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THE NEW ERA OF MULTIMESSENGER ASTRONOMY

Interview with Marica Branchesi, astrophysicist, researcher at the Gran Sasso Science Institute and associated researcher at the INFN Gran Sasso National Laboratories.
Head of the LIGO/Virgo team committed to alert partner observatories in case of gravitational waves signal

16 October 2017 was a historic day, because the joint announcement of the first detection of gravitational waves with observation of the electromagnetic counterpart of their source, marked an epochal change in our way of studying the universe with the beginning of the era of multi-messenger astronomy. We got one of the protagonists of this result to tell us what happened and what is its meaning: Marica Branchesi, astrophysicist, researcher at the Gran Sasso Science Institute (GSSI), associate at the INFN-Gran Sasso National Laboratories. Branchesi was also among the scientists who presented the result during the LIGO and Virgo conference, held in Washington at the National Science Foundation (NSF), at the same time as many other conferences worldwide, including that in Italy of the INFN, of the National Institute of Astrophysics (INAF) and of the Italian Space Agency (ASI), in collaboration with the Ministry of Education, University and Research (MIUR).

I would like to start with the facts: what happened on 17 August?

Around 2:40 pm the phone rang, gravitational wave alert message. As coordinator of the LIGO and Virgo collaboration team which sends alerts to telescopes, I immediately connected to the computer in conference call with data analysis experts and scientists at the three sites, Cascina, Livingston and Hanford. A signal in the data collected by LIGO and Virgo coming from the coalescence of two neutron stars, a gamma burst seen by the Fermi satellite two seconds after the gravitational wave signal. Four hours later we were able to send a precise position, the source was in the southern hemisphere, ideal for the Chilean telescopes that start to observe at dusk. The Virgo interferometer, in Cascina, funded mainly by INFN and CNRS, played a key role in the discovery, allowing signal localisation. From hundreds, thousands of square degrees of signals from star mass black hole systems detected by the LIGO detectors

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alone, the triangulation of the LIGO and Virgo network and location of the source in the "blind" zone of Virgo provided a position of only 30 square degrees. The distance of the astrophysical source was found to be pretty close, 40Mpc, 130 million light years from us. The region of the universe where to look for the counterpart was relatively small and close, a region where we know the distribution and properties of the galaxies. In one of these galaxies, NGC4993, after 11 hours the first light in the visible band was detected as a very bright object (hundreds of millions of times the brightness of the sun) not present in images prior to the coalescence. NGC4993 is located at the same distance as the gravitational wave signal. From that moment, 70 observatories, involving 100 instruments, ground telescopes and satellites, observed NGC4993 for weeks. The optical emission showed a rapidly cooling object, initially a rapidly diminishing blue emission, and an evolution towards red and infrared in a week. From the same position in the sky, 9 days later, an X signal was detected and 16 days later a radio signal.

How did you live that day?

It was extremely exciting: the dream for which we had been working for years was in front of us.
Feeling part of history, of an epochal discovery... the beginning of an adventure that in the coming years will lead us to so many other discoveries. At the same time, the need to be operational, efficient, lucid: coordinate LIGO and Virgo operations to send useful information to astronomers and be ready to respond to astronomers focusing satellites and telescopes. I am an astronomer and have also participated in the INAF observations with the ESO telescopes. every day started with new data to understand the physics of neutron stars and the mechanisms of sound and light emission. The largest observational campaign ever carried out on all spectral bands. The most beautiful gravitational and electromagnetic data I have ever seen. We had almost 100 seconds of gravity wave signals and all the colours of the coalescence of two neutron stars, the last moments of the dance of the two stars, the fusion into an ultra-dense object, probably a black hole, and the light of one the most energetic phenomena in the universe. In short, it was the best of our dreams...

How did the work proceed in these months to arrive at the announcement of 16 October?

The LIGO and Virgo collaboration worked to carefully analyse and verify all the results and write the articles. The astronomers continued to observe the gravitational wave source, the surrounding environment and the galaxy for weeks and will continue to do so for years. About 90 articles have already been published, 8 of which from the LIGO and Virgo collaboration. In particular, I was involved in the interaction with the astronomer groups and worked in the writing team (10 LIGO and Virgo scientists) which wrote the article with all the astronomer groups. An article signed by some 3500 authors, which marked the collaboration

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of thousands of scientists from six continents, the beginning of multi-messenger astronomy and of the work of a global network of observers. In the history of astronomy there are few articles written by different communities, this has unified the work of physicists, astrophysics, astronomers and theorists. For two months I slept little... and worked a lot, but what a great satisfaction!

What are the most significant scientific results presented on 16 October?
So many scientific results, impossible to define an order of importance. Many confirmations of ten-year-old theoretical models able to explain the set of data collected. At the same time, we are in the presence of a wealth of data whose details will require a great theoretician and other observations in the coming years to be interpreted.
It was the first observation of gravitational waves from the coalescence of two neutron stars, with detection of the electromagnetic counterpart in all spectral bands and identification of the host galaxy.
The gravitational event called GW170117 marks the birth of multi-messenger astronomy that uses gravitational waves and electromagnetic emission.
This observation also marks the beginning of cosmology with gravitational waves. The Hubble constant, i.e. the universe's expansion rate, was measured by combining the measurement of the galaxy's recessive velocity due to the expansion of the universe and the distance of the source measured by the gravitational waves. Moreover, it was the first observational evidence and definitive confirmation that the progenitors of short gamma ray bursts (duration of less than 2 seconds) are represented by neutron star coalescence, almost fifty years after their discovery by military satellites monitoring nuclear tests on Earth.
The gamma, X and radio signals measured are interpreted as Gamma Ray Bursts (GRB,) observed at larger angles than the emission cone. We are in the presence of the first observation of an off-axis GRB, am emission theorised for about two decades but never observed before.
The tiny 1.7 second delay between the gravitational wave signal and that of the gamma rays once again confirms that Albert Einstein was right: gravitational waves travel at the speed of light, like photons.
The colours observed from ultraviolet to infrared show (as predicted by the theory) that during the coalescence of two neutron stars, the mass ejected at extremely high velocity in the interstellar medium is the ideal site for the formation of heavy elements for rapid neutron capture. While the radioactive decay of such elements determines the visible emission observed (called kilonova): the universe is enriched with elements heavier than iron, including gold. Coalescences of two neutron stars are very rare events; in our galaxy they can happen a dozen times every million years, but the quantity of heavy elements that can be formed is enormous - for gold an amount equal to approx. 10 Earths is estimated. Our jewels very probably come from the coalescence of two neutron stars that occurred billions of years ago in our galaxy

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that dispersed heavy elements in the interstellar medium from which stars and planetary systems were formed.

What does it mean when we say that a new era for astronomy has been opened? What is multi-messenger astronomy?

Gravitational wave detectors are now able to observe millions of galaxies, which gives us the possibility to observe very rare, but crucial, events in the evolution of the universe. We now have a network of observatories able to give a more accurate position that allows traditional satellites and telescopes to capture the possible electromagnetic signal emitted by the astrophysical gravitational wave source. Now we can observe the universe with multiple messengers, gravitational waves and photons. Have a complete picture of black holes and neutron stars and their interaction with the environment. Multi-messenger astronomy uses waves and particles, including neutrinos, to observe the universe. For GW170817, neutrinos were not observed, but we hope to soon add this additional messenger to our observations.

LIGO and Virgo, having terminated RUN O2, have entered a new upgrade phase. What will be enhanced and with which scientific goals?

Detector sensitivity will be increased in order to observe a greater volume of the universe, reaching a sensitivity greater by a factor of at least 3 compared to that of the current network, a factor of 30 in volume. This will allow us to observe more neutron star and black hole coalescence signals and possibly observe new signals such as the coalescence of neutron star-black hole systems, the gravitational collapse of massive stars in our or surrounding galaxies, continuous pulsar emissions and stochastic signals. And like every time a new observation window is opened, I also expect exotic objects/signals. The closest goals are to have a mass and frequency distribution of black holes that will allow us to understand how they form and evolve. Have more observations in order to understand the structure of neutron stars and carry out general relativity tests.

What does it mean when we say that thanks to gravitational waves, we could get even "closer" to the moment of the big bang?

The difficulty of detecting gravitational waves is what makes them extremely special, interacting weakly with matter. Unlike photons, they are not absorbed, so they can come from distant regions of the universe and regions where photons cannot escape. We expect future detectors to be able to listen to gravitational waves produced directly by the big bang, providing us with direct information on the birth of the universe.

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What are the prospects for gravitational astronomy?

The LIGO and Virgo network has opened a window on the universe, but the observed frequencies and universe are relatively small. The Einstein Telescope project will allow us to increase the sensitivity by a factor of 10 compared to the Advanced detectors such as LIGO and Virgo, reaching the entire universe. This will allow us to observe many more events and observe them better. We will be able to study the cosmological evolution of gravitational sources throughout the cosmological history of the universe, study the populations of astrophysical sources and their evolution and do precision cosmology. The events observed by LIGO and Virgo will be able to be studied with a higher signal noise ratio allowing better location to search for the electromagnetic counterpart, detailed studies to understand the structure of neutron stars and possible deviations from general relativity. There will be a higher probability of observing signals of the gravitational collapse of massive stars, instability signals of neutron stars, continuous pulsar signals and stochastic signals. Going down to slightly lower frequencies, we can imagine to detect signals before coalescence and point telescopes in the fusion phase, with crucial information for understanding where and how the first multi-band electromagnetic emission originated. Space observatories such as LISA will open the low frequency band from milli-Hertz to 0.1 Hertz, with the possibility of observing large cosmological sources, the coalescence of more massive black holes that reside in the centre of the galaxies and observing them up to the time of their formation. We will be able understand how galaxies formed in the universe and how they have evolved. We will be able to follow stellar mass black holes in their slow orbiting one around the other or observe their fall into massive black holes. The multi-messenger network that has come to life with GW170817 is also a milestone for the future, in which similar observation campaigns will have to follow gravitational wave signals. Within twenty years time, we will have to think of observatory projects that allow combined observations to maximise the scientific return of every gravitational wave observation.

On 16 October, in the Washington conference, out of 11 speakers, four were Italian and all women. And also in the other conferences that were held at the same time, for example that of ESO in Europe, Italy and women were present. A satisfaction, and a significant and encouraging fact for many young women...

A great satisfaction and honour to be with six other women who have had fundamental roles in this discovery. Despite the difficulties, the gender stereotypes, science, and in particular (astro)physics, is also a woman (ed. science and physics in Italian are female nouns). You can be a woman, mother and scientist... for example, I am a mother of two beautiful children who were born with the gravitational waves, one two years and one ten months old. Before I started this job I would never have thought of being able

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to speak in front of hundreds of people in public, to go on air worldwide for a wonderful discovery... but all this has happened! To young female researchers I would like to pass the message that they must believe in what they do, work with passion, humility and honesty, without setting limits but pursuing great goals... because all their dreams can come true. ■