Historic Discovery: Gravity Waves!

Detected: September 14, 2015, Announced: February 11, 2016

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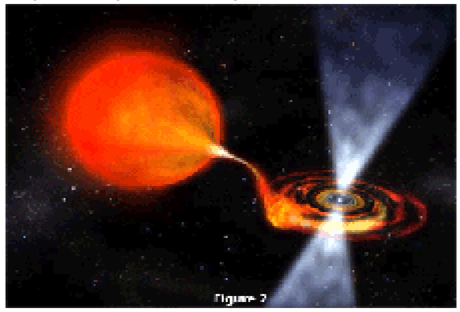

A neutron star such as shown here can fall into each other and create gravity waves

Gravity waves have been detected for the first time! Einstein's theory of general relativity predicted these waves. This is the first time the direct action of gravity waves on earth instruments has been measured. But, what are gravity waves? Why is it important? We will tackle these two key questions and in the process learn about how they are detected.

Why is this important?

The physical world reveals the glory of God! Every new discovery of science tells us something new about the world around us and through that something new about God. Indeed, the three greatest scientists of the modern era, Newton, Maxwell and Einstein, all said that their goal was to better see the beauty and intelligiblity of God.[1] As we know, we must have the eyes to see and the ears to hear this beauty, but we also must have someone explain it to us. We cannot hear and see what is not put in front of us.

Everything we know is known through our understanding of the physical world. It is only through the physical world that we know that God exists. Indeed, *everything* we know comes through what we get through our senses (see *Kid's Introduction to Physics and Beyond*, by Anthony Rizzi). In case you doubt, note you are only learning about this article by using your sense of sight to look at this page! So, what then did we learn about the physical world by this historic discovery?

What was found?

We found something new about that common everyday force, gravity, that gives impetus to bodies to fall to the ground and holds you and I to the earth even against our strongest efforts to jump away from it. We found that it can transmit in a way similar to light.

What are gravity waves? Gravity waves are like light waves.

Just as a light bulb transmits light throughout the room, certain objects in the sky, which are much more massive than the planets, transmit gravity waves. They can even reach us from distances the size of the universe away. Gravity waves travel at the same

[1] Each said this in his own way. It should be noted that Einstein had a rather unclear idea of God, coming as he does as one of the last of the great scientists before the scientistic world view effectively swallowed the scientists ability to see clearly the world beyond his equations (see *The Problem of Our Failing Culture and its Solution* at the Institute for Advanced Physics' *Physics and Culture* magazine site: www.iapweb.org/iapmagazine.htm)

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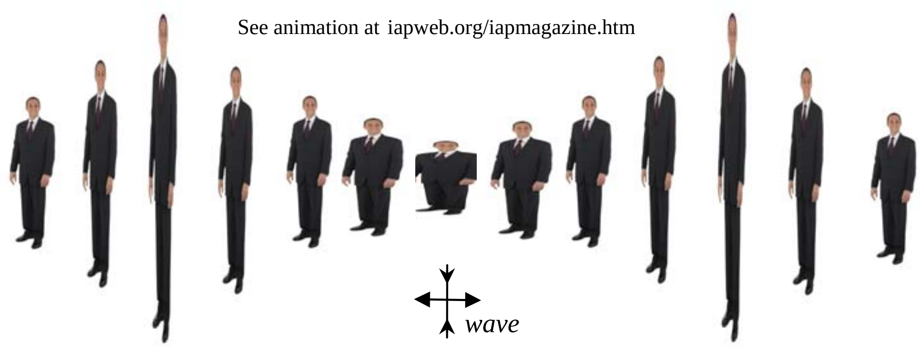
speed as light. Like light, gravity waves have different colors. Visible light has seven distinct colors of the rainbow, red, orange, yellow, green, blue, indigo, and violet. Each color of visible light is associated with a certain range of frequencies of back and forth wave-type motion; this is why we talk about light *waves*. But, there are many other colors than these seven. Of course, there are mixed colors, but there are also colors we cannot see. For example, there are all kinds of colors that have frequencies slower than red light, we call this infra-red light. Indeed, radio waves are a kind of very, very slow frequency light. Light can be generated by moving an electron back and forth. If I could shake an electron back and forth at a rate of 500,000,000,000,000 times in one second, I would make yellow light!

