosion. Supernovae are prime examples of a cosmic collapse and explosion. Emission of gravitational waves can occur, however, only if the explosion is non-spherical, causing a non-symmetrical acceleration of matter.



Super Nova 1987A[10]

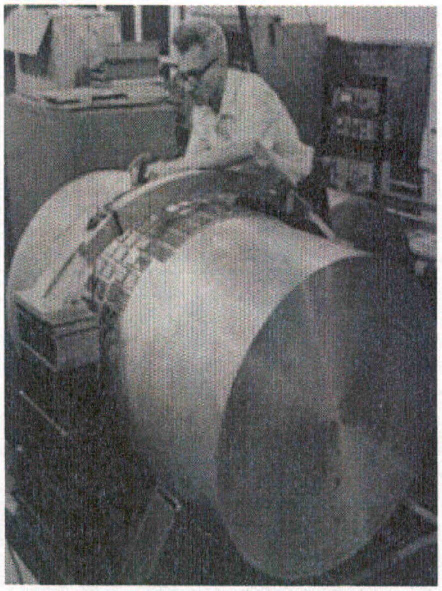
The sources of gravitational radiation produce characteristic gravitational signals. As in any wave-like signal, a gravitational wave has a characteristic frequency and amplitude. Several of these characteristics have been classified in describing their arrival to Earth. For example, one signal is called a chirp and occurs as a binary system ends its inward spiraling and coalesces. The binary system produces a signal that increases in amplitude and frequency, or chirps, as the masses combine. After the masses come together, the signal dies off as the united system stabilizes. A burst signal describes the collapse of a Supernova and, as the name indicates, the wave comes as a burst to Earth. This same signal describes the "burplike oscillations of a black hole's event horizon just after it swallows a star."[11] A periodic signal describes sources such as the binary system Hulse and Taylor measured. Because the signal is cyclical, the variations in frequency and amplitude from cycle to cycle describe the inward spiraling of the stars. Stochastic signals are random signals that describe gravitational background radiation that may have occurred as early as the beginning of the universe. Through analysis of the many signals we hope to better unravel the history of our universe.

Teams of physicists are working together to detect these signals. For example, at Louisiana State University, one group seeks success with a resonant mass detector called ALLEGRO. Their resonant mass detector is a bar that vibrates with a characteristic frequency. When a gravitational wave of the same resonant frequency passes through it the bar vibrates. The vibrations are detected electronically and analyzed.[12] Kip Thorne explains that as the gravitational waves pass through the detector, the bar is first compressed and then stretched and compressed again by the wave. He further adds that the compression is caused by tidal forces in the same way the moon stretches and compresses the oceans of the earth. The gravitational pull of the moon stretches the Earth in one direction while compressing it in the orthogonal direction. The gravitational wave has the same effect on the resonant bar, but the effect is much smaller. In reference to gravitational waves Thorne states that because "tidal forces are proportional to the size of the object on which they act, the waves will tidally distort any object by about lOE-21 of its size."[13] We show below a diagram of the tidal forces on the Earth due to the moon.



[14]

Joseph Weber first proposed the use of a resonant mass detector in the 1960's. His idea was to use a piezoelectric crystal to detect the small displacements caused by the stretching and compressing of the bar. Weber completed his first working detector in 1966 (see picture below). He used a cylindrical bar in a vacuum at room temperature. With this setup he was able to detect strains as small as a few parts in lE-16. Although Weber built several detectors and claimed to have observed coincidental vibrations, none of these were ever confirmed to be actual gravitational waves.[15]



Weber's resonant bar detector[16]

