First direct detection of gravitational waves

September 14th 2015, 09:50:45 UTC the whole Earth has been "mildly shaken" by the passage of a gravitational wave and has produced what in my opinion has been the most intense half second of the whole history of physics on this planet.

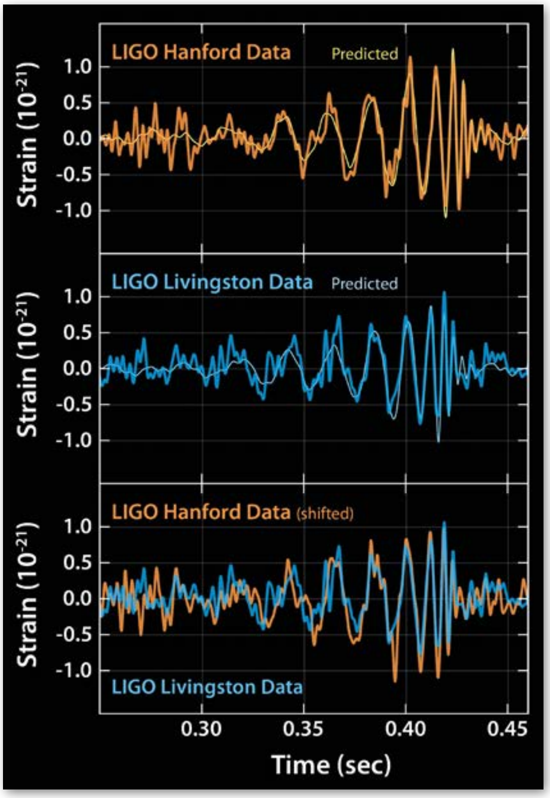
A messenger never seen before has arrived after a journey lasting 1.3 billion years, bringing us the news that a massive black hole was born as the result of a merger of two smaller black holes.

The two detectors of the Laser Interferometer Gravitational-Wave Observatory, Ligo, simultaneously observed a transient gravitational-wave signal. The signal swept upwards in frequency from 35 to 250 Hz, and its noise margin with respect to background noise is good.

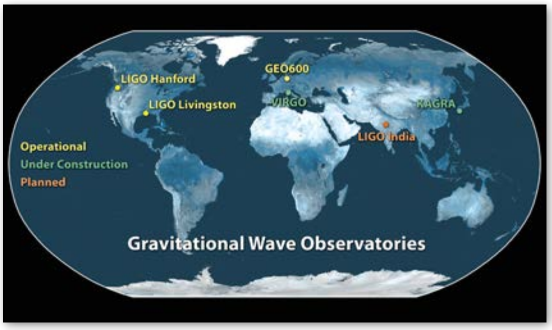
The agreement with General Relativity predictions is very high: models tell us that it was a merger of two massive Black Holes, with mass 36 and 29 $M_\odot$, distant 410 Mpc from us. Such an event has a false alarm rate of less than 1 event per 203,000 years, which is equivalent to say that the significance is greater than 5.1σ. The merger has produced a Black Hole with 62 $M_\odot$, while an energy equivalent to 3 $M_\odot$ was radiated as gravitational waves emission. The two interferometers tell as well that the source was located on an annulus section of 590 deg^2, primarily in the southern hemisphere.

The beauty of this is in front of us; detailed information is quickly becoming available: already 11 papers provide detailed information on the nature of the event, errors are typically of the order of 20%. The fact that gravitational waves interact weakly, on one side has made direct detection very challenging, on the other side the detection, once done, brings very clear information on an event distant in space and time. This is what has motivated the effort of many scientists for so many years.

Not only scientific papers, but a big impact on the world outside fundamental science.



▲ FIG.1: These plots show the signals of gravitational waves detected by the twin LIGO observatories at Livingston, Louisiana, and Hanford, Washington. The signals came from two merging black holes, each about 30 times the mass of our sun, lying 1.3 billion light-years away. The top two plots show data received at Livingston and Hanford, along with the predicted shapes for the waveform. These predicted waveforms show what two merging black holes should look like according to the equations of Albert Einstein's general theory of relativity, along with the instrument's ever-present noise. Time is plotted on the X-axis and strain on the Y-axis. Strain represents the fractional amount by which distances are distorted. As the plots reveal, the LIGO data very closely match Einstein's predictions. The final plot compares data from both detectors. The Hanford data have been inverted for comparison, due to the differences in orientation of the detectors at the two sites. The data were also shifted to correct for the travel time of the gravitational-wave signals between Livingston and Hanford (the signal first reached Livingston, and then, traveling at the speed of light, reached Hanford seven thousandths of a second later). As the plot demonstrates, both detectors witnessed the same event, confirming the detection.



◂ FIG.2: Current operating facilities in the global network include the twin LIGO detectors—in Hanford, Washington, and Livingston, Louisiana—and GEO600 in Germany. The Virgo detector in Italy and the Kamioka Gravitational Wave Detector (KAGRA) in Japan are undergoing upgrades and are expected to begin operations in 2016 and 2018, respectively. A sixth observatory is being planned in India. Having more gravitational-wave observatories around the globe helps scientists pin down the locations and sources of gravitational waves coming from space.

What we have is the first gravitational wave direct detection, the first experimental evidence of a two-bodies merger, the first direct evidence of the existence of black holes. More will come in the future since shortly the two Ligo detectors will be back operational with improved sensitivity and two more instruments, Virgo and Kagra, will be operational, giving the possibility to trace back the event and identify the location of the source. GEO600 is the antenna in Germany, it is a bit less sensitive since it has shorter arms (600m), and it is used for high sensitivity developments as for example the squeezing.

The universe is fascinating and has always new surprises for us, there is always something new to see, but the effort behind the realization of these interferometers has been huge. Behind these results there is the coordinated effort of a community that started to form 30 years ago when the basic ideas were established and is now a large and well organized group. The maximum difference in length between the two arms of the interferometer is now $dx=4.10^{-18}$ m, the background noise of the instrument is 24 times less than that. The amplitude of the wave is measured measuring its strain, and large apparatuses are necessary: the present interferometers have arm length L=4 kilometers, the strain of the wave is dx/L. We are

▲ FIG.3: The LIGO Laboratory operates two detector sites, one near Hanford in eastern Washington, and another near Livingston, Louisiana. This photo shows the Livingston detector site.

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talking of a large experimental apparatus in which every single cable must be positioned with adequate care! Interferometry was ready since many years, theory of resonant optical cavities and the topology of the apparatus as well, but it has been necessary to implement it as a well organized ROBOT in order to guarantee a very high duty cycle, as the arrival time of an event is unknown. This progress has been made possible by the evolution of lasers, reference stable sources, developments in mirrors manufacturing, study of the material and the definition of the details of the suspension in order to reduce as much as possible thermal noise. The development of large mirrors with top quality performances has been necessary. As well control theory and the related electronics have also been pushed to their theoretical and technological limits to allow a robust implementation of the interferometer. Gravitational waves detectors are instruments in which top sensitivity and robustness must be combined. Some of these technical achievements have been realized by the industry for other applications, but most of it is the product of the careful and patient study of dedicated people. Let me remind as well the importance to extend the detectability window to lower frequencies: with a detector with a bandwidth above 100Hz it would have been hard to distinguish this event from a normal glitch, and part of the significance of this event would have been missed. In the '80 gravitational waves detectors were focusing at high frequency, above 100Hz. The signals expected from a gravitational wave are extremely small, and a large effort has been dedicated to reduce all noise sources, in order to enlarge the bandwidth of the antenna as much as possible. In particular it has been commonly thought that the detection would have not been possible below 100 Hz, since the seismic noise, which affects all experiments based on Earth, is rather high. The seismic motion at low frequency is nano-metres high for 1 second measurements, and a large piece of experimental work has been dedicated to the seismic isolation and the control of the mirrors, which must keep the whole interferometer on the so called dark fringe, which is the position in which the noise is minimum.

Not only that: to keep people motivated for such a long time has been another big issue, all the analysis pipelines were ready when the event has arrived.

Finally the decision to come out with the discovery 5 months after the event, which I must say was clear since the beginning, has been as well a good decision: it has given to this community the opportunity to support and describe this fraction of a second with the authoritativeness it deserves.

This is the birth of gravitational astrophysics, and we should not forget to cite the fathers of the interferometric gravitational antennas: Reiner Weiss, and Kip Thorne in US, Adalberto Giazotto and Alain Brillet in Europe. ■

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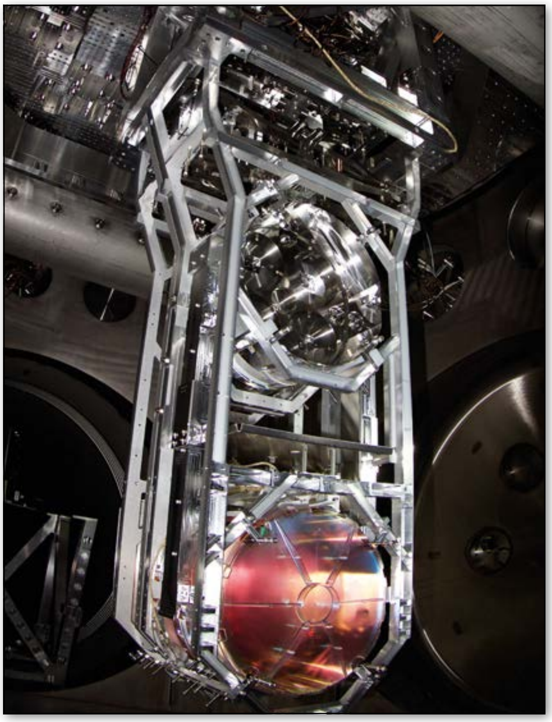

▲ FIG.4: The photo shows one of LIGO's test masses installed as the 4th element in a 4-element suspension system. "Test masses" are what LIGO scientists call the mirrors that reflect the laser beams along the lengths of the detector arms. The 40 kg test mass is suspended below the metal mass above by 4 silica glass fibers.

▼ FIG.5: Basic schematic of the gravitational wave interferometers, with an incoming gravitational wave depicted as arriving from directly above the detector. The light from the Laser source is divided in two beams by the Beam-Splitter. The two beams produced travel along the two 4km arms. Inside each arm there are two mirrors forming a resonant Fabry-Perot cavity; they are essential to enhance the gravitational wave signal. The interference of the two beams reflected back from the two cavities is modulated by any change in the length of the two cavities. The interference is detected by the photodiode, and the signal acquired. The mirrors and the beam-splitter are suspended in order to reduce seismic noise.