Notes on discoveries of gravitational waves as new History of Physics frontier research programme

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Abstract: The detection on September 14, 2015 at 09:50:45 UTC of the LIGO Scientific Collaboration and Virgo Collaboration opened a scientific era towards a new cosmology. The physics of waves is one of the main current frontier fields of physics, although these detections happened 100 years after their predicted existence by Albert Einstein's (1879-1955*) Theory of Relativity*. Recent roots reach as far back as to Sir William Kingdon Clifford (1845–1879). The latter proposed that the nature of space was non-Euclidean, and worked on the shift in light polarization during an eclipse. However, an early mention of gravitational waves *per se* seems belong to Henri Poincaré's (1854-1912) *Sur la dynamique de l'électron* (1905) in which he talks about the existence of "onde gravifique". We briefly present historical notes on the discovery of gravitational waves as currently object of doctoral research by one of us.

Keywords: Astronomy, History and Epistemology of Physics, Nature of Science Teaching, Gravitational waves, Physics–Mathematics Relationship, Intellectual History

1. What is the story?

1.1. On gravitational waves (1920; 1937; 2015-present)

The LIGO (Laser Interferometer Gravitational-Wave Observatory) and Virgo (Virgo Cluster) Scientific Collaborations addressed to the direct[1] detection of gravitational waves in the emerging field of gravitational waves; science as a tool for astronomy and cosmology research, upgrading and exploitation of detectors, in order to inquire the fundamental physics of gravity.

Albert Einstein's theory of General Relativity made predictions, for instance, about the perihelion precession of Mercury, the Universe as dynamic structure, problems with trajectory of light (Einstein 1920, pp. 148-159), to name a few, and of course, gravita-

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[1] As in https://www.ligo.caltech.edu/ through the use of interferometers and by opposition of the indirect proof of the existence of gravitational waves made by observing the orbital decay of the Hulse-Taylor binary pulsar that lead to the Nobel Prize in Physics of 1993.

tional waves (Einstein 1937). Generally speaking, the *Relativity*, space and time magnitudes are no longer separate entities: they are unified as one unique entity: *spacetime*. In this new – at that time – conceptual framework, the gravity has a geometrical structure (Einstein 1920); different from Keplerian–Newtonian paradigm (Pisano, Bussotti 2017; 2012; see also Newton 1729, III, Pr. VIII, Th. VIII, p. 226). The gravity arises from a topology inquiring and included *ad hoc* geometrical properties of *spacetime*.

In this context, "*spacetime* tells matter how to move, and matter tells *spacetime* how to curve" (Wheeler, Ford 2000, p. 235). In other words, gravity is conceptualised as a field; a gravitational field, co-dependent with (the presence of) matter and/or energy. In this new structure, the more mass-energy in a region of *spacetime*, the more the associated region of *spacetime* is curved as a result (Einstein 1920, pp. 135-137).

Let us now consider two extremely massive objects orbiting around one another like a pair of neutron stars or a pair black holes. According to Einstein's theory (Weisberg, Taylor 2005), this binary system should be spiralling closer and closer, more and more rapidly our two celestial bodies get. In this case, two black holes may be slowly spiralling for billions of years and end up coalescing together in an instant, progressively rotating faster and faster until reaching relativistic speeds some moments before the merge. Such catastrophic events involving very massive objects exert extreme constraints on the surrounding regions of space and produce very intense disturbances in *spacetime,* and these disturbances then propagate at the speed of light in all directions, through the entire universe, passing through matter almost unaffected but decaying in power following an inverse square law with distance. Because of this last fact, when gravitational waves reach us after having travelled for billions of years, they are minuscule. Einstein himself doubted (Einstein 2005, p. 122) that we could ever manage to measure them if they existed as the scales involved are preposterous.

Recently, on September 14th 2015, about 100 years after their existence had been predicted (LIGO 2016, p. 6), a first direct detection of gravitational waves was made by the Advanced LIGO detectors, which are part of the LIGO-Virgo collaboration. The two LIGO detectors are located far from one another in order to minimize the risk of detecting a signal unrelated to gravitational waves due to environmental noise. The event that generated the gravitational waves detected was the collision of two black holes, and took place about 400 Mparsecs or 1.3 billion light-years from Earth, which is equivalent to say that this incredible event took place 1.3 billion years ago. This binary black hole merger involved a pair of black holes of estimated 36^{+6}_{-4} and 32^{+4}_{-5} solar masses (LIGO 2016, p. 6).

1.2. On History of Physics research program (2017-present)

Historically, we perform a re-thinking about the role played by physics-mathematics relationship and the measurements-procedures for inquiring gravitational waves, also examining correlated scientific and NoS-historical-epistemologically items. Particularly, part one of Vincent Ph.D. thesis is focused on the *Physics of Waves* also for nonphysicist readers (Vincent 2017). The second part of that thesis is on the history of waves and the case of gravitation: gravitational waves theoretical methods, experimental observations and data, how gravitational wave signal detection has evolved to the interferometers methods. The last two final parts are focusing on the *Analysis of Teaching-Learning as Nature of Science Inquiry* and *Didactic and Epistemological Inquiring* with sections on the *Nature of Science Teaching*.

2. On Sir William Kingdon Clifford (1867; 1870)

William Kingdom Clifford was an English mathematician who worked with Bernhard Riemann (1826-1866). As his follower, Clifford was interested in Riemann's mathematical-geometrical work and ideas about his theories regarding curved spaces. He translated some of Riemann's works from German to English (Riemann 1854; Clifford 1867).

