Sources of Gravitational Radiation.

Edited by Larry Smarr
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Scientists have tried to understand the behavior of our universe by identifying four forces responsible for all interactions: gravitational, electromagnetic, weak, and strong. The strong force is short-ranged and responsible for the attraction betweeen protons and neutrons in nuclei. The weak force, also short-ranged, is responsible for radioactive beta-decay of nuclei. The electromagnetic force is long-ranged, and accounts for electric and magnetic behavior. The 1979 Nobel prize in physics was awarded to Steven Weinberg, Abdus Salam and Sheldon Glashow for "unifying" the electromagnetic and weak forces, showing them to have a common origin. There is also much work being done to try to include the strong force in this unification. But the gravitational force as the first to be understood, is the patriarch of this family of forces.

Gravity was revealed by Newton in his 1686 *Principia*, sparking a revolution in science lasting to this day; namely, attempting to describe the universe through mathematical laws. One of the most profound implications of Newton's law of gravity was that it took what had long been thought a terrestrial phenomenon and put it out into the universe, the law equally describing the fall of an apple and the fall of a moon. The theory was reproachless for over a century, but subtle discrepancies started to be noticed between observation and prediction. In particular, the 43 seconds per century discrepancy in the precession of Mercury's perihelion was puzzling. A further shaking of the foundation occurred in 1905 with the establishment by Albert Einstein of the special theory of relativity. The concepts of time and determinism in particles' motion were revised in light of the new, close relationship between space and time. Newton's theory of gravity did not allow this relationship, illuminating the need for a revised theory. In 1916, Einstein presented his new formulation of gravity, incorporating his special theory of relativity and the curved geometry of Riemann. It was to be called the general theory of relativity. It accounted for the 43 seconds of arc in the perihelion precession, and predicted light bending by the sun. The latter was verified by Eddington's solar eclipse party in 1919, bringing Einstein instant, worldwide fame. The third "classical" test of general relativity, the gravitational redshift, was also verified decades later by the physicists Pound and Rebka's experiment. Special relativity, general relativity, and quantum mechanics (born in 1926) are now the foundation of modern physics.

The general theory of relativity also provides the framework for Einstein's pioneering analysis (introduced in 1918) of gravitational radiation. In the general theory, the presence of matter (i.e. gravity) implies space-time curvature, and vice-versa. This is represented, in tensor form, by Einstein's equations:

$$R_{ab} - \tfrac{1}{2} g_{ab} \quad R = 8\pi G T_{ab}$$

R_{ab} is the Ricci tensor of the metric tensor g_{ab}; R is the Ricci scalar: G the universal constant of graviation; and T_{ab} the energy-momentum tensor. The left-side represents the curvature in the space-time metric; the right side the presence or absence of matter. Gravitational radiation, or gravity waves, are small perturbations or ripples on the space-time metric, analogous to ripples on a flat or slightly curving pond. There are competing theories of gravity, and for the three classical tests (mentioned earlier) their differences with general relativity are minor or absent. But, for other phenomena, their predicted differences can be quite drastic. Though there is no direct evidence yet of gravity waves, experimental determination of its properties, such as speed of propagation and polarization, can help to decide which of the competing theories is viable and provide a strict test for general relativity. There is indirect evidence for gravitational radiation in the change in the period of the binary pulsar 1913 + 16, but the final word is not in yet. It does, however, provide much moral support to experimenters endeavoring to detect gravity waves.

Gravity waves are emitted by the bulk motion of matter. In the general theory of relativity (the only gravity theory I will use throughout the remainder of this article), gravity waves propagate at the speed of light, with two orthogonal polarization states. A determination of a gravitational wave-form can give detailed information about the processes, the matter motion, that gave rise to it. Now, gravity waves are emitted most strongly in regions of great space-time curvature, regions associated with compact objects such as white dwarfs, neutron star, black holes and supernovae cores about which information is difficult to obtain by established electro-magnetic radiation astronomy (e.g. X-ray, radio, ultraviolet, optical, and gamma ray astronomy). Such is the tremendous potential of gravitational radiation as an astronomical tool.

If there is to be such a thing as gravity wave astronomy, gravity waves must first be detected. What are the physical manifestations of a gravity wave as it interacts with matter? Since the gravity wave produces a slight distortion in the space-time metric as it passes through a region, two nearby particles in that region should experience different gravitational fields (since curvature = gravity). Hence one particle would have a net acceleration with respect to the other. The result is a change in the separation of the two particles, given by (in tensor form)

