

The birth of the gravitational-wave astronomy

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Summary. — Last years marked the beginning of a new era of observations of the Universe. Gravitational waves were detected from a binary black-hole merger by the Advanced LIGO detectors. Simultaneously, LISA Pathfinder demonstrated the technology for gravitational-wave observation in space beyond its planned requirements. Many gravitational observations and discoveries are expected in the next years with the Advanced LIGO and Virgo detectors, with strong impact on various astrophysical fields, from the physics governing compact object formation and evolution to the physics of the emission process and to nuclear astrophysics. I summarize here some historical milestones that led to the first detection and report the perspectives of the field. I also discuss the importance of the so-called multimessenger astronomy in which gravitational-wave sources will be observed in all bands of the electromagnetic spectrum with ground and space observatories and with neutrino telescopes.

1. – Introduction

Long is the path of knowledge that has led *Homo Sapiens* to detect for the first time gravitational waves on September 14, 2015 [1]. The waveform agreed with the prediction of general relativity for the emission of gravitational waves during the inspiraling and merging of two black holes of, respectively, 36 and 29 solar masses, at a distance of 1 billion and three hundred million light-years from the Earth. A single final black hole of 62 solar masses was formed from the collision. The 3 missing solar masses are equivalent to the energy emitted in the form of gravitational waves during the event. This was the first direct detection of a gravitational wave, 100 years from Albert Einstein's theoretical prediction and after more than 50 years of experimental efforts. It was also the first time that the merging of a binary black hole system was observed. These measurements give us for the first time direct access to the space-time properties in a regime of strong gravitational field and high speed (the two black holes at the time of the fusion have a speed of more than half that of light). It has been a historical moment for science

and for mankind. We actually are able to perceive the vibrations of space time, which can be compared to the ability to “listen” to the Universe, so far only “seen” with photons. Let us look at some of the steps that have led to this result, and at some future perspectives.

2. – 50 years of experimental efforts

In 1916, the year after the formulation of the equations of general relativity, Einstein predicted the existence of gravitational waves. He found that in the weak field approximation, where the metric tensor was that of Minkowski’s flat space-time with the addition of a small perturbation, its field equations linearized and had simple solutions: transverse waves of spatial deformation traveling at speed of light, generated by time variations of the mass quadrupole moment of the source [2].

Einstein immediately understood that the gravitational waves would have been of very small amplitude (“a practically vanishing value”) and for many years the issue of gravitational waves fell into oblivion. The steady progress of astronomy, in particular the discovery of compact objects like neutron stars and black holes, and the significant developments in technology, changed the perspectives. It should be considered, however, that up to the 1950s a debate was alive, that today can look surprising: were gravitational waves a real, measurable effect, or were they just a fictitious effect, eliminable with a transformation of the coordinates? Einstein oscillated between these two positions and was often on the second front [3].

A turning point in the history of the search for gravitational waves occurred in 1957 at the “Conference on the Role of Gravitation in Physics” held at Chapel Hill, University of North Carolina [4]. Key events at this conference are very well narrated by Peter Saulson [5]. The question on the agenda was the physical reality of gravitational waves and their interaction with a possible detector.

Felix Pirani proposed to observe the gravitational effects by measuring the relative acceleration of two bodies in free fall. He clearly connected the equation of geodesic deviation of General Relativity with Newton’s second law, identifying some components of the Riemann tensor with the second derivatives of the Newtonian potential, that is, with the tidal field. Hermann Bondi, present at the conference, immediately understood the essence of the message: in presence of a gravitational perturbation, or rather a gravitational wave, a system of two bodies connected with a spring would absorb energy, a measurable effect, because of their relative acceleration. Or if one of the two bodies is equipped with a source of light and a detector and the other with a mirror, the time taken by the light to travel back and forth the distance between the two bodies would change, as their distance would change, and this effect can also be measured. Richard Feynman, also present, blessed this conclusion.

