How the detection of neutrinos and gravitational waves can maximize the potential of multimessenger astronomy

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In multimessenger astronomy, scientists combine information from detections of messengers—neutrinos, gravitational waves, cosmic rays, and electromagnetic radiation—to piece together a more complete picture of the source the messengers originated from. Presently, there have been no concurrent detections of neutrinos and gravitational waves from the same source. This paper provides background on the types of messengers, their sources, and recent detections of neutrinos and gravitational waves. Following this, the paper discusses why no concurrent detections have happened—detections are more likely to occur where emissions from sources are pointed in the direction of the Earth. The paper also discusses how with these ideal conditions, concurrent detections could be achieved through more sensitive sensors. The paper ends with the information concurrent detections would reveal such as neutrino production in binary black hole mergers.

Introduction

Early astronomers observed the sky with the naked eye. With the invention and development of the optical telescope, scientists were then able to gather and focus visible light to study stars and galaxies, and with modern-day telescopes, observe the entire electromagnetic spectrum. However, the scope of information gained from electromagnetic emissions is limited. Astrophysical objects that could reveal information on the origins of the universe, like black holes, emit very little electromagnetic radiation, making it difficult for scientists to study them. Furthermore, even if electromagnetic radiation is emitted, the signals are easily distorted on their journey from their source to Earth. For example, visible light can be scattered and reflected. With multimessenger astronomy, new discoveries can be made on these mysterious astrophysical objects. In multimessenger astronomy, scientists combine information from messengers such as neutrinos, gravitational waves, cosmic rays, and electromagnetic radiation, to better understand the universe. Alone, these messengers may reveal parts of the puzzle, but when combined together, they reveal information that the other can not, and provide a more complete picture of their source.

Recent advancements in multimessenger astronomy, with the detection of gravitational waves by the Laser Interferometer Gravitational-wave Observatory (LIGO) and the detection of neutrinos by the IceCube Neutrino Observatory (IceCube), have aided scientists in discovering new information, like formation and evolution, on the sources from which these messengers originated; examples include using LIGO data to place a limit on the idea that neutrinos are evenly emitted in all directions from a binary black hole merger and IceCube data to indicate blazars are sources of high-energy neutrinos. However, presently, no gravitational waves and neutrinos have been detected from the same source as both neutrinos and gravitational waves are difficult to detect; neutrinos rarely interact with matter, while extremely sensitive detectors are needed to detect the distortions created by gravitational waves. Detections of neutrinos and gravitational waves from the same source could provide further information on the location of their source and the astrophysical processes that power it.

This review paper seeks to examine how the detection of neutrinos and gravitational waves from the same source could maximize the potential of multimessenger astronomy. To accomplish this stated research goal, the remainder of this paper is organized as follows. First, in sections two and three, the paper provides background on the relevant astrophysical sources and messengers involved in multimessenger astronomy. This is followed by how these messengers are detected and information gained through their detections in sections four and five. Section six describes recent multimessenger detections involving gravitational waves and neutrinos. The paper ends with an outlook on the field, with what the detection of neutrinos and gravitational waves from the same source could reveal.