$$\delta\ell_j = \tfrac{1}{2} \mathrm{M}^{TT}_{jk} \ell_k.$$

where ℓ_k is the initial separation of the two particles; $\delta\ell_j$ the change in their separation due to the gravity waves; and M^{TT}_{jk} represents the properties of the space-time metric transverse to the wave propagation direction (thus the TT, "transverse traceless", superscript). If the two particles are replaced by an object, the wave will distort the object's shape as it passes throught it. The primary gravity wave mode is quadrupolar, i.e., it will distort a sphere by alternately making it prolate and oblate, or by stretching out or pushing in a cylinder about its long axis. The effects on both free particles and on solid objects play a role in detection schemes, which will be discussed shortly. Unfortunately, gravity wave efects are very weak. The gravitational force is 10^{-37} as intrinsically strong as is the electromagnetic force. This manifests itself in extremely weak interactions. Theorists estimated that the strongest gravity wave producers, which are astrophysical in origin, would produce a change in the separation of two free particles, one hundred centimeters apart, of 10^{-15} cm. This is 10^{-2} times the typical radius of a *nucleus*, or 10 million times smaller than a typical *atom*! It is for this reason alone that it took over four decades since Einstein's predictions before experiments to detect gravity waves were initiated.

It was in 1959 that a paper by Joseph Weber of the University of Maryland started the gravity wave detection search. Within a few years he had a detection apparatus, or antennae, built and soon after actually claimed to have evidence for their existence. The claim has since been disputed, but it started a flurry of activity by other scientists hoping to corroborate or refute his findings. The pace set by the theorists was feverish. So much has happened since those early days that conferences and workshops were organized, in order to provide a means for disseminating and understanding what has been happening in the field. One of these workshops was held at the Battelle Seattle Research Center in the summmer of 1978, devoted to discussion of gravity wave sources and detection. A proceedings of this workshop, containing a collection of the papers presented, has recently been published as *Sources of Gravitational Radiation* (Cambridge University Press, New York, 1979), edited by University of Illinois astrophysicist Larry Smarr. That this highly technical, very advanced, and specialist-oriented book has been made available by the Library of Science and the Astronomy Book Club attests to the strong interest in this area by non-specialists and lay people.

This book is a boon to the specialist who desires to know the state-of-the-art (as of 1978) in gravity wave generation and/or detection. I would like to use the book as a guide in order to survey what has been happening, and what may happen in the gravity wave game.

There are four main sections to the book. One section deals with the numerical and analytical techniques developed to solve the partial differential equations used to determine gravity wave source strengths. The techniques discussed also find applications in other areas of physics which deal with non-linear equations.

Two other sections deal with the physics of black holes and neutron stars. Generally, according to current thinking, when a star reaches the end of its fuel burning life, matter is ejected and the core collapses into one of three things. If the core is less than 1.4 solar masses, it is called a white dwarf. A white dwarf is a very small, dense and hot, burned-out core of a star. If the core mass is greater than 1.4 solar masses, but less than about 2.5 solar masses, electrons in the atoms of the star core are driven into the nuclei, creating a core of neutron matter. This is a very dense object, as dense as nuclear matter, and is called a neutron star. If the core is greater than 2.5 solar masses, the gravitational forces are so great that the space-time curvature is forced into what is called a singularity, a "hole" in the metric. The result is known as a black hole, a region having such severe space-time curvature that even light can't escape from the region. Since these objects are so compact, and the metric in their vicinity so distorted, they are prime sources for gravitational radiation.

Another section in the book outlines and discusses the various astrophysical sources. These can be divided into three main categories by the radiation they produce: periodic, burst, and stochastic. Periodic sources are of relatively long duration, characterized by radiation of one frequency. Examples of this type are binary systems (whose members are compact objects), rotating deformed neutron stars and white dwarfs, and pulsating white dwarfs. Burst sources are short-lived, and produce radiation having a range of frequencies, the range being determined by the sources life-time. Examples of these sources are supernovae collapse into compact objects, neutron star core-quakes, black hole collisions and black hole neutron star collisions, and the coalescence (merging) of compact binary systems. Burst sources are typically considered the strongest. Stochastic sources provide the background gravitational radiation "noise", one such source perhaps being the big-bang.

The theoretical analysis of gravity wave production provides a guide for experimenters attempting to detect this radiation. The remaining section of Smarr's book deals with the attempts and problems of detection.

These efforts fall into two main categories: resonant-mass experiments and free-mass experiments.

Free-mass experiments, currently underway by about a dozen groups, monitor the change in the separation of two objects directly. There are two types of these experiments being undertaken. The first is the Doppler tracking of spacecraft. A passing gravity wave produces a tiny relative motion between earth and a distant spacecraft, this motion causing a Doppler shift, a change in frequency, of the radio tracking signal. The noise sources affecting the sensitivity of this detection scheme include interference from the solar wind; refractory changes in the upper atmosphere; frequency fluctuations in the maser clock needed to regulate the frequency of the tracking signal; and the effect of leaking gas from the spacecraft on its motion. Ingenuity and money can reduce these noise sources. Though not quite as sensitive as the best resonant-mass experiments for burst sources, its sensitivity is much better for periodic and stochastic sources.

