Listening to the Universe

On January 4, 2017, astrophysicists working with the Laser Interferometers Gravitational-Wave Observatory (LIGO) were thrilled to record a third detection of gravitational waves originating from the merging of two supermassive black holes. This was no small event. The black holes were located approximately three billion light years away with a combined mass of 49 times our sun, and the energy they gave off was colossal[1]. LIGO is a high-cost experiment installed and functioning since 1994[2]. The Virgo Observatory in Italy has worked in partnership with LIGO for the first three detections. In addition, Universities CalTech and MIT collect data from LIGO alongside the LIGO Scientific Collaboration in an effort to use their findings to broaden understanding of the unseen regions of the universe. With a third gravitational wave measurement, space exploration for astronomers may extend beyond seeing. The invisible oscillations can be used to explain the formation, behavior, and spinning of black holes. Moreover, each detection tests Einstein's Theory of General Relativity through the observation of large masses bending time and space. In operating LIGO, scientists are doing their job to check and confirm scientific theories in order to learn more about the universe.

In the first place, scientists wanted to detect gravitational waves because of how they are uniquely immune to random obstructions in the universe. Matter and gravitational fields do not alter the waves' paths, unlike how visible light is often bent and reflected as it travels through space. This means that their place of origin can be more easily discovered once the signal is recorded, since the journey between the waves' creation and reaching Earth has not been altered[2]. Unfortunately, the LIGO teams waited ten years after activating ther interferometers before sensing any disturbance in mirror length[2]. After increasing the sensitivity of the detectors by making minute improvements to the interferometers' design, LIGO detected a first, second, then third collision created by supermassive black hole mergers whose vibrations lightly tapped the interferometers' mirrors. As a result, the observatory and Earth as a whole, experienced a slight contraction the size of a proton radius. The atomic-sized contraction was caused by a merger three billion light years away. Excitingly, the vast distance proved Einstein's calculations: varying frequencies or gravitational waves all travel at the speed of light[3]. However, this revelation was not as controversial as Einstein's challenging perception of spacetime.

Einstein's Theory of General Relativity first mentioned how mass changes spacetime by altering the distance between two points[3]. In other words, mass bends the path of everything: light, gravity, spacetime, and length. An analogy often used for this difficult concept depicts space wrapping around a ball of extreme mass, potentially prohibiting light from escaping[4]. Earth flexing during the third event in 2017 was a result of a distortion of gravity and spacetime from two supermassive black holes moving their weight around. Before colliding, the black holes were spinning slowly. As the attraction between the two masses increased, they spun faster and faster to maintain a stable orbit, in accordance with Kepler's Third Law. Each time a mass passed Earth, a ripple in spacetime occurred. Furthermore, as their spinning accelerated Earth was struck by these ripples at a greater frequency. Amazingly, Albert Einstein predicted this exact sequence in his Theory of General Relativity: a mass will emit gravitational waves as it accelerates[5]. As the ripples occurred in 2017, LIGO recorded the change in beam length and the wave frequencies in order to measure the speed at which the black holes orbited one another before colliding[6]. The frequency increased to 180 cycles-per-second as LIGO's mirrors moved almost imperceptibly.

After collecting billions of dollars in funds over several decades, LIGO and its sponsors were proud that their data would explain more about black holes in our universe[4]. The third gravitational wave detection proves that binary black holes exist and also explains how they are formed close together, resulting in their eventual union.

Before the first detection in February of 2015, LIGO astronomers lay in wait for atomic-sized tremors that would indicate a massive event light-years away. To sense these tremors, LIGO had to make their equipment extremely sensitive. Two LIGO interferometers exist in the US, one located in Louisiana and the other in Washington. Having two observatories allows data collectors to double check each signal and confirm whether the source is legitimate or simply noise from nearby automobiles[5]. Moreover, LIGO is able to pinpoint where the collision is in space by comparing measurements between the two interferometers. Then, physicists can direct their telescopes toward the estimated position and view the collision. In a way, LIGO utilizes parallax measurements to find approximately where gravitational waves originate. LIGO's twin observatories are constructed 3000 km apart with L-shaped mirrors with a laser of light passing between them. The light beam is split as it is in phase, and the two beams recombine to form either constructive or deconstructive interference. It is important to note that light travels as a wave at a finite speed with oscillating peaks and troughs. In the case that the beams are constructive, the peaks overlap each other and the brightness increases, along with the amplitude. In contrast, deconstructive interference results from a peak and trough overlapping and cancelling each other out, resulting in no visible light. To reiterate, a constructive event is bright and a deconstructive one is dark[2]. In the case that a gravitational wave reaches LIGO, the lengths of the mirrors' arms changes. This interference leads to a change from bright to dark, indicating a ripple in spacetime. When a mirror moves, physicists can rapidly capture the frequencies of the gravitational waves and learn about what emitted them[2].