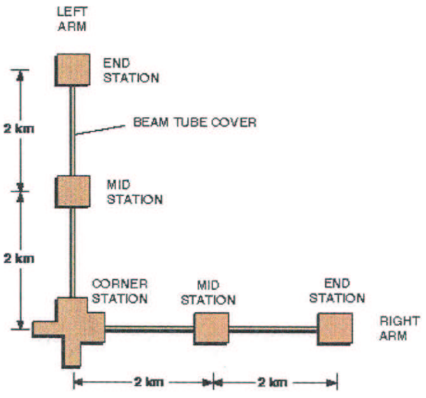
Because of the required sensitivity, the detector picks up unwanted noise produced by many terrestrial sources. Improvements on Weber's original design have succeeded in reducing this external noise. One such improvement lowers the temperature of the mass detector to that of liquid helium (4 Kelvin). Because thermal activity can be a large part of the noise that the detector picks up, the use of low temperatures minimizes thermal effects.[17] Another improvement isolates the detector from external vibrations through suspension of the bar. Terrestrial vibrations play the biggest role in producing unwanted noise. Most recently, many advanced suspension mechanisms have been used with resonant masses yielding success in reducing external noise. The ALLEGRO team reported: “ALLEGRO has had unprecedented immunity from local acoustic and mechanical sources. Normal laboratory activities are conducted near the detector, with no effect on the stationary noise or the background. Even the passage of Hurricane Andrew on 8/27/92, which blew down trees all over the city, did not increase the noise or background significantly."[18] We will continue to make improvements in order to isolate the gravitational wave signal from terrestrial noise.

Other groups have taken another approach with the resonant mass detectors. The cylindrical antenna used by Weber detects gravitational waves primarily along its length and therefore only detects waves propagating in one orientation. Rather than construct multiple cylindrical detectors, each oriented in different directions, an alternative "spherical" detector was developed. In this case, "spherical" describes the detector's approximation of a true sphere. Most importantly the mass detector has equivalent quadrupole vibrational modes as that of a true a sphere. This means that the vibration of any structure that is highly symmetrical in many directions will be equivalent to a true sphere.[19] Because the detector has no preferred orientation it can detect waves coming from any direction. The spherical distribution of mass also allows a uniform compressing and stretching of the mass as a wave passes through it, regardless of the direction. By attaching small resonators to the surface of the sphere, a strain gauge can then detect radial motion.[20]

This is a truncated icosahedral gravitational wave antenna (TIGA).[21]

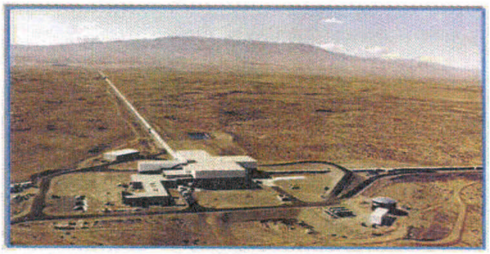
The resonating mass detectors have other technical difficulties and limitations. DeSalvo comments that "they are sensitive mainly to signals with a frequency corresponding to the bar mechanical ringing frequency, of the order of 1 kHz. A bar would respond to the hammer blow of an asymmetrical supernova explosion by simply ringing at its own bell tone, and would be excited by a twin neutron star in spiral only in that brief instant when the two stars chirp up through the bell tone frequency."[22] Each detector is useful only at its resonating frequency.

Several groups have used an entirely different detection technique called interferometry to avoid complications with resonant frequency. Interferometry indirectly measures a change in distance too small for direct measurement. Michelson and Morley developed this technique in the end of the nineteenth century to verify the existence of an ether frame. While we learned in class that they did not find an ether, Michelson and Morley's technique has since been developed as an effective measuring method. The interferometry stations now being built for gravitational wave detection have two perpendicular arms. In the several stations under construction these arms range from one-half to four kilometers in length. A mass at the vertex of each arm is free to move horizontally. A powerful laser beam is split down the two arms to monitor the distance between the masses at the vertex and the mirrors at the end of the arms. When a gravitational wave passes through Earth, the distance between the masses and the mirrors oscillates. When the system is undisturbed, the split laser beam interferes destructively. Any oscillation of the suspended mass due to a gravitational wave will produce an interference pattern. This pattern reveals the frequencies and other wave characteristics of the event that produced it.[23] Successive detection will enable us to interpret the burps, chirps and periodic signals of the characteristic sources of the waves.