The other free mass design is the laser interferometer. Based on the Michelson interferometer with a laser light sources, relative change in the positions of the test masses due to a passing gravity wave can be monitored through observation of the output intensity pattern. The fundamental limit to the sensitivity is due to the statistics of counting photons at the output, but other noise sources which must first be overcome are: laser frequency and amplitude fluctuations; seismic vibrations; and noise due to residual gas in the evacuated interferometer arms. Sensitivity to burst sources is probably as good as the best resonant-mass experiments, and better for periodic and stochastic sources. The technological problems are more severe for the laser interferometer design, but its ability to be sensitive over a large range of frequencies (which resonant-mass experiments are not) makes the rewards more than worth the effort.

There are nearly a dozen resonant-mass experiments underway in the world today. These designs monitor the fundamental mode of oscillations, or vibration, of a solid object. The expermenter monitors the object and hopes to be able to detect a change in its behavior due to the passing of a gravity wave. Weber's pioneering experiment used a massive aluminum cylindrical bar as the object (the antenna), and several other groups are also using cylindrical bars. I will focus upon experiments using this type of antenna.

Since the gravity wave will change the length of the cylinder on order of 10^{-15} to 10^{-19} cm, to be able to monitor this change one must reduce all sources of noise as much as possible. The antenna is specially supported so that vibrations and tremors from the floor are eliminated. There is also oscillation of the bar due to the fact that it has a finite temperature.

This thermal noise is called Brownian noise. This Brownian noise causes the length of the bar to jiggle. If the jiggle is larger than the change due to a gravity wave, then gravity wave effects will not be observed. It turns out that the gravity wave will be greater than the jiggle, providing Brownian noise is the *only* noise source, if

$$\Delta\ell > (kT/m\omega^2)^{1/2}\ (\omega\tau/Q)^{1/2}$$

where $\Delta\ell$ is the change due to the gravity wave; T is the temperature of the bar; m is the mass of the bar; k is Boltzmann's constant; ω is the resonant frequency of the bar; τ is the time needed for a measurement; and Q is the quality factor of the bar, a quantity representing the ability of the bar to store energy at its resonant frequency. This relationship helps determine the physical parameters of the antenna. In order to be sensitive to 10^{-15} cm, the parameters in the equation must be chosen accordingly. Generally, this requires that the mass of the bar be very large and the temperature very cold. The resonant frquency is dictated by the length of the bar, and the Q by the bar's substance. The measurement time depends on the monitoring apparatus. The parameters of the LSU experiment to which I am affiliated are these: mass=11,000 pounds; T=4 °K, with a potential of .05 °K; $\omega \cong 1900$ radian/second; $Q=10^6$; and $\tau=.1$ s.

Unfortunately, the antenna is not an isolated system. A transducer is required to change the energy of the mechanical motion of the oscillation of the bar to an electrical signal, which then requires amplification. The schematic for a typical detection scheme looks like:

antenna	transducer	amplifier

Among the groups using cylindrical bar antennae, their "signature" is given by their transducer design, which is the part of the scheme involving the most ingenuity. This is because the transducer and amplifier stages, by the fact that they are coupled to the antennae, can feed energy and noise back into it, thus affecting the monitoring process. This is called back-action, and is the most severe experimental problem in gravity wave detection. Another problem with current experiments is that they are also limited by quantum mechanics in the amount of sensitivity that can be achieved. This is called the quantum limit, and is the subject of a very interesting paper in the Smarr collection by Kip Thorne of the California Institute of Technology.

To the experimentalists now using resonant bar antennae, the quantum limit imposes an ultimate sensitivity of about 10^{-19} cm. This severely reduces its effectiveness as an astronomical tool, and in fact may prevent detection of gravity waves entirely, if source strengths have been over-estimated. As the experimenter monitors the position of the end of the bar (to determine length changes), he or she is also obtaining information about the momentum of the bar end (as todays experiments are currently designed). The quantum limit then appears as a direct consequence of the uncertainty principle.

$$\Delta x \cdot \Delta p \geqslant \hbar/2$$

where $\hbar$ is a very small constant, and Δx and Δp represent the accuracy of a measurement of position and momentum, respectively; Δx is a time-dependent quanity. A measurement of position to a given accuracy worsens the accuracy of a subsequent measurement.

Led by V. Braginsky of Moscow University and K. Thorne and C. Caves at Cal Tech, physicists are attempting to undercut the quantum limit by considering the measurement of quantities other than position. These quantities can be measured repeatedly at the same accuracy and give orders-of-magnitude improvement in the sensitivity. They are called "quantum non-demolition" quantities, and will be the focus of the next generation of gravity wave detectors. Results of these future investigations should, aside from the gravity wave detection goal, provide valuable insight into the little understood area of the quantum theory of measurement. The philosophical ramifications of this area have been debated for years, by luminaries such as Einstein, and it would be a marvelous benefit if gravity research could play an enlightening role in a matter of such fundamental importance to modern physics.