Astrophysical Sources

While space probes are reaching distances billions of miles away—Earth's farthest probe Voyager 1 is over 14.1 billion miles away [1]—there are multitudes of large astrophysical objects and events that can potentially help describe the origins of the universe beyond the present reach of probes. For example, we have little information on blazars, binary black hole mergers, and supernovae, which all have masses many times that of the Sun and are billions of light-years away. These objects are targeted by multimessenger astronomy. To provide the necessary context to the reader on why these astrophysical sources are relevant to multi-messenger astronomy, we provide more information on each below. Blazars are galaxies with relativistic jets at their center powered by supermassive black holes[2]. These relativistic jets, which are formed as gas is twisted and squeezed by black holes, shoot out at speeds close to that of light along the axis of rotation of the black hole[3]. Blazars are sources of electromagnetic radiation from high-energy gamma to radio rays, and also high-energy neutrinos. The detection of neutrinos from blazars suggests that blazars are also sources of cosmic rays, as collisions of cosmic rays and particles can produce neutrinos[2]. Furthermore, since they are found at the centers of galaxies, they can potentially reveal information on galaxy formation. Black holes, found at the centers of massive galaxies, are places in space where a great amount of mass is highly condensed. This causes the gravitational field around black holes to be so strong that nothing, including electromagnetic radiation, can escape[4]. Important for the massive amounts of energy they release upon merging, binary black hole mergers are pairs of black holes that are orbiting around each other. As two black holes orbit around each other, they release energy in the form of gravitational waves, making binary black hole mergers one of the strongest known sources of gravitational waves. Their existence was confirmed by LIGO's detection of GW150914 in September 2015, which was the first observation of a binary black hole merger[5]. The detection observed the final milliseconds of the two black holes merging, an event that generated gravitational waves that radiated energies greater than that of all light radiated by all the stars in the observable universe[6]. Important as the light they produce can help measure cosmological distances, supernovae are the explosions of stars at the end of their life. During these high-energy explosions, 99% of the gravitational binding energy[7], which is the energy needed to separate objects bound together, is released in neutrinos. Energy is also given out across the entire electromagnetic spectrum.

Messengers

The messengers involved in multimessenger astronomy —electromagnetic radiation, neutrinos, gravitational waves, cosmic rays— are created in different astrophysical events and reveal information about those events. The term messenger is used as these emissions carry information on where they came from, and when we study these emissions, we can learn about their sources and the processes within them. Each messenger has limitations on the information it provides, but by combining the information revealed by each messenger in multimessenger astronomy, we are able to discover more about their source. We discuss each of the messengers in-depth below.

Electromagnetic Radiation

Electromagnetic radiation, which includes the visible light that humans see, gamma rays, and x-rays, consists of waves from the electromagnetic field. With telescopes, scientists have been able to observe objects across the entire electromagnetic spectrum. Gamma rays produced in space are observed with satellites, x-rays are created in interactions between relativistic jets and interstellar gas, and black holes are observed with x-ray telescopes[8]. A limitation of electromagnetic radiation would be its reflectability, making it difficult to trace the messenger back to its source.

Neutrinos

On the contrary, neutrinos do not have this limitation. Neutrinos, one of the fundamental particles, are created in collisions between particles produced in cosmic accelerators and slower particles. They have no charge, are the lightest of all subatomic particles, and are the most abundant particle in the universe. Neutrinos only interact through the weak force, making it very hard for scientists to detect them. However, neutrinos' properties also make them ideal for providing information on the universe. Because they only interact through the weak force, they travel over long distances without being obstructed by matter. Furthermore, since they have no charge, neutrinos are unaffected by magnetic fields, and thus travel in straight lines from their source[9].

Gravitational Waves

First predicted in Einstein's general theory of relativity, gravitational waves are ripples in space-time produced by massive objects. As the massive objects accelerate, they change the curvature of space-time around them; the effects propagate away from the objects as gravitational waves. While gravitational waves are only produced by massive objects as gravity is so weak compared to other fundamental forces, this minimizes the interactions between gravitational waves and matter, which allows waves to travel through the universe without being absorbed.

There are four categories of gravitational waves: Continuous, Compact Binary Inspiral, Stochastic, and Burst. Continuous gravitational waves are produced by single spinning massive objects. While spinning, bumps in these massive objects create gravitational waves. Furthermore, if these objects spin at constant rates, the gravitational waves emitted will propagate continuously at the same frequency and amplitude, giving them the name ”Continous Gravitational Waves.” Compact Binary Inspiral Gravitational Waves are produced over millions of years by orbiting pairs of massive objects, also known as compact binary systems. As the objects orbit closer together, they emit stronger gravitational waves. There are three compact binary systems: Binary Neutron Stars, Binary Black Holes, and Neutron Star-Black Hole Binary. As the objects involved orbit closer, stronger gravitational waves are emitted. Making up ”background noise”, Stochastic Gravitational waves are waves that may have originated from the Big Bang. Finally, Burst Gravitational Waves are short-duration waves that come from unknown sources [10].