Gravity is similar. However, the pattern of shaking must be different,[2] and one must have very heavy bodies (i.e. bodies with lots of mass) that accelerate greatly to get a strong enough gravity wave to be detected. What effect does a gravity wave have? Well, like a light wave, it can cause impetus in an ordinary body—note: impetus moves a body in a constant direction at a constant speed.[3] When light hits you, believe it or not, it exerts a force on you. The light tries to push you in the direction of its travel. If the light hits you in the stomach, it tries to push you backwards. The force is so tiny that you cannot feel it.

A gravity wave hitting you straight on in the stomach doesn't try to push you backwards; it tries to stretch and smash you. It tries to make you taller and thinner and shorter and fatter as shown below (but much exaggerated to make the point). As the wave goes by, it pulls harder and harder to make you taller and thinner until it reaches its peak force. And, then it decreases in strength and starts trying to make you shorter and fatter and then after that effort reaches its peak it declines and the cylce starts all over again and repeats until the wave passes! Again, the effect is so small that you do not see or feel it.



The gravity wave comes into the page, hits the man's stomach, and stretches and smashes him over time. The man starts his normal size on the left, and, as the gravity wave goes by, we see him change at various points in time. Note that the wave stretches everything so the earth is also stretched.

Detecting Gravity Waves

Now, you can see how we might detect a gravity wave. If we have three bodies floating in space, arranged as shown below, then, as the wave goes by into the page, the distances between the bodies will expand and contract like this (the center mass is made black only to mark it as such):

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[2] They radiate most efficiently when they move in what is called a quadrupole pattern.

[3] See my *Kid's Introduction to Physics and Beyond* and *Physics for Realists: Mechanics*

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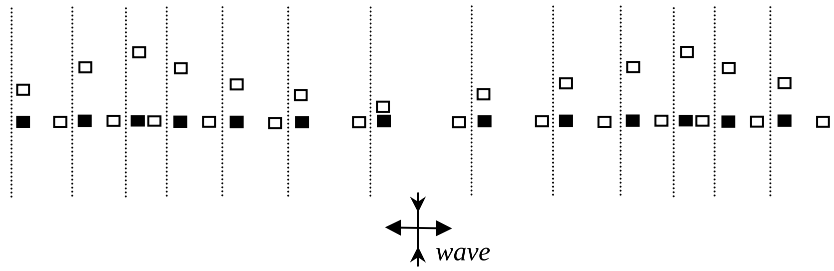
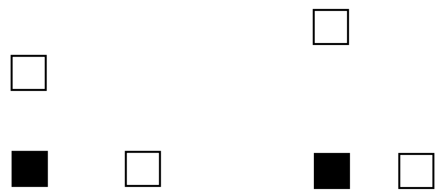


And, also something very interesting begins to happen from the beginning; it is an even smaller effect, but real. Over time, the gravity wave leaves a permant mark that it went by. It, for example, leaves the system stretched and thinned out! The system is permanently changed by the passage of the gravity wave, as shown here:



before gravity wave *after gravity wave*

But, you may ask: how do you measure the change in these distances? This is too complicated to go into detail; but, we can say that we use lasers bouncing between the three end bodies. These bodies, shown as squares, are called "test masses;" these test masses are hung so that they are free floating in the direction of contraction and expansion that the gravity waves cause. The bodies (test masses) are as if they are floating in space. By monitoring the interference caused by the lasers, we can detect very, very small distance changes. You will notice that my pictures show huge, easily discernable, changes in position of the test masses. However, for LIGO's (Laser Interferometer Graviational wave Observatory) first detection, the test masses only moved, not the size of an atom, not the size of the nucleus of an atom, not the size even of one of the protons in the nucleus, but only a few thousandths of the size of the proton! An incredible feat!