Schematic layout of the LIGO site at Hanford, WA[24]

Six interferometry stations are currently in use or under construction around the world.[25] One team from the California Institute of Technology and the Massachusetts Institute of Technology are designing and constructing a laser interferometer device called LIGO. Both institutions have smaller working prototypes already in operation. One of these prototypes can detect the movement of a test mass 40 km away that is moved almost imperceptibly.[26] LIGO stations are located in Hanford, Washington and Livingston, Louisiana. Other projects include VIRGO near Pisa, Italy; GEO in Hanover, Germany; AIGO in Perth, Australia; and Tarna-300 in Tokyo, Japan.



Hanford Observatory[27]

Although laser interferometers, are not limited to a resonant frequency, they are subject to an incomplete range of frequencies. External noise again is the source of the limitations. For example, terrestrial vibrations create noise at low frequencies limiting detection accuracy in that range. Thermal noise affects midrange frequencies. Like the resonating mass, the test masses and the arms themselves are contained in a vacuum. In addition, the masses must be kept at a temperature very close to that of absolute zero, to reduce thermal effects.[28] This presents several large-scale mechanical challenges. Furthermore, the strain produced on matter by a gravitational wave is on the order of 10E-21. This is so small that it “would jerk masses spaced at 1 km by a mere 10E-18 m--one thousandth of the diameter of a proton!” Because light wavelengths and even the atoms of the mirrors themselves are much larger than this, it may seem impossible to detect so small an effect. Mirror instability, seismic noise, and thermal noise all contribute to the challenges these groups face. Nevertheless, DeSalvo asserts that “it is theoretically possible and this is reason enough to try!”[29]

Each station's design tends to magnify the effects of a particular external noise. In the battle against these challenges several noise-reduction methods have been implemented. Mirror suspensions are designed to reduce the effects of terrestrial vibrations. The GEO group has designed a support that has “a pendular oscillation factor of tens of millions corresponding to swinging lifetimes measured in years...a pendulum requiring years to dissipate its oscillation energy will need the same time to be excited by the seismic motion of its support points thus effectively isolating the mirror from perturbations.”[30] They have also isolated the detection band of the instrument from seismic motion. Methods involving thermal reduction have also found success. Several groups have succeeded in lowering the temperature in the arms to near absolute zero. The best method for improving the detectors will come through decreasing the temperature from its current value of about seven milli-Kelvins.[31] Today we continue to envision new ways of fine-tuning detection techniques. For instance, LISA is a joint project with NASA that proposes the construction of an interferometry space station in order to eliminate terrestrial noises. It will be most sensitive at low frequencies. The LIGO team is already implementing improvements that will increase the sensitivity of their detectors ten fold.[32]

With continued improvements, all of the stations hope to successfully detect the gravitational waves. One detector is not enough to ensure detection of an anomalous gravitational wave signal above all the non-related random noise. It has been beneficial to construct several interferometer stations as well as mass resonator antennas for at least two reasons. First, while a single detector may receive a signal, this signal must be confirmed by another detector, preferably at the furthest distance possible, to verify that the signals coincide. Coinciding signals prove a non-terrestrial source. Second, the signals must be detected by at least three stations separated by a distance in order to triangulate on the source of the signal. The source of the signal and its location can then be determined. Also, none of the stations can operate continuously - maintenance, repairs, and improvements require periodic shutdown. With many stations operating we hope to measure any fleeting signal of a gravitational wave.[33]

Due to large frequency range of interferometers and the recent successes of the controlled experiments with the prototypes in LIGO, we predict that initially a confirmed detection will come through coincidental detections among the several interferometer stations. In the collaborated effort of the current projects, we hope to gain confirmed detection within the next two or three years. As detection methods improve, more and more reliable and exact detection of the gravitational waves will be obtained. In a truly global effort, teams of physicists eagerly work to discover the gravitational waves Einstein predicted in 1916. Succeeding detections of the waves will enable us to better interpret the characteristic signal of each wave. Each gravitational wave tells a story about our universe as successful detection gives us a new way to study our universe.

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