Cosmic Rays

The fourth type of messenger would be cosmic rays, which are extremely high-energy subatomic particles that travel close to the speed of light. While their origins are unknown, for ultrahigh-energy cosmic rays to have energies of at least 1,000 PeV, they must be produced by extreme astrophysical events deep in space that could accelerate particles to that level of energy. Since cosmic rays are diverted by electromagnetic fields they travel through, scientists are unable to trace them to their source. However, neutrinos, which are not affected by electromagnetic forces, are thought to be produced in the same processes that produce cosmic rays. Through the detection of neutrinos, scientists hope to further our knowledge of cosmic accelerators and rays [11].

Detection of Gravitational Waves

Since gravitational waves distort spacetime, to detect them, a detector must be extremely precise to be able to detect any changes in its space. The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a gravitational wave observatory used to detect gravitational waves predicted by Einstein’s General Theory of Relativity. It comprises two laser interferometers separated by 3002 km, one which is located in Hanford, Washington, and the other in Livingston, Louisiana [12]. Using them, scientists study waves’ patterns to determine whether a gravitational wave has passed. Having multiple interferometers, which are structured the same way, help scientists narrow the direction of gravitational wave sources as well.

An interferometer comprises a laser, two mirrors, a beam splitter, and a screen. When the laser shines light against the beam splitter, half of the light passes straight through to the mirror directly in front of the laser, while the other half is reflected to another mirror. The two mirrors reflect the light beams back to the beam splitter, where they interfere and reach the telescope/screen for measurement. When the lengths of the arms are the same, the two waves interfere destructively. When the lengths of the arms are different, when the two waves interfere, their phases difference creates a unique pattern of interference which depends on the extra distance that one of the beams has traveled. LIGO’s interferometers’ arms are 4 km long and lights from the lasers enter the interferometers at around 40 watts [10].

Gravitational waves cause space to stretch in one direction while also compressing in a perpendicular direction. When a gravitational wave passes through LIGO, it squeezes one of LIGO’s arms in one direction while expanding the other in the orthogonal direction [10]. This changes the distance the light waves from the laser beam travel and creates a unique pattern of interference, which affects the brightness of light at the output. LIGO collects data on the intensity of the light which tells us how much the length of LIGO’s arms change. Scientists perform multiple time series analyses on this data to search for significant signals. They also use Fourier analysis to look at the time series as a function of frequency. With the data, scientists are able to determine the wave’s time of arrival and calculate the masses of objects producing the gravitational waves. Furthermore, when a gravitational wave passes through Earth, it would pass through both LIGO interferometers. Depending on the difference in times that each interferometer detects the gravitational wave, and combining information on the masses of objects producing the wave, scientists can determine the direction from which the gravitational wave originated [5].

Detection of Neutrinos

It is very difficult to detect neutrinos as they only interact through the weak force, and thus rarely interact with the atoms of the objects they pass through. Neutrino-observatory IceCube’s location and structure make neutrino detection possible. IceCube is located at the South Pole, making Earth a filter against other particles. As the name suggests, IceCube is a giant cube of clear ice with two and a half kilometer deep holes drilled into it. Inside each hole at a depth between 1450 m and 2450 m is a string with 60 evenly-spaced phototubes, called Digital Optical Modules (DOM), that observe light. IceCube’s 86 strings coverage at the surface and its 5160 DOMs are able to detect single photons, digitize their signals, and operate reliably in the harsh Antarctic environment for long periods of time [13].