A few years later, in 1870, Clifford gave a lecture entitled "On the Space-Theory of Matter" (Clifford 1976) to the Cambridge Philosophical Society, where he referred to Riemann's research:

> Riemann has shewn that as there are different kinds of lines and surfaces, so there are different kinds of space of three dimensions; and that we can only find out by experience to which of these kinds the space in which we live belongs (Clifford 1870, pp. 157-158).

In this lecture, he focussed on the results on the relations between physical space and the geometric axioms of three-dimensional spaces of constant curvature and presented some of the ideas he developed. For instance, he postulated that the intrinsic nature of physical space is non-Euclidean and therefore that the axioms of Euclidean geometry are not valid in them. He then proceeded to explain their apparent validity being a question of an averaged deceptive flatness due to the scale considered by using a sheet of paper as an example:

> In particular, the axioms of plane geometry are true within the limits of experiment on the surface of a sheet of paper, and yet we know that the sheet is really covered with a number of small ridges and furrows, upon which (the total curvature not being zero) these axioms are not true. Similarly, he [Riemann] says, although the axioms of solid geometry are true within the limits of experiment for finite portions of our space, yet we have no reason to conclude that they are true for very small portions; and if any help can be got thereby for the explanation of physical phenomena, we may have reason to conclude that they are not true for very small portions of space (Clifford 1870, pp. 157-158).

Particularly important in above example is what conclusions an observer would draw depending on the chosen scale. When looking at the sheet of paper, one could see it as flat and representing a Euclidean two-dimensional space – not counting its thickness – in which "the ordinary laws of geometry" are true. However, when changing scale and looking closer at the constituents of the paper, one would observe a completely different kind of space. Still ignoring the thickness of the sheet of paper, the observer, if looking close enough, would notice that this space is clearly not flat, but a collection of intertwined fibres. Clifford continues by also stating that “the motion of matter” – gravitation – could be formally represented by this underlying geometry:

> I hold in fact (1) That small portions of space *are* in fact of a nature analogous to little hills on a surface which is on the average flat; namely, that the ordinary laws of geometry are not valid in them. (2) That this property of being curved or distorted is continually being passed on from one portion of space to another after the manner of a wave. (3) That this variation of the curvature of space is what really happens in that phenomenon which we call the *motion of matter*, whether ponderable of etherial. (4) That in the physical world nothing else takes place but this variation, subject (possibly) to the law of continuity (Clifford 1870, p. 158).

Regarding these statements, and in particular his points “(2)” and “(3)”, Clifford was onto something when talking about the property of space to be curved or distorted after the manner of a wave and that this variation is influencing the *motion of matter*.

3. On Henri Poincaré’s (1905)

As good as the intuition of Clifford was, and despite using the keyword “wave” when saying “after the manner of a wave” to describe the propagation of a variation in the geometry of space almost a decade before Einstein was even born and almost three decades before Einstein’s theories, the first mention of gravitational waves *per se* could be attributed to Henri Poincaré.

In Poincaré’s paper *On the dynamics of the electron* (Poincaré 1905), talking about “determining the absolute motion of the Earth” with respect to the ether, as opposed to its motion “with respect to other celestial bodies” thanks to “the aberration of light and related optical and electrical phenomena”, Poincaré discusses Lorentz’s postulate of the contraction of all bodies in the direction of the motion of the Earth as an explanation for Michelson’s experiment results:

> But Michelson, who conceived an experiment sensitive to terms depending on the square of the aberration, failed in turn. It appears that this impossibility to detect the absolute motion of the Earth by experiment may be a general law of nature [...]. An explanation was proposed by Lorentz, who introduced the hypothesis of a contraction of all bodies in the direction of the Earth’s motion (Poincaré 1905, p.77).

From this postulate and, according to Poincaré, as Lorentz judged necessary to extend his hypothesis for all forces and not just electromagnetic forces, Poincaré reflected on what modifications could be applied to the laws of gravitation in order for them to follow Lorentz postulate.

In order to do so, Poincaré thus had to make the assumption that the transmission of gravity is done at the speed of light even if "Laplace demonstrated that this cannot be the case":

> It was important to examine this hypothesis closely, and in particular to ascertain the modifications we would have to apply to the laws of gravitation. We find first of all that it requires us to assume that gravitational propagation is not instantaneous, but occurs with the speed of light (Poincaré 1905, p.80).

Poincaré then continued his reflexion about the transmission of gravity done at the speed of light between different bodies and finally coined the term "gravitational wave":

> Remember that when we speak of the position or velocity of the attracting body, this refers to its position or velocity at the instant the gravitational wave [*onde gravifique*] takes off; for the attracted body, on the contrary, this refers to the position or velocity at the instant the gravitational wave arrives (Poincaré 1905, p. 80).

Unfortunately, Poincaré refrained from continuing his analysis further and concluded his paper with a few remarks regarding the deviation with the ordinary law of gravitation and the precision of astronomical observations.

4. Concluding Remarks

Following Riemann's researches, Clifford postulated that the geometry of physical space was influencing the "motion of matter" which can be understood as gravitation.

According to Poincaré, Laplace postulated that the transmission of gravity was not instantaneous but done at a speed much faster than that of light; however, Poincaré set it to the speed of light and coined the term "gravitational wave" during his analysis.

The roots of our "history of the discovery of gravitational waves" try to detail on less known specific research-contributors to the scientific breakthroughs and innovative ideas in physics-mathematics.

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