So far, black hole cases have been more easily detected due to their greater masses. Neutron stars are difficult to pinpoint because of how little light they radiate. When the mass of a neutron star exceeds three times the mass of our sun, then the star's escape velocity is greater than the speed of light. As a result, light cannot escape and a black hole is formed. The merging of black holes or neutron stars produces an immense amount of gravitational power comparable to the energy of all the stars in our universe combined[4]. The waves emitted from the motion of these supermassive objects informs physicists about their masses, location, orientation, and rate of acceleration. The data collected has led physicists to believe gravitational waves from collisions hit Earth every 15 minutes[2].

Each time LIGO senses a distant collision, astrophysicists gain understanding about these extreme cases of gravity[6]. The signals captured explain how black holes behave before colliding, or, more specifically, how they were spinning. The black hole's rotating behavior that occurs simultaneously as they orbit one another tells physicists that black holes behave much like how planets in the Milky Way solar system do[2]. For instance, Earth rotates on its axis as it orbits the sun like black holes orbit on their own axes as they orbit one another. The direction that the black holes are spinning explains how they were initially formed. The first possible explanation is that the black holes were born as two stellar binary giants, eventually dying, blowing up in a supernova explosion, and collapsing into black holes. The second option is that the black holes were formed separately before attracting each other gravitationally. If the black holes demonstrate orbital precession, meaning they are wobbling rather than steady, they were likely formed separately. On the other hand, if the spinning of the black holes are aligned and they do not demonstrate precession, the black holes were likely formed together[5]. For the third event in January 2017, scientists assume that the black holes were born in a non-binary system due to their irregular spinning motion[4]. Without the aid of telescopes, astronomers were able to learn much more about the behavior of the third pair of black holes. However, it took years of research and fine-tuning before reaching this new field in astronomy.

Before LIGO had collected enough funds and support to construct the interferometers, astrophysicists utilized other methods in an attempt to capture barely discernible gravitational waves. For example, in the 1950s physicist Joseph Weber built an instrument made of metal cylinders that was designed vibrate when hit by gravitational oscillations[6]. However, Weber was largely unsuccessful and produced no consistent data. Up until LIGO was established, astronomers primarily used X-ray binaries (XRBs) to study black holes. XRBs are detected when a star is orbiting and being pulled into the extreme gravity of a black hole. After the star falls inward it emits X-ray light which can be measured to determine the mass of the black hole. Yet, the majority of the black holes detected have been located within the Milky Way, in contrast with the tremendous distance between the black holes detected by LIGO and Earth. Moreover, much of the universe, perhaps even 99 % of matter, has not yet been seen[3]. Celestial objects that do not produce light can now be studied based off of the frequency of gravitational waves they generate. Furthermore, the strict limitations of the visible spectrum and/or x-rays wavelengths are no longer in place, and physicists are hoping to gain more understanding of black holes, universal expansion, and the age of the universe.

From what LIGO has determined so far, Einstein is proven correct in his Theory of

General Relativity. The movement of great masses causes contractions here on Earth, meaning spacetime itself is bending. In addition, astronomers know that the specific way black holes spin tells them whether the mergers were born as binary or non-binary. At this moment, another LIGO observatory is being installed in India, while Japan is busy constructing The Kamioka Gravitational Wave Detector in Gifu Prefecture. Scientists are excitedly pursuing this new field in astronomy: the birth and death of black holes. Physicists are hoping that gravitational-wave astronomy will eventually uncover the unseen regions of the universe. In addition, they aim to learn more about the nature of black holes, neutron stars, and how the universe is expanding. By utilizing hyper-sensitive technologies that go beyond the visible and x-ray spectrum, astronomers are able to see and hear the invisible. Further advancements in this research could allow astronomers to detect supermassive bodies twice as far, therefore increasing the area of observable space matter by eight times[6]. This means much more research to come, and more exciting detections to be analyzed.

Works Cited

[1] "LIGO Detects Colliding Black Holes for Third Time." *UChicago News*, 1 June 2017, https://news.uchicago.edu/story/ligo-detects-colliding-black-holes-third-time.

[2]"The First Measurement of a Black Hole Merger and What It Means." *LIGO Scientific Collaboration - The Science of LSC Research*, LIGO, https://www.ligo.org/science /Publication-GW150914Astro/index.php. Accessed 11 November 2019.

[3]Palen, Stacy, et al. *Understanding Our Universe Second Edition*. W.W. Norton & Company, Inc., 2015.

[4]Overbye, Dennis. "Third Gravitational Wave Detection, From Black-Hole Merger 3 Billion Light Years Away." *The New York Times*, 1 June 2017, https://www.nytimes.com/2017/ 06/01/science/black-holes-collision-ligo-gravitational-waves.html.

[5]"Was Einstein Right about Strong Gravity? Using Gravitational Waves from Merging Black Holes to Test General Relativity." *LIGO Scientific Collaboration - The Science of LSC Research*, LSC, https://www.ligo.org/science/Publication-GW150914TestingGR/index. php. Accessed 15 November 2019.

[6]Grant, Andrew. "Weiss, Barish, and Thorne Share 2017 Nobel Prize in Physics." *Physics Today*, American Institute of Physics, 1 Dec. 2017, https://physicstoday.scitation.org/doi/10. 1063/PT.3.3782. Accessed 10 November 2019.