When neutrinos interact with the nucleons of ice, deep-inelastic scattering occurs; the high-energy neutrinos break up the bound nucleons, and a large portion of momentum is transferred to the secondary particles of the collision. If a neutrino interacts directly with the nucleons of ice inside the IceCube detector, this interaction only happens once. However, the secondary particles created in the collision re-interact and release their energy throughout the detector. Observing and measuring the properties of these secondary particles allow for the indirect detection of the primary neutrino. There are two approaches for this indirect neutrino detection: optical detection of the secondary particles through the Cherenkov effect and the detection of radio signals induced by interactions of high-energy neutrinos[14]. The first approach is used at IceCube.

The secondary particles released during the collision between high-energy neutrinos and the nucleons of ice travel at nearly the speed of light in a vacuum. Light, on the other hand, travels through the ice at a speed of roughly $2 \times 10^8 m/s$, compared to its speed of $3 \times 10^8 m/s$ in a vacuum, because ice is a more dense medium compared to a vacuum. When the charged secondary particles traverse through the ice, they polarize the molecules along their track and quickly de-excite by emitting spherical waves. The constructive interference of these spherical waves leads to the Cherenkov effect, where a blue glow produced by Cherenkov radiation is seen[14].

IceCube's cubic kilometer of large, dense, glacial ice is perfect for observing this effect. Its 5160 DOMs are able to detect photons from Cherenkov radiation occurrences and digitize their waveform signals. Scientists then investigate these waveforms for clustering to determine the event signatures induced by the neutrinos; scientists are able to generate a digital grid of IceCube's sensors where colored spots indicate DOMs that have detected light. Figure 1 includes a visual example of a digital grid generated by IceCube's sensors. Each DOM is shown by a white dot, and colored spheres show DOMs that have detected light. The color of the sphere indicates the arrival time of the particle, with red as the earliest arrival and green/blue as the latest arrival[13]. The size of the sphere indicates the intensity of Cherenkov radiation emitted. Using this data, scientists are able to calculate various properties of the particle such as its energy. Likewise, we can determine for its source: declination, which is the angular distance of an object from North or South of Earth's equator, and right ascension, which is the angular distance of an object from East or West of Earth's equator[16].

Recent Detections and Limitations

LIGO's Detection of Gravitational Waves from a Binary Black Hole Merger

Following LIGO's upgrade to Advanced LIGO which improved its sensitivity, on September 14, 2015, LIGO's two detectors simultaneously observed a gravitational-wave signal, leading to the first detection of gravitational waves and the first observation of a binary black hole merger. The signal, named GW150914, provided information on binary black hole formation, the black holes merging, and various properties of the gravitational wave detected. First detected at LIGO Hanford, GW150914 reached LIGO Livingston 10 milliseconds later. Using this relative arrival time, scientists were able to determine the general direction the wave originated from. Furthermore, by analyzing the frequency, amplitude, and period of the detectors' frequency band, scientists were able to identify that the frequency and amplitude of the wave increased. As the objects in compact binary systems emit stronger gravitational waves as they orbit closer to each other, the measured increases in frequency and amplitude indicated that the detected wave came from a compact binary system. Further analysis estimated the masses and distances between the two objects involved, narrowing down that they were two merging black holes also known as a binary black hole merger[5].

Immediately after detection, estimates of time and location were also shared with observatories around the world, providing various multimessenger astronomy opportunities. Since the source was a binary black hole merger, electromagnetic emissions were not expected, and follow-up observations did not result in any detections of electromagnetic waves from the source. The accretions around binary black hole mergers are possible neutrino sources. The ANTARES neutrino telescope conducted a follow-up search for neutrino events that could have been detected around the time of the gravitational wave alert and no significant events were found. However, due to this non-detection, scientists were able to place a limit on neutrino emissions from binary black hole mergers[17]. A possibility for the lack of detection is that the direction at which neutrinos were emitted was not in the direction of Earth.