There was another physicist present at that conference, following all the talks. His name was Joseph Weber. He was professor of Electrical engineering at the University of Maryland, and had already a brilliant idea for the realization of what would then become the maser. In 1955, he was in Princeton with a Guggenheim fellowship, working with John Archibald Wheeler. Shortly after the conference at Chapel Hill, Weber and Wheeler wrote a paper where they illustrated how to extract energy from a gravitational wave. In February 1959, Weber made another step forward, publishing on Physical Review “Detection and Generation of Gravitational Waves”, in which he described his program for the realization of gravitational-wave detectors [6]. His detector consisted of an aluminum cylinder of a couple of tons of mass, where the vibrations

of the fundamental longitudinal mode were monitored. The cylinder played the role of the two test masses of Pirani connected by a spring. Ultimately, it was a giant diapason equipped with piezoelectric ceramic to convert the mechanical vibrations in electrical signals.

Weber realized two detectors, placed them at 1000 km distance and analyzed the data in search for coincident signals. In fact a gravitational wave would put in vibration simultaneously the two oscillators (by 3 thousandths of a second at most), allowing to distinguish the signal from the possible causes of local noise.

It took great faith to start this research at a time where black holes and neutron stars were objects just barely imagined, but not known in any astrophysical context.

In the late 1960s, Weber found some coincidences in its antennas and believed that he had detected gravitational waves coming from the center of our Galaxy [7]. Years of emotions followed, with the birth of new groups all over the world to replicate the experiment. Years of controversy. Finally, from the mid-1970s, a growing consensus was reached in the newborn community on the incorrectness of the conclusions of Weber. However, in the meantime the seeds planted by the Chapel Hill conference and by Weber with his announcement were flourishing.

Then came Hulse and Taylor with the observation of the loss of energy of the binary pulsar PSR 1913 + 16, providing the earlier possible evidence, albeit indirect, of the existence of gravitational waves [8].

Experimenters, since then and in four continents, have been engaged in these researches without stopping using sophisticated cryogenic versions of Weber resonant antennas, or by building giant detectors based on laser interferometry.

These researchers are heirs of two great experimental traditions. One is the tradition of the precision mechanical experiments, exemplified by the work of Cavendish, Eotvos, Dicke, Braginski. At the heart of any experiment on gravitational waves there are masses isolated from the external noise, in conditions as similar to the ones of ideal bodies in free fall as possible. The other tradition is the one of precision optical measurements, started with Michelson, and supported by the developers of lasers and by the pioneers of microwave technology.

Several countries have a tradition in the quest for gravitational waves. For a significant historical panorama of the activity of the GW community in mid 90s, where both the past experiments and the future projects were represented, see [9].

Some words about Italy, where the activity is as old as 1970, when Edoardo Amaldi and Guido Pizzella in Rome started an Italian activity on resonant antennas to become protagonist for many years at international level, first at CERN with the antenna Explorer, then at the INFN Laboratories in Frascati with Nautilus and at the INFN Laboratories of Legnaro with Auriga (conducted by Massimo Cerdonio).

In the 80s Adalberto Giazotto proposed successfully to INFN the realization of an ambitious project: a great laser interferometer in Italy. From the work of Giazotto and a few pioneers, including Alain Brillet who led the French CNRS to cofund the project, the Virgo Collaboration flourished in Cascina, near Pisa, where an international laboratory was established: EGO, the European Gravitational Observatory.

USA was the first country where the leading vision of large laser interferometers—started in MIT and Caltech—won the competition with resonant bar detectors. A vision which became a reality with the two LIGO detectors, that with Virgo are recognized today as the most advanced GW Observatory.

3. – The first detection

A gravitational-wave observatory is based on detectors widely spaced to distinguish signals from local instrumental and environmental noises. This also allows to locate the position of the source from the time of arrival of the signal received by the individual detectors, and also, in principle, to determine the wave polarizations thanks to the measured amplitude of the signals at the different sites. The detectors involved in the discovery are Michelson interferometers, and measure the deformation imposed in space by the passing gravitational wave through the different effect in the lengths of their perpendicular arms. In the LIGO detection, the distance $L = 4$ km of each arm varied of about $dL = 10^{-18}$ m. The wave amplitude h (by definition it is a deformation and therefore adimensional) is: $h = dL/L = 10^{-21}$. 50 years of experimental efforts were needed to measure a change of a billionth of a billionth of a meter.

