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Gravitational Waves and Multimessenger Astronomy

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Abstract
The 2015 first detection of gravitational waves opened the door for a new observational method in astronomy. Measurements of gravitational waves by laser interferometers such as LIGO and VIRGO allow study of phenomena inaccessible by traditional observations on the electromagnetic spectrum. Working in tandem with conventional observatories, gravitational wave detectors have the potential to probe the mysteries of the universe, including the early phases of galaxy evolution and the sources of various mysterious high-energy transients.

Keywords
gravitational waves, multimessenger astronomy, general relativity, galaxies, black holes, compact objects, astronomy, physics, astrophysics, cosmology, astronomical methods, astronomical instrumentation, physical sciences, science

Cover Page Footnote
The Faculty Mentor for this Honors project was William Koch, Astronomy.

A new window has been opened into the universe—astronomers can now listen to the heavens as well as look at them. This powerful new tool, only a few years old, is the result of a century of intricate theory. A cascade of earth-shattering scientific discoveries have already come—and far more await—from the partnering of gravitational-wave astronomy with traditional observation on the electromagnetic spectrum in a new field known as multimessenger astronomy.

Gravitational waves emerge as a necessary consequence of general relativity. According to Einstein's famous theory, mass curves spacetime around itself; it is this curvature that we experience as gravity. When mass is redistributed, the curvature changes. The resulting change propagates outward at the speed of light, the ultimate speed limit for any signal by special relativity. Gravitational waves are a ripple in the gravitational field—the curvature of spacetime—and carry the potential energy lost by the system that generated them.

A theoretical description of gravitational waves set forth in a public lecture by JCCC Astronomy Professor William Koch begins with Einstein's field equation

[1] $$G^{\mu\nu} + \Lambda^{\mu\nu} = T^{\mu\nu}$$

which, for flat spacetime, reduces to

[2] $$G^{\mu\nu} = 0.$$

The Einstein tensor for curvature, used in the field equation, is

[3] $$G^{\mu\nu} = R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} R,$$

where $g^{\mu\nu}$is the metric tensor, R is the Ricci scalar curvature, and $R^{\mu\nu}$ is the Riemann curvature tensor, which is composed of $g^{\mu\nu}$ and its derivatives (Koch; Le Tiec 22). For the special case of flat spacetime, the metric is the Minkowski metric

[4] $$\eta^{\mu\nu} = \begin{matrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{matrix}.$$ (Koch; Le Tiec 26)

To derive the wave equation, we add a small disturbance $h^{\mu\nu}$and insert

[5] $$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$

into the equation for the Einstein tensor (Koch; Le Tiec 25). The resulting wave equation is

[6] $$\frac{\partial^2 h^{\mu\nu}}{\partial t^2} - \nabla^2 h^{\mu\nu} = 0,$$

which is solved by the wave function

[7] $$h^{\mu\nu} = A^{\mu\nu} e^{ik_a x^a},$$

a sinusoid with amplitude $A^{\mu\nu}$where k_a is the wave vector (Koch).

When mathematician Henri Poincaré proposed this theory to Einstein in 1905—based on inferences from Special Relativity—Einstein initially dismissed the suggestion (Cervantes-Cota 4). In 1915, however, Einstein published his Theory of General Relativity and within the following year published the result predicting gravitational waves. Doubting himself, Einstein attempted in vain in collaboration with Nathan Rosen to remove gravitational waves from his field equation (Cervantes-Cota 5).

The theoretical prediction was meaningless without experimental support. Therefore, in the late 20th century, several notable attempts were made to detect gravitational waves. A maverick electrical engineer turned experimental physicist conducted the first such attempt in the 1960s, and his story tells a cautionary tale.

With funding from the National Science Foundation, American physicist Joseph Weber built a set of two aluminum cylinders, one at Argonne National Laboratory, the other at the University of Maryland (Weber 1321; Cho). A gravitational wave passing through his so-called “Weber bars”, he hoped, would cause them to vibrate at their resonant frequency of 1660 Hz. Although this was the same frequency as the vibrations due to random thermal motion, Weber expected a gravitational wave to produce a synchronized oscillation across both cylinders. In 1969 and 1970, he claimed to have detected a gravitational wave in this manner.

Weber, however, is not credited with the discovery of gravitational waves. He calculated the significance of each coincidence event as the period of time per expected random coincidence of equal significance (Weber 1321). Unfortunately, he neglected to define the significance threshold for a detection, jumping instead to the subjective conclusion that “it is quite certain that all of the coincidences cannot be accidental (Weber 1322)”. As an electrical engineer by training, Weber was not familiar with the standards of data analysis in his new field of experimental physics.

Scientists also claimed that Weber’s apparatus produced false positives, unbeknownst to Weber himself. In discussion of such a false positive situation, Weber claims, “Extreme care was taken to guarantee that signals from one detector would not cross couple into the other…”(Weber 1324), without any detail on what is meant by “extreme care”.

Weber’s detection technique laid the groundwork for the modern field of gravitational-wave astronomy. However, his blatant carelessness held back the progress of science for half a century.

