Gravitational Wave Astronomy: The Dawn Has Arrived

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Today I would like to talk about this really brand new topic of astrophysics and cosmology known as gravitational wave astronomy. During my talk please do not hesitate to interrupt me, blame me, complain, or ask questions. Let me first explain what gravitational waves (GWs) are. Many of you may know, but in case some people dont know, GWs are so-called ripples of space-time; fluctuations of space-time itself. Why does space-time fluctuate? This is because of the famous theory of Einsteins known as General Relativity, which was discovered one hundred years ago in 1915. The next year after discovering General Relativity, Einstein discovered these GWs will propagate at the speed of light. However, at the time he never thought these waves would actually be detected due to their incredibly small amplitude, but at least theoretically it was predicted.

Gravitational waves are produced by any system that has mass-energy and motion. Once you have a system with mass-energy undergoing some type of motion, this produces a so-called quadrupole moment in space-time. These quadrupole moments are similar to an elongated ball such as a rugby ball and if you rotate this rugby ball your quadrupole moment is changing in time. In this case you are producing some GWs and because of this quadrupole nature they are referred to as spin-2, but maybe I shouldnt say that yet. Anyway, compared to electromagnetic waves, which are essentially dipolar in nature, with the electric field pointing towards the transverse direction, and the magnetic field perpendicular to the electric field, this will be dipolar because you have a vector which is propagating. In this case physicists call it spin-1. Now in the case of quadrupolar fluctuations if the propagation waves are going towards you, they become oblate and prolate and are known as spin-2. In this case you have the so-called cross mode pattern and plus mode pattern. In total, there are two polarization patterns. So these waves will be produced whenever there is some dynamical motion. For example, even me, or you, when we are walking around like this then our quadrupole moment is changing but the amplitude is so tiny that nobody notices it; but when it comes to all these astronomical bodies, things can change dramatically.

In fact, compact astronomical bodies are one of the most promising candidates in gravitational wave astronomy. The most promising being neutron star (NS) or black hole (BH) binaries. These objects are very compact and are the densest astronomical objects we know of in the Universe. In the case of BHs for example, if the sun (which is about 100 times bigger than the diameter of the Earth) collapses to about a few kilometers then it forms a BH and just before collapse to a BH you have an incredibly dense star called a neutron star. The star itself is so dense it is essentially one huge nucleus. If you have two of these things orbiting each other then they are changing a huge quadruple moment and emit potentially measurable GWs. If you have some slowly changing orbits at first, then because of the gravitational wave emission the system loses energy, the two bodies approach, and the rotation period becomes shorter and shorter. The frequency becomes higher and higher and the amplitude becomes larger and larger. This is called the chirp signal. In the end, the two bodies coalesce and probably form a black hole.

This was the expectation and there have been many theoretical studies into this phenomena. In fact, we had indirect evidence of this occurring in 1974 with the observation of the Hulse-Taylor pulsar system whose period was changing with time. The observation matched the theory so well that it led to the Nobel Prize being awarded for this in 1993. After that, many observational astronomers found many similar systems; but this is still all in- direct evidence because we had not seen any actual gravitational waves, just the result of the wave emission. This all changed in Feb 2016 when LIGO (The Laser Interferometer Gravitational-Wave Observatory) announced that they had actually detected gravitational waves with their detector. The waves came from a black hole binary system- two black holes orbiting, then inspiraling into each other, and merging into a single, larger, black hole. The mass of each progenitor black hole was much bigger than expected, about 30 solar masses each, located roughly 1 billion light years from Earth. It was also a really lucky observation because LIGO was planned a long time ago, took about 20 years to build a nice detector, and then, on the second day during a test run, they found the signal!

LIGO is not just one gravitational wave detector, but actually consists of two detectors. One is located in Livingston, Louisiana and the other is located in Hanford, Washington and they are separated by about 3000 km. Two detectors are necessary to confirm whether or not a wave really truly passed through the Earth or not, and that it was not just some systematic error. The detectors have an arm length of 4 km and an accuracy of 10^{21}. This is so accurate that you can detect a slight change in the distance between the arm lengths at one-hundredth the size of an atomic nucleus. The observed signal matched up incredibly well with the signal predicted by theory. In addition, with two detectors you could actually measure the travel time of the wave from one detector to the next: 7 ms. This observation tells us that the waves are propagating in a particular direction which we can now try to pin-point, albeit not very accurately. It was concluded that the waves came from the approximate direction of the Large Magellanic Cloud.

This is like the time of Galileo; pointing a telescope at the sky for the first time and finding something outside the Earth which we can never see otherwise. Besides this one particular observation of gravitational waves, there are many more events to come.

Just like light, gravitational waves are used as a tool to explore the unknown Universe. Already we know there are unexpectedly many black hole binary systems radiating gravitational waves and we have to explain why there are so many. This poses a very interesting question for the current generation of astrophysicists and cosmologists and may be related to the dark matter problem. This is also the first direct detection of a strongly relativistic gravitational field. All of our previous evidence of black holes has always been indirect; we never actually saw space-time consisting of black holes, but in this case we did. In the case of observing black holes, you also have this so-called quasinormal ringdown tail because black holes can also oscillate in addition to emitting gravitational waves, but the emitted oscillation damps away. The damping rate and frequency is charactisitc to the nature of the black hole. Both of these observations were also consistent with the measured ringdown signal.

Once you have confidence in the theory, you can then use gravitational waves to see astronomical phenomenon. For example, we know how electromagnetic waves are generated and propagate, so we can use them to observe and understand the Universe. So this is only the beginning and we expect gravitational wave astronomy to become more developed in the coming years. We have a new detector nearing completion in Italy called Virgo, which will hopefully be ready soon. In Japan we are building another detector called KAGRA which will hopefully start by 2018. And it was also recently announced that there will be a LIGO India; same as LIGO in America, but in India. Hopefully soon we will eventually have these five large scale detectors operating together and we can then really do a lot of interesting astrophysics.

In addition to ground based detectors, we also plan to go to space to observe gravitational waves.

From space we can observe an even wider range of gravitational phenomena. One such planned detector designed by a Japanese group is called DECIGO and it will hopefully launch by 2030, but nobody knows for sure. In addition there is also the LISA project, from Europe and the U.S., which will also launch around the same time.

Furthermore, there is also the so-called pulsar timing array method for observing very low frequency gravitational waves. In this case you can use natural astronomical objects as the detector; in this case pulsars (rapidly rotating neutron stars). Pulsars are distributed all throughout the galaxy and act as very accurate clocks with a rotational period often on the order of milliseconds. Any changes due to gravitational wave emission will affect these clocks and you can then use them to observe gravitational waves with frequencies as low as 10^8 Hz.

Between ground based detectors, space based detectors, and pulsar timing arrays, we will soon be able to observe gravitational waves with the relative frequency difference on the order of 10^{10}. This is very similar to the electromagnetic case, where we have low frequency radio astronomy, visual optical astronomy, high frequency ultraviolet electromagnetic radiation, x-rays, and gamma rays; a whole band of frequencies by which we can explore and understand the Universe better. In this case we hope to do the same with gravitational waves. By combining gravitational waves with electromagnetic waves and neutrinos, we hope to understand the Universe very deeply.

In summary, the LIGO detection is the first milestone in gravitational wave astronomy- the dawn has arrived! The observed signal is fully consistent with Einstein's theory of general relativity. This was also the first direct evidence of black holes existing in the Universe. The LIGO observation also indicates a need for a new theory for understanding stellar populations that would give rise to such black hole binary systems. Future detector networks, both on ground and in space, will accelerate progress in gravitational wave astrophysics. Gravitational waves are an essential tool for explaining the physics of the unknown Universe in this century! Thank you very much.