The discovery paper illustrates the results of the analysis of 16 days of observation in coincidence between the two LIGO detectors, from September 12 to October 20, 2015 [1]. That is just a part of the overall data taking period, lasting until January 12, 2016 and subject to further analysis. The signal was baptized as GW150914, from its date of arrival, and has emerged from two types of analysis. One is optimized to detect signals of coalescence of compact objects, using filters fitted with the waveforms predicted by general relativity. The other identifies a broad range of generic transient signals with minimal assumption on the expected waveform. Both analyses have clearly identified the GW150914 event.

The features of GW150914 indicate that its origin is the coalescence of two black holes, that is, the final phase of their mutual orbiting motion, their collision and the formation of the final black hole. In about 0.2 s, the signal increases in frequency and amplitude, running in 8 cycles from 35 Hz to 150 Hz, frequency at which the amplitude reaches the maximum value.

The natural explanation of this evolution is the spiraling of two masses, due to gravitational-waves emission. This waveform is called conventionally chirp and its evolution is characterized by the parameter known as chirp mass, depending on the values of the two masses. To reach a gravitational frequency of 150 Hz, and hence an orbital frequency of 75 Hz (the gravitational signal frequency is twice the orbital frequency, consequence of the quadrupolar nature of the gravitational radiation) the two objects must be very close and therefore very compact. Two equal masses (resulting in the measured chirp mass) would be orbiting at 75 Hz when approaching a distance of 350 km. Two neutron stars, though compact, would be much lighter (typically 1.4 solar mass each one) and on the other hand a binary system consisting of a black hole and a neutron star would have a very large total mass and would collide at much lower frequency. This leaves two black holes as the only pair of compact objects able to reach as distinct objects an orbital frequency of 75 Hz. In addition, the waveform amplitude decay after the peak is consistent with the damped oscillation of a rotating black hole that reaches the stationary configuration. I leave aside the detailed results and the description of the analysis, reported in the discovery paper. It is however worth mentioning here that several analyses have been accomplished with the aim of determining whether GW150914 is consistent with a black holes system in general relativity, with affirmative answer. Gravitational waves were not “dispersed” in the observed signal, that is, all the Fourier components of the signal have propagated at the same speed (within the limits of sensitivity of the experiment, of course). This limits the Compton wavelength of the graviton to be greater than 10^{13} km. The data can also be interpreted as a limit on the graviton mass, which

must therefore be less than $10^{-22} \text{ eV}/c^2$. This improves all other previous limits due to measures in the Solar System and to the Hulse and Taylor pulsar system.

In short, all tests on GW150914 are consistent with the predictions of general relativity [10].

GW150914 demonstrates for the first time the existence of black holes of stellar mass greater than 25 solar masses, more massive than those hitherto identified by the study of X-ray binaries where a compact object accretes matter taken by a star companion (as in the case of the famous Cygnus X-1). It also establishes, obviously, that a binary system of black holes can form and merge into a time lower than the age of the Universe. None of these statements was obvious.

The study of the astrophysical implications of the existence of such a system, only possible as a result of stellar evolution in environments of low metallicity is only at the beginning.

4. – Multimessenger astronomy with gravitational waves

One of the most promising issue of contemporary astrophysics is the investigation of the most powerful and violent events in the Universe, taking advantage of the simultaneous observations of all possible cosmic messengers: photons at all wavelengths, cosmic rays, neutrinos and gravitational waves. The goals are to gain a more complete understanding of cosmic processes through the combination of information from the different probes, and to increase search sensitivity over an analysis using a single messenger. For a recent and detailed review, see [11].

The first direct detection of GWs has created excitement. Some of the most promising astrophysical sources of GWs are expected to produce broadband electromagnetic (EM) emission and also neutrinos. The presence or absence of any EM or neutrino signature will provide constraints on emission mechanisms, progenitors and energetics of the GW source, as well as its environment. New windows in unexplored domains of the physics of supranuclear density matter and very strong, time-varying gravitational fields can be opened.

