AstroSat contributes to the saga of Gravitational Wave Astronomy

On August 17, 2017, scientists seeking the holy grail of gravitational wave (GW) astronomy struck gold. The elusive and long sought after GW signals from merging binary neutron stars were found and multi-messenger observations provided tell-tale signs of this merger to clinch the issue without any qualms. Two of the GW detectors in the US picked up the signal and a third, working in Europe, confirmed it. Several of the satellites in the sky detected signals from this event across various bands of the electromagnetic spectrum, and a vast array of optical and radio telescopes worldwide trained their vision into this new phenomenon, finding a variety of corroborating signals.

The *AstroSat* scientists, who pitched in with their efforts, today stand shoulder to shoulder with a few thousand scientists across the globe (including three Nobel Prize winners and a few scores of other Indian scientists) to announce this momentous discovery and an `open sesame' moment of staring at the huge cache of scientific discovery that this new era of `multi-messenger, time-domain astronomy' opens up.

Gravitational Wave Astronomy: the last frontier

Any accelerated electronic charge emits electromgnetic radiation: scientists routinely use this to generate and send electromagnetic waves like radio waves, optical light, and X-rays. Any moving mass disturbs the space time and a `quadropole' moment in the moving mass should generate gravitational waves: theorised Albert Einstein a hundred years ago. Einstein's words are treated as ***Veda Vakya*** or Gospel Truth, and astronomers routinely use this to understand the dynamics of compact large masses in the cosmos. Russell A. Hulse and Joseph H. Taylor, Jr discovered two radio pulsars going around each other, slowly hurtling towards each other, and they invoked Einstein's gravitational wave theory to understand their behaviour: they were duly awarded a Nobel Prize for this work. This opens up an interesting question - shouldn't astronomers, who use every branch of electromagnetic radiation from radio to gamma-rays to prise open the secrets of the Universe, use gravitational waves to understand exotic features of the cosmos - like the ripples of the Big Bang or merging of black holes when galaxies collide ?

Well, they should, but the catch lies in the fact that the gravitational force is extremely weak compared to the electromagnetic force, and common sense deems that even the most sensitive detectors that humans can build cannot detect the most exotic gravitaional wave sources that we can imagine. However, during the past few decades, a huge number of dedicated scientists have built the most sophisticated detectors capable of measuring infinitesimal movement of mass corresponding to a tiny fraction of a nanometer in kilmoter sized objects so that they would be sensitive to the gravitational waves from outer space. Year after year, they kept looking for signs of merging neutron stars, but the quest was in vain !

Mother Nature usually likes to keep surprises up her sleeve! When the GW detectors with highly improved sensitivity were switched ON in 2015, they found something: not a neutron star-neutron star merger, but a totally unexpected event of two massive black holes merging and spewing out energy equivalent to the complete burning out of mass corresponding to two Suns. This is indeed a momentous discovery, and the architects of this humongous human effort, Kip Thorne, Rainer Weiss, and Barry Barish, duly got this year's Nobel Prize.

What about the elusive case of the merger of two neutron stars anticipated from the discovery of Messers Hulse and Taylor? During the past two years, four GW events were discovered, however, they were all due to mergers of black holes. The problem with merging black holes is that they are, as apparent from the name, `black'; i.e., apart from the GW events, there are no tell tale signs of the merger in any other branch of electromagnetic radiation. So, we cannot determine where they are coming from, or what are their progenitors. This is not the case for neutron star mergers. It was firmly believed that when GW events are discovered from neutron star mergers, they would be accompanied by huge amounts of electromagnetic radiation, which will help us pin down the sources of these events.

The whole scientific community was eagerly waiting for this much anticipated event.

CZT Imager of *AstroSat* pitches in

AstroSat was launched on September 28, 2015 and the CZT Imager (*CZTI*) instrument of *AstroSat* was the first instrument to be made operational. On October 6, 2015, the first day of operation, *CZTI* detected a gamma-ray burst (GRB) and proved to be an efficient GRB detector. The scientists working with the *CZTI* data realised that it would be a wonderful instrument to detect any gamma-ray events accompanying the GW sources.

The problem with detecting such gamma-ray events is that they are rare, unpredictable, and can come from any direction in the sky. Hence, the detectors need to have all sky sensitivity, and generally, there is a trade off in their observing capabilities. Currently, there are three sensitive operating GRB monitors, along with a few more less sensitive detectors, each having their own capabilities and limitations. The most sensitive GRB monitor currently operating is the *Swift* satellite, however, it can observe only one tenth of the sky at any given time. *CZTI* and the *Fermi* satellite, on the other hand, are sensitive to much larger regions in the sky, but have very limited capability to localise these events. The anti-coincidence shield of the *INTEGRAL* satellite, too, can act as a GRB monitor.

Each of these instruments played their part in the race to detect gamma-ray signals accompanying the GW events. During the very first GW event on September 14, 2015 (before the launch of *AstroSat*), *Fermi* claimed that it had detected a GRB like event within 0.4 s of the GW event. Observations from the *INTEGRAL* satellite, however, disagreed: the consensus was that this could be some unrelated spike in the background. During another GW event detected in January 2017, optical astronomers saw, the very next day of the event, some source gradually diminishing in brightness. Could this be the tell-tale signs of something happening in the GW source? *CZTI* chipped in with a firm No! It had detected a GRB, 21 hours after the GW event. The fading optical source was shown to be this GRB, unrelated to the GW event.

Aug 17, 2017: a red letter day

On August 17, 2017, the much anticipated event occurred.

The GW detectors in US registered a very long series of signals, or `chirps', closely resembling what the scientists have simulated for decades to be coming from neutron star coalescence. Even before they could announce this discovery, the *Fermi* satellite had detected a GRB at the same time: in fact within a couple of seconds of the GW event. Could this also be an unrelated background fluctuation event? Very unlikely, because, at exactly the same time, the anti-coincidence shield in the *INTEGRAL* satellite had also detected this GRB. What about *Swift* and *CZTI*? They didn't detect any! The event should probably be outside the narrow field of view of *Swift*. What about *CZTI*? It was active and operating and the GRB should have been detected. The only way to reconcile was to assume that the source was blocked by the Earth: this helped to narrow down the possible source regions of the GW event.

Soon, the GW detectors from Europe too pitