GRAVITATIONAL WAVES: THE "SOUND" OF THE UNIVERSE

José Manuel Carmona[1]
Departamento de Física Teórica, Universidad de Zaragoza, 50009 Zaragoza (Spain)

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One thousand and three hundred million years ago, in a very, very distant galaxy, an astonishing event took place. A cataclysm of proportions difficult to imagine, whose record has been an extraordinary scientific and technological achievement. To illustrate what happened, let us think for a moment about something relatively familiar: the Sun.

Our star contains no less than 99.8% of the mass of the entire solar system, but it is also very large: about one million three hundred thousand "Earth planets" would fit inside. Well, let's take not one, but 29 suns, and compress all that amount of matter to occupy a region about 150 km in diameter, something like the metropolitan area of Madrid or Barcelona. That enormous concentration of matter gives birth to a black hole. Now imagine such an object moving at half the speed of light. Let's take another mole even bigger, of 36 solar masses and similar size, and also at that speed. Finally, let's bump those two monsters, thus giving rise to one of the most extreme events in the Universe. This was the fact that, as we say, happened at a remote time and place.

In that event, the two black holes of 36 and 29 solar masses were merged into a new black hole of 62 solar masses (instead of 65, the sum of 36 and 29). That means 3 solar masses were annihilated, transformed into pure energy, according to Einstein's famous equation $E = Mc^2$. To give us an idea, in an atomic bomb, a few grams or kilos of uranium are converted into an enormous amount of energy. The one produced during the fraction of a second that lasted the black hole collision was the equivalent of 10 billion trillion trillion (a 1 with 34 zeros behind) of Hiroshima bombs. The emitted power (energy per unit of time) thus surpassed that of all the stars of the observable universe together!

Curiously, if we had been more or less near there, we would not have heard the noise of an explosion, since in the outer space there is no air that can carry the sound; we would not have seen a flash of light either, since black holes have the characteristic that nothing, not even light, can come out of them. What the tremendous energy of that collision caused was a deformation in the very structure of space and time, which extended around the newly formed black hole, spreading like a wave.

Right there, that distortion was undoubtedly brutal, creating a kind of hurricane that curved space, stretching and shrinking it in different directions, and speeding up and decelerating time exaggeratedly; something to which we would certainly not have survived. But all this happened in a galaxy far away, one thousand three hundred million light-years from us. This means that this space-time wave, this gravitational wave, travelled to us for one thousand three hundred million years, spreading into ever larger spheres from the source and therefore more weakened.

One fine day, on September 14, 2015, at 09.50 UTC (11.50 hours in Spain at that time), the wave reached Earth. However, its ability to alter space-time was already small. Really small. The wave vibrated several times, and for just a few hundredths of a second, the 4 km arm of the LIGO detector in the USA, changing its length by ... a thousand times less than the size of a proton! Such an inconceivably tiny change is what LIGO scientists could measure, obtaining information on the astrophysical event described above.

[1] E-mail: jcarmona@unizar.es

Such a feat was announced by the LIGO collaboration on February 11, 2016, at a press conference followed live on the Internet by thousands of scientists and science aficionados, who listened holding their breaths and rubbing their eyes, hardly believing that the detection of gravitational waves, predicted by Albert Einstein exactly one hundred years ago, was finally a reality. The various articles with detailed analyzes made public that day by the collaboration, however, left no room for doubt. The impact on the media was immediate. Once again, they remarked, Einstein was right.

So it is curious that Einstein himself, having deduced mathematically the propagation of gravitational waves from his theory of general relativity in 1916, later believed that he had proven they had no real existence in an article entitled *"Do gravitational waves exist?"* which he, along with his collaborator Nathan Rosen, submitted to the journal *Physical Review* in 1936. However, the editor of the journal returned the article to its authors asking for corrections after having received a negative report from the specialist who had reviewed it. Peer review is a common practice today as a quality assurance of scientific publications, but the American magazine was beginning to put it into practice at the time, and Einstein had never been subjected to it. Annoyed with the editor, he withdrew the article without replying to the comments of the anonymous expert who had examined it. He eventually published the paper in a now much less prestigious journal, the *Journal Franklin Institute*, but with a title *("On gravitational waves"*) and conclusions which were very different from those of the original work, since by then Einstein was convinced that, indeed, he had made a mistake and gravitational waves did really exist. It seems that this change of attitude was influenced by conversations with a renowned American relativistic physicist, Howard P. Robertson, who, as we now know, thanks to the archives of the Physical Review, was the anonymous reviewer who had evaluated that first article.

Einstein's doubts were not unwarranted. General relativity is a complicated theory, in which the freedom of choice of coordinates (its main characteristic) can lead to identify as an apparent physical effect something that is really an artifact of a bad choice of coordinates. Since quite some time, however, the international community had already found firm but indirect evidence for the reality of gravitational waves.

In 1974 the first binary pulsar was discovered, an astrophysical object formed by two neutron stars that orbit around each other and that, according to general relativity, should lose energy by emitting gravitational waves. The modification of the orbit due to this emission was measured experimentally in the following years[2], noting that the separation between the two stars decreases about two centimeters a day (they will end colliding in about 300 million years)[3]. These results are in agreement with the predictions of general relativity, and constitute an indirect demonstration of the existence of gravitational waves.

LIGO (for Laser Interferometer Gravitational-wave Observatory) has been able, however, to obtain *direct* evidence of gravitational waves. In order to do so, it has measured the changes that occur in the distance between two mirrors that are suspended as pendulums, separated by a distance of 4 kilometers that is maintained very precisely using all kinds of mechanisms to reduce seismic, thermal or electronic vibrations. These vibrations produce a background noise in the monitoring of the distance between the mirrors, which is performed by what is called an *interferometer.*

In this interferometer, two beams of laser light are sent respectively through two tunnels placed perpendicularly, inside of which a maximum vacuum has been made so that nothing disturbs their path. Both arms, 4 km long, have at their ends exquisitely carved mirrors between which the laser bounces several times. Finally, the two beams of light are gathered together and projected onto a screen. When both rays have traveled exactly the same distance, 4 km, the result of combining them produces dark on the screen (the two light beams interfere *destructively*). If there is a small difference in the length traveled, such as the one that would be produced by the passage of a gravitational wave, both beams are no longer "synchronized" and light

[2] A pulsar emits radiation that can be detected from Earth and from which we can infer orbital properties, for example.
[3] The reduction of the distance due to emission of gravitational waves also occurs in the Earth-Sun system, but it is nothing to be worried about. The loss of power is of about 200 watts (less than the consumption of a toaster), to be compared with the 10^{25} watts emitted in the binary pulsar indicated above.

is collected on the screen. The amount of light can be very small, but it is a direct measure of that difference and, because the wavelength of the light used is of the order of the micrometer and the laser is very intense (which means that the number of photons collected on the screen is large even with a tiny desynchronization in the beams), the experiment has such incredible sensitivity.

Now, how to distinguish the variations produced by a gravitational wave from the background noise, which, as we have said, is constant and produced by other causes? This is the biggest trick: actually there are two LIGO detectors in northern and southern United States, separated about three thousand kilometers. A gravitational wave, which, according to general relativity, moves at the speed of light in the vacuum, takes about ten milliseconds to travel between both venues. This means that the signal produced by the wave, camouflaged over a random noise, will stand out when comparing the data of both LIGO sites, taken with a time difference of a few milliseconds.

The precise shape of the signal, an oscillation in the intensity of light collected as a result of the vibration produced in the LIGO arms, reveals the properties of the gravitational wave and the astrophysical event that gave rise to it. We have thus discovered, not only that general relativity is correct in a very high degree of precision and that gravitational waves exist and can be detected, but also that Nature produces binary systems of black holes with masses dozens of times that of the Sun, and that these black holes come to merge throughout the evolution of the Universe. Just as the sound waves produced by a musical instrument stimulate our ears, the gravitational waves of that fusion have excited the LIGO interferometer. We have not "seen" a black hole, but, following the analogy above, we could say that we have "heard" it.

The detection of September 2015 is just the beginning of a new branch of physics, the astronomy of gravitational waves, whose practical future applications can be difficult to predict[4], but that it will soon revolutionize the way we see the Universe[5]. With it, figuratively speaking, we have acquired a new sense to explore the cosmos.

To date, we had essentially two ways of perceiving the Universe. The first one is through the sense of "sight": our telescopes, both optical, radio or X-ray, collect electromagnetic waves, photons that act as messengers of the sources that produce them and of everything that affects their propagation on their way to us.

The second is by means of instruments that use large extensions of polar or sea ice to detect the elusive neutrinos, particles that are produced in enormous quantities in many astrophysical processes, but that they barely interact, being thus as faint as, perhaps, a fragrance. This sense of "smell" allows one to study, for example, the interior of the Sun or the bursting of a supernova.

With the detection of gravitational waves, we have the ability to "hear" what we might call the "sound" of the Universe. LIGO and other detectors that will soon join it as a global network of gravitational wave observatories will be the "ears" that will bring us the echoes of black holes or neutron stars, but also of other more exotic objects. Today unknown objects that, although like black holes, do not emit light or neutrinos, they will be affected like them by the only truly universal interaction: gravity, which connects the very space with the mass and energy of the bodies that are inside it. Each of these objects will sound with a characteristic pattern in the received gravitational wave, and the careful analysis of this signal will allow us to understand its properties.

What new sounds will these ears hear? What new findings will reveal us, which we still cannot even imagine?

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[4] In fact, a major oil company is already testing the usage in prospecting of a seismic detector which had been designed for use in gravitational wave detectors. Every basic research ends up producing practical applications, and even more so in cases like this field, which requires the most cutting-edge technology in disciplines as diverse as seismology, vacuum engineering, engineering of control systems or quantum optics, among other.

[5] In fact, the LIGO collaboration has recently confirmed a second detection occurred on December 25, 2016. The merging of black holes in the Universe is more frequent than we had previously imagined.