IceCube's detection of a high energy neutrino from blazar TXS 0506+056

On September 22, 2017, IceCube detected a high-energy muon neutrino when the muons created in its collision with ice nucleons emitted Cherenkov radiation. Immediately following the high-energy neutrino detection, IceCube's real-time alert system alerted observatories around the world with an estimate of the direction and energy of the event, allowing for various multimessenger opportunities. While approximately 70,000 muon tracks are recorded from the area in the sky that scientists identified, most of these tracks originate from atmospheric events that create low-energy neutrinos. The detection of a high-energy neutrino from this area in the sky signified that the neutrino came from an astrophysical source. Furthermore, on September 28th, 2017, the Fermi Large Area Telescope Collaboration (Fermi-LAT) reported that in the direction estimated by IceCube, there had been a gamma-ray source in a state of enhanced emission since April 2017[16]. Later, through further analysis of the path of Cherenkov photons emitted and with the Fermi-LAT's previous observation of gamma rays from the calculated direction, scientists were able to determine the direction of the detected neutrino was consistent with the location of blazar TXS 0506+056, showing the power of multimessenger astronomy with neutrinos and electromagnetic radiation.

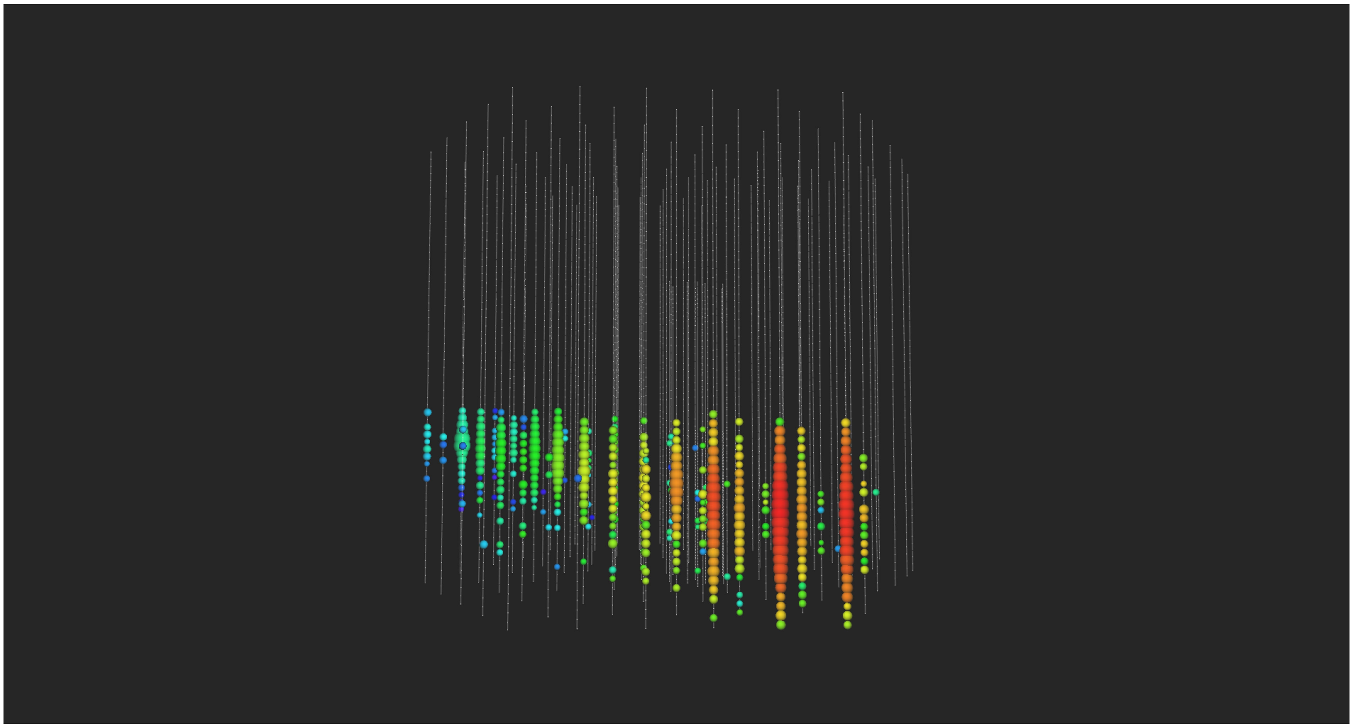

Fig. 1 Visualization of the high-energy neutrino detected on September 22, 2017 by IceCube **Note**. The colors, from red signifying the earliest to green/blue signifying the latest, show the particle's time of arrival [15].