Focusing the attention on joint GW and EM observations, one can say, in general, that EM observations are key to localize and characterize the astrophysical source, to probe the physics of its environment and the distribution of magnetic fields, while GWs provide insight into its mass distribution and gravitational fields in the strong regime. Several detectable GW sources, like core-collapse supernovae, binary NS (BNS) or NS-BH (NSBH) mergers, and the early evolution of new born highly magnetized NSs, are expected to be accompanied by EM emission across the spectrum and over time scales ranging from seconds to years.

For transient GW sources, multiwavelength observations are crucial to find an EM counterpart and improve the source localization down to the arcsecond level, leading to the identification of the host galaxy and measurement of the redshift. This will allow not only to determine the EM intrinsic luminosity of the GW source, but also improve upon the measurement of its extrinsic GW properties, among them the GW luminosity distance. This will allow to break degeneracies present in the signal and to obtain for the first time an independent measure of the Hubble constant using general relativity as the only calibrator [12,13]. EM observations will also help in supporting and guiding searches for continuous GW sources, like asymmetric spinning NSs (*e.g.*, pulsars), both isolated and in binary systems, ranging from the radio to the gamma-ray band, and will be crucial to probe the physics of matter at supra-nuclear densities that cannot be tested on Earth

laboratories and the environment of strongest gravitational fields in the Universe, leading to a breakthrough of paramount importance to both physics, astrophysics and cosmology.

Let us be more specific considering the important example of a compact binary coalescence (CBC). In a CBC event, a tight binary comprised of two neutron stars, two black holes, or a NS and a BH, experiences a runaway orbital decay due to gravitational radiation. In a binary including at least one NS, we expect EM signatures due to energetic outflows at different timescales and wavelengths. The coincident detection of a short gamma-ray burst (GRB) and GW signal would provide the first direct evidence that short GRBs are associated to the merging of two compact objects and will discriminate on their nature (BH or NS). It will further yield a wealth of information on the mechanism powering the GRB. If a relativistic jet forms, the prompt short gamma-ray burst (GRB) lasting on the order of one second or less, will be followed by X-ray, optical, and radio afterglows of hours to days duration. Rapid neutron capture in the sub-relativistic ejecta is hypothesized to produce a kilonova or macronova, an optical and near-infrared signal lasting hours to weeks. Eventually, we may observe a radio blast wave from this sub-relativistic outflow, detectable for months to years. Furthermore, several seconds prior to or tens of minutes after merger, we may see a coherent radio burst lasting milliseconds. As it is evident from these examples, a NS binary can produce EM radiation over a wide range of wavelengths and time scales.

On the other hand, in the case of a stellar-mass BBH, the current consensus is that no significant EM counterpart emission is expected (and the GW150914 observation confirms this view) except for those in highly improbable environments pervaded by large magnetic fields or baryon densities.

In short, the benefit of coupling GW and EM observations will be tremendous, and will bring the study of the GW signals fully into the realm of astrophysics and cosmology.

The new field of multimessenger astronomy includes also neutrino observations. While GWs are produced by the bulk motion of the progenitor, typically carrying information on the dynamics of the source's central region, high-energy neutrinos require hadron acceleration in, *e.g.*, relativistic outflows from a central engine. Astrophysical processes that produce GWs may also drive relativistic outflows, which can emit high-energy radiation, such as GeV–PeV neutrinos or gamma rays.

The search for common sources of GWs and high-energy neutrinos has recently become possible with the construction and upgrade of large-scale observatories. High-energy neutrinos of cosmic origin have been observed, for the first time, by IceCube [14,15]. Their detection represents a major step towards multimessenger astronomy.

IceCube is also sensitive to low-energy (MeV) thermal neutrinos from nearby supernovae, and contributes to the Supernova Early Warning System (SNEWS) network along with several other neutrino detectors in underground laboratories in Kamioka, Gran Sasso and Sudbury. Supernovae have been at the forefront of astronomical research for the better part of a century, and yet no one is sure about how they work. Hence there are important scientific motivations for a joint analysis of GWs and low-energy neutrino data to probe the processes powering a supernova explosion.

5. – Conclusion

The detection of the first GW signal marks the birth of the GW astronomy.