Where did the wave come from?

What makes gravity waves in space? Where do they come from? Well, the ones just detected by LIGO, the first ever directly detected, came from outside of our galaxy. They were caused by two very big black holes. Each one about thirty times more massive than the sun! Black holes are places where gravity is so strong that below a certain radius nothing can get out, not even light or gravity waves! Well, with the advent of the advanced area of physics that came after Einstein's theory, quantum mechanics, there are things that come out of the horizon. The black hole slowly evaporates! But that's another article.

These two black holes orbit each other kind of like the earth orbits around the sun, but there is a very big difference. Because the black holes are so massive, they strongly

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radiate gravity waves. This activity results in the black holes losing impetus, thus losing some of their ability to move out of each others gravitational pull. It is as if the energy of the motion of the black holes is transferred to the gravity waves they are emitting. Indeed, the gravity wave has the ability to dump energy into things it runs into; and, unlike visible light, it is very hard to stop a gravity wave. The *gravity wave* just detected carries a massive amount of energy; it carries an energy equivalent to the mass of three suns. Now, as the black holes lose their ability to move away from their mutual gravitational attraction, the orbit tightens and, thus, the holes go faster around each other. This means the color of the gravity wave changes. The waves that we saw coming from this black hole system start out at a frequency of about 35 cycles per second and end when the holes crash into each other at about 250 cycles per second: a huge change in color.

If we make an analogy to sound, it would be a chirping sound, starting out like a hum and then raising up to about middle C, but it only lasts a fraction of a second (.2s) so there are not many cylces to hear and in fact it would sound more like a thump were it a sound. So, the black holes spiral into each other extremely fast at the end, taking only .2 seconds to give their remaining energy to the gravity wave we detect.

There we have it. The wave goes by, leaves its mark (though the mark is too small for us to detect *yet*), and we learn about black holes! This is the first observation of the inspiral of stellar mass black holes. We found that they are about 1.3 billion light years away, which is one twentieth the length of the universe;[4] it is way outside of our galaxy which is only 100,000 light years in diameter. (A light year is how far light travels in a year.)

A new branch of astronomy

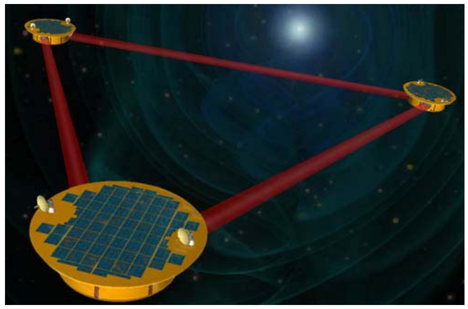
Indeed, a whole new branch of learning has opened up with this discovery. In the past, we could look using telescopes, like Galileo did. Later, we developed telescopes that looked at objects in the sky using radio waves, so called "radio telescopes," like the one at Arecibo, Puerto Rico. Later came gamma ray and x-rays that allowed us to see more about the sun and the stars and other things in the sky. Now, we have gravity wave telescopes, such as this one here in Livingston, Lousiana.

Gravity waves go through things much better than x-rays. This will give us a deep view of the universe: the ability to see much farther. They also reveal a totally different aspect of things than do x-rays. Consider how large the difference is between what x-rays

[4] The universe is about 13.8 billion light years in radius, so we multiply by two to get the total diameter.

reveals about an object such as a star relative to what light reveals. It is a huge difference. Think of an x-ray of a broken hand compared to just looking at the same hand. What is revealed is very different. The difference between the type of things gravity waves reveal relative to x-rays dwarfs even that great difference.

And new gravity-wave telescope, LISA (shown below) which is a kind of space based LIGO, will open up a different color spectrum (different frequencies) of gravity waves.