After determining TXS 0506+056 as the source of the detected high energy neutrino, scientists were able to make various advancements in the study of blazars. On years of IceCube data, they applied standard time-integrated analysis and time-dependent analysis, which took into account time, energy, and spectral index, which is the intensity of emissions from radios sources compared to frequency, as parameters, to determine if any neutrino events could have possibly originated from TXS 0506+056 in the past. Particles created in atmospheric events create standard background data. The influx of neutrinos from an astrophysical source creates a significant difference in data. Time analyses involve splitting data into chunks of time and determining if any chunks have significant differences. Outside of the September 22nd, 2017 high-energy neutrino detection, scientists identified 13 ± 5 significant events that all occurred from 2012 to 2015 [16]. The detection of these events indicates that blazars are sources of high-energy neutrinos.

Furthermore, in the weeks following IceCube's detection, observatories around the world observed TXS 0506+056 at various electromagnetic wavelengths including radio waves and x-rays [16]. The multimessenger observation of TXS 0506+056, allowed scientists to estimate the probability that a detected neutrino was correlated with a flaring blazar and also create a new theory on how blazars create neutrinos.

Although scientists knew of the high emissions of gamma rays and radio waves from TXS 0506+056 and the several blazars near it, prior to the detection of high-energy neutrinos from TXS 0506+056, scientists had not identified blazars as neutrino sources. Scientists were able to detect neutrinos from TXS 0506+056 specifically and not other nearby blazars is because IceCube is more sensitive to high-energy neutrinos from sources like TXS 0506+056 that are at declinations near the equatorial plane [16].

Outlook and Conclusion: Multimessenger Observations of Gravitational Waves and Neutrinos

As we continue to explore the universe, multimessenger astronomy will help with answering questions about the universe's most extreme events and the processes that power them. Presently, there have been no multimessenger observations of gravitational waves and neutrinos from the same source; it is difficult as many factors such as type and direction of astrophysical source affect whether or not detectors are able to detect any messengers. However, concurrent detection could reveal a more complete picture of the source. Neutrinos provide a detailed direction of their source as they rarely interact with matter while gravitational waves provide information on their sources' mass, direction, and energy. Furthermore, concurrent detections could also reveal more about the processes within the source. In the case of the detection of signal GW150914, while there were no concurrent detections of neutrinos and gravitational waves, in the search for neutrinos from the binary black hole merger, scientists began by assuming it emitted neutrinos equally in all directions. Given this assumption, neutrinos should have been detected during the time window gravitational waves were detected. However, no significant neutrinos were detected, helping scientists place a limit on the idea that neutrinos are evenly emitted in all directions from a binary black hole merger[17]. Thus, concurrent detections of neutrinos and gravitational waves could also reveal information on neutrino production in binary black hole mergers.

To achieve the observation of gravitational waves and neutrinos from the same source, we can build more gravitational-wave observatories to observe more of the universe and also increase the accuracy of direction estimates. We can also upgrade the sensitivity of existing gravitational wave detectors. Neutrino observatory IceCube is most sensitive to higher energy neutrinos from the Southern hemisphere, as Earth acts as a shield from background events. Coincident detection of gravitational waves and neutrinos would be more likely to occur from sources located in the Southern Hemisphere. Furthermore, detections would be more likely to occur from sources where emitted material, whether it be through high-energy jets or accretion, is pointed in the direction of Earth.

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