The LIGO Hanford and Livingston sites are just the first two advanced detectors nodes [16] of a growing global network of highly sensitive GW facilities, soon to include Advanced Virgo [17], later KAGRA [18], and in the future LIGOIndia. In the

next decade, observatories based on interferometers with arms as long as 10 km, located underground to reduce seismic and Newtonian noise, and probably cooled to low temperatures to reduce thermal noise, are planned. The European project named Einstein Telescope is an example [19].

These Earth-based instruments are limited at low frequency, say below 1 Hz, by the Newtonian noise. There are fascinating GW signals (and sources) at lower frequencies that these instruments cannot perceive.

The most fascinating GW enterprise in preparation to study the GW spectrum at lower frequency is LISA, the first observatory in space to explore the Gravitational Universe [20]. LISA can be thought of basically as a high precision Michelson interferometer in space with three spacecrafts in heliocentric orbit and arm lengths of 1 million km. Its frequency range goes from 0.1 mHz to 10 mHz. Expected to fly in 2034 as an ESA mission, this observatory will be dominated by the signals (a dream for a GW physicist). Known binary compact systems, still far from the coalescence phase, will calibrate the observatory and signals emitted by supermassive black holes and possibly even the stochastic background of gravitational waves can be detected and studied. The LISA demonstrator of technology, LISA Pathfinder, under the leadership of Stefano Vitale, is now flying successfully, surpassing all performance expectations [21].

To complete the experimental panorama, one more set of running facilities must be mentioned: the pulsar timing array (PTA) projects, where a set of pulsars are analyzed to search for correlated signatures in the pulse arrival times [22]. The most well-known application is to use an array of millisecond pulsars to detect and analyse gravitational waves. Such a detection would result from a detailed investigation of the correlation between arrival times of pulses emitted by the millisecond pulsars as a function of the pulsars' angular separations. Millisecond pulsars are used because they appear not to be prone to the starquakes and accretion events which can affect the period of classical pulsars. PTA can be used to study low-frequency gravitational waves, with a frequency of 10^{-9} Hz to 10^{-6} Hz; the expected astrophysical sources of such gravitational waves are supermassive black hole binaries in the centres of merging galaxies, where tens of millions of solar masses are in orbit with a period between months and a few years.

Globally there are three active pulsar timing array projects, which have begun collaborating under the title of the International Pulsar Timing Array project: the Parkes Pulsar Timing Array at the Parkes radio-telescope; the European Pulsar Timing Array (EPTA) using data from the largest radio telescopes in Europe (Lovell Telescope, Westerbork Synthesis Radio Telescope, Effelsberg Telescope, Nancay Radio Telescope, and soon the Sardinia Radio Telescope will be added); the North American Nanohertz Observatory for Gravitational Waves using data collected by the Arecibo and Green Bank radio telescopes [23].

A new golden age is announced for experimental gravitation, also thanks to the theoretical work consisting in source modelling and numerical simulations.

Let me conclude reporting two dates. I like to see them as two milestones in the history of our understanding of the Universe.

January 7, 1610. – By raising his telescope to the sky, Galileo Galilei observed the moons of Jupiter. A small solar system appeared up there, where nothing was expected to disturb the clear serenity of the Jupiter crystal sphere. The big planet dared mimic, in the eyes of the great scientist, the special role that the Sun had just assumed in the Copernican vision. Galileo was the first witness of the universality of gravitation. Nothing would be as before. New eyes, looking increasingly distant and sensitive also

to new electromagnetic windows (radio, microwave, infrared, X, gamma) would then be open to observations, and unimaginated surprises manifested: powerful radio emissions from galactic centers, stars dense as atomic nuclei and heavier than the Sun in swirling rotation, the echo of the Big Bang, ultra-high energy photons generated by particles accelerators that we cannot even dream of here on Earth, stellar explosions capable of fertilizing the cosmos forming planetary systems like ours.

September 14, 2015. – Two great sensational microphones on Earth recorded for the first time the vibrations of spacetime, the most elusive waves that have ever been imagined. Generated over a billion light-years away, the first cosmic “sounds” detected by humanity indicate the existence, otherwise unperceivable, of pairs of large black holes merging. And it is just the beginning. The Universe will be less obscure and, again, nothing will be as before.

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