Others attempted to replicate Weber's results with no success. In 1987, the NSF severed Weber's funding and diverted it to the development of LIGO, which would ultimately make the first confirmed detection of a gravitational wave in 2015 (Cho).

But the story of gravitational wave astronomy before LIGO is not one of doom and failure. In the late 20th century, Princeton University physicists Russel A. Hulse and Joseph H. Taylor, Jr. conducted an empirical test of the existence of gravitational waves based on the theory by Einstein and Poincaré. From 1974 to 1982, they observed a pulsar in a binary system (PSR1913+16) using the Arecibo radio telescope in Puerto Rico (Haynes). Hulse and Taylor reasoned that the pulsar was at periastron with its partner when the pulses were at a maximum in frequency. Their pulsar showed a cumulative relativistic shift in periastron time as the pulsar's orbit decayed. Their data showed a strong correlation with a relativistic model for gravitational wave emission, in which the objects lose gravitational potential energy over time and spiral toward each other. Hulse and Taylor were awarded the 1993 Nobel Prize in Physics for their work (Press Release).

The Hulse-Taylor system provided strong observational evidence for the existence of gravitational waves. However, the first direct detection of a gravitational wave would not occur until fewer than three years ago—September 14th, 2015. This historic detection by the Laser Interferometer Gravitational-Wave Observatory (LIGO) created a new branch of astronomy.

A consortium of California Institute of Technology and Massachusetts Institute of Technology, called LIGO Laboratories, operates the detectors. A group of physicists and astrophysicists— the LIGO Scientific Collaboration (LSC) — carries out the science of LIGO.

The machine itself consists of two enormous pairs of perpendicular laser arms (About the LSC). This setup is called a Michelson interferometer, after its inventor Albert Abraham Michelson. A device of this variety was used in the famous 1887 Michelson-Morley experiment to measure the relative velocity of the luminiferous aether, which resulted in the refutation of the aether's existence. In the case of the LIGO detectors, a laser beam passes through a beam-splitter, where half the beam is transmitted to one 4-kilometer arm and the other half is reflected to the other (Michelson and Morley, without the luxury of lasers, used light passing through a small aperture). At the end of each arm is a mirror, reflecting the beams back to the beam-splitter, where they are reunited and directed toward a detector. A very sensitive interference pattern develops as a result of a difference in distance traveled by the beams.

When a gravitational wave passes through the detector, one arm extends and the other contracts. Then, the other arm extends and the first contracts. The displacements involved are near ¼ the diameter of a proton. The length of LIGO's arms increase its sensitivity; LSC measures the machine's stress, the ratio of its change in arm length to its initial arm length. The use of two detectors rather than one allows LSC to locate the sources of gravitational waves using a method analogous to binocular vision. The two detectors— in Hanford, WA and Livingston, LA— are approximately 2000 miles apart.

The date of the first detection established a convention for the nomenclature of gravitational waves— it was given the name GW150914. Since then, other detectors have come online worldwide, joining the search. They include VIRGO near Cascina, Italy, KAGRA deep within the Kamioka mine, Japan, and LSC's own GEO600 near Hannover, Germany. They are also Michelson laser interferometers and function similarly to LIGO.

LIGO is presently able to detect rotating anisotropic neutron stars and compact object mergers (About the LSC). Its detections of these objects have produced beautiful, cutting-edge science results, and are the first observations of these events by any means. GW150914 was determined to be a merger of two black holes— an event which some astronomers did not believe possible.

And LIGO has made a splash in the scientific community. The 2017 Nobel Prize in Physics was awarded to three members of LSC: Kip S. Thorne of Caltech, Barry C. Barish of Caltech, and Rainer Weiss of MIT. This was a public recognition of a groundbreaking milestone; the award was presented “for decisive contributions to the LIGO detector and the observation of gravitational waves” (Press Release).

But compact object dynamics occupy only the high-frequency edge of the gravitational wave spectrum. Emission of a gravitational wave is associated with a change in quadrupole moment, therefore the wave will carry information about the motion that produced it. The wave’s frequency depends inversely on its wavelength, which in turn depends directly on the scale of the system that produced it. The high-frequency range, detectable by ground-based interferometers, is occupied by compact object dynamics. Massive black hole formation and mergers occupy the low-frequency range, detectable with future space-based interferometers, and the stochastic gravitational-wave background from the Big Bang—the “relic” background—dominates the very-low-frequency range, detectable by its imprint on the CMB (Creighton).

The information yielded by gravitational-wave astronomy is of a fundamentally different type than that available to astronomers of the past, relying solely on traditional electromagnetic observations. The synthesis of these observational methods into a multimessenger astronomical approach gives us a vibrant window into the largely unexplored high-energy universe. As well as photons and gravitational waves, multimessenger astronomy includes cosmic rays and neutrinos (Santander 1).

While cosmic rays and neutrinos are not the topic of this paper, their study constitutes a robust field and merits discussion. Cosmic rays comprise the astrophysical particle flux. They are particle by-products of astrophysical processes, and consist of two varieties: low-energy rays with energy $<10^{15}$eV, and high-energy rays above 10^{15}eV (The Mystery of High-Energy Cosmic Rays). The low-energy rays are accelerated by Fermi magnetic shocks resulting from supernovae, and are mostly from galactic sources. The high-energy rays come from unknown extragalactic sources. The Pierre Auger observatory in

Mendoza, Argentina, observes cosmic rays by means of the air showers produced when they interact with molecules in the upper atmosphere.

One type of cosmic ray of particular interest—and also of particular challenge—is the neutrino. Neutrinos are high-energy, weakly interacting, electrically neutral particles. They are by-products of nuclear reactions. The mass of the neutrino is a mystery; the Standard Model predicts neutrinos to be massless, but experimental evidence suggests neutrinos do have mass (how much mass is unknown) (All About Neutrinos). The IceCube detector at the South Pole, Antarctica, detects Cherenkov light emitted by interactions of neutrinos with ice molecules. The released particles travel through the ice faster than the speed of light through ice, and a ghostly blue ring-shaped light pattern occurs, in a similar process to supersonic shock waves. An array of tubular detectors records this pattern.

Whether cosmic rays, neutrinos, gravitational waves, or photons carry the relevant information, multimessenger astronomers use correlation studies to conduct their science. A multimessenger correlation search can proceed one of two ways. An initial detection in one messenger can lead to a search for correlating transients in another. In this case, the follow-up observation must be made before the source fades—a time-critical pursuit. Alternatively, two autonomous detectors of different messengers can be allowed to operate for an extended period of time and accumulate catalogues of data, which astronomers can then search for correlations.

A breathtaking example of such a multimessenger search involved a neutron star merger on August 17th, 2017 (Abbott 1). LIGO detected a gravitational wave, and LSC determined the source to be a neutron star merger. Within 3 seconds, the gamma-ray space telescope Fermi's Gamma-ray Burst Monitor (GBM) detected a short-duration gamma ray burst from the same region in the sky.

The sources of short-duration gamma ray bursts were unknown to astronomers at the time. To establish association between the gamma ray burst and the gravitational wave, LSC first assumed the two transients were not associated. The probability the events could occur simultaneously and in the same pixel of the map is 1/20,000,000. This study confirmed the leading hypothesis—neutron star mergers are a source of short-duration gamma ray bursts.

Spectral analysis followed for this merger's gamma ray signal as it evolved through the electromagnetic spectrum. Potential results may explain the origin of much of our universe's heavy elements, as a large quantity of lanthanides seem to be present in the spectral lines (Abbott "Multi-messenger" 7).

LSC's gamma-ray study is just one example of multimessenger astronomy's power. But the seamless collaboration of all participating observatories is critical for multimessenger astronomy to develop to full capacity. The Astrophysical Multimessenger Observatory Network (AMON) exists to fill this need. Offering an alert system and data sharing to its participants, Pennsylvania State University's AMON is a network of multimessenger observatories that makes correlation studies more efficient (Astrophysical Multimessenger Observatory Network). AMON had 5 participants and 8 prospective participants as of March 22nd, 2018, 8:16 PM CDT.

Multimessenger astronomy has yielded astounding breakthroughs in the few years since its emergence. Even greater paradigms await us as this field matures and technological capabilities improve.

It is well-established that large galaxies host supermassive black holes (SMBHs) in their nuclei. However, it is disputed whether the galaxies or the SMBHs formed first—and the dispute is critical to the major astronomical discipline of galaxy evolution. It is well established that the primary means of growth and development for galaxies early on was mergers and collisions—astronomers believe they were quite common. Nuclear SMBHs, if present, would have interacted during such events. Their interactions would produce low-frequency gravitational wave signatures.

Additionally, it has been noted that some quasars show an unexplained X-shaped morphology (Centrella 6). One hypothesis is that a collision with another galaxy caused a realignment of the beam. Again, the nuclear SMBHs of the quasar and the impactor would have interacted, producing a low-frequency gravitational wave signature.

To investigate either of these questions requires a detector with arm length much longer than the diameter of the Earth. This can only be achieved with space-based precision formation flying arrays. Expected to launch in 2034, the European Space Agency-led Laser interferometer Space Antenna (LISA), with partnership from the National Aeronautics and Space Administration, will take the LIGO mechanism to a scale achievable only in orbit. LISA will be composed of an array of three spacecraft flying in an equilateral triangle at 5,000,000km separation, in Earth-trailing heliocentric orbit (LISA). High-precision lasers will be aligned between the spacecraft. LISA's isolation from thermal noise will allow for unprecedented sensitivity, and its sheer magnitude will grant the detector access to the low-frequency band.

A proof of concept mission, LISA Pathfinder, tested the necessary technology over a period from March to June 2016, and exceeded expectations. ESA measured the acceleration of two test masses in LISA Pathfinder's core, and declared it "the quietest place in space." The force acting on the masses was equivalent to the weight of a single virus on Earth's surface (LISA).

LISA will bring multimessenger gravitational-wave astronomy to its maturity. A detector in space is a significant investment that shows the scientific community takes this promising new field seriously.

The discoveries that have been made have not gone unnoticed, nor have the enticing opportunities for further discoveries that will unlock the mysteries of the universe. This is one mistake Einstein can be very proud to have made.

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