New physics

We have verified another element of Einstein's general theory of relativity with this detection. It is a complicated theory, but beautiful when understood. Beauty springs from the whole; beauty is the goodness of the truth. The beauty of a woman's face or mountain scene cannot be summarized by pointing to "that part of the nose" or "this tree there." One must see the whole. Now, all the above explanation of the stretching and smashing can be described in terms of stretching of "space," which provides a natural way of working with Einstein's equations of general relativity. Here are the equations: (Don't run away; we will just show them; there will be no test!)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} .$$

This is actually a very complicated system of equations for 10 variables that are a function of time and space. These equations need to be unpacked, which is what I have done for you, but only in one realm of the area of gravity waves. It gives you a glimpse of its wonder.

Gravity waves are predicted by these equations, but you cannot easily tell that there are such things as gravity waves: even if you write out all the complicated equations. In fact, no one took gravity waves seriously until the 1960's, which was 45 years after Einstein's 1915 discovery of these equations. Even people that found the right equations for gravity waves thought they were just artifacts of Einstein's equations, not real!

My work on angular momentum (roughly: understanding how things rotate) in Einstein's theory relates to this issue of gravity waves; it is only by understanding how energy moves around in space that one can understand how spinning works in general relativity. Angular momentum is a key aspect of physical reality, so it is important in understanding all aspects of general relativity including gravity waves.

Did we expect to find gravity waves? Yes, but like with the recently discovered Higgs boson, we did not know they were there till we detected them. We had indirect evidence. But direct evidence is better. That is, evidence in which one's own instruments are being influenced by gravity waves is better than previous evidence. Previous evidence was from watching binary stars fall inward and deducing that they were giving their energy to gravity waves. Furthermore, the more we can probe the details of gravity waves the more we learn about the nature of gravity. LIGO lets us look directly, and in detail, at the wave as it passes by.

We expected Einstein's theory to be correct; so, we came up with a whole bunch of "fingerprints." That is, each type of astrophysical object will emit gravitational waves that are unique in some way to it. This is how we knew that we had found two black holes falling into each other (and, for example, not a supernova). It matches the "fingerprint" of the changing gravity wave frequency predicted by using Einstein's equations.[5] In particular, the signal matches the "fingerprint" of a black hole pair (one of 29 and the other 36 times the mass of the sun), one of which is spinning fairly fast!

We are now set to begin seeing all kinds of objects in the sky through our new window: gravity waves. Perhaps we will find things that we never thought could exist, but, certainly, we will find more about the amazing things we already know exist.

Remember the song: *What a Wonderful World!*

Anthony Rizzi, Ph.D.

Dr. Rizzi worked on the LIGO gravity wave detection project from near its inception, having done his thesis at MIT in 1982 and was the first senior scientist at Caltech's LIGO Livingston site, helping to build up the detector. He is unique in his involvement since he a theorist as well as an experimentalist (rare in any discipline of physics), knowing the LIGO experiment from both angles. He also worked on the early stages of the LISA project and continues to work on gravity waves, though no longer officially involved in LIGO, now working also to understand how quantum mechanics affects our understanding of gravity waves. He is the founder and Director of The Institute for Advanc ed Physics, gained worldwide recognition in theoretical physics by solving an 80-year old problem in Einstein's theory; has physics degrees from MIT and Princeton University. His other work includes projects for the Manned Mars Craft and the Mars Observer and he has received the NASA Award, as well as, a Martin Marietta New Technology Award. He is author of several books, including *The Science Before Science: A Guide to Thinking in the 21st Century* and *A Kid's Introduction to Physics (and Beyond)*. In addition to his professional articles, Dr. Rizzi recently authored two ground breaking textbooks. He appears on TV and radio and is known for his ability to make complex things simple and understandable.

[5] Actually, numerical relativity calculations (i.e., Einstein's equations solved on a computer) are done along with so called post-Newtonian approximations.

A layman's magazine article on Dr. Rizzi's discovery appears in "Science," October 1998, Vol. 282, No. 5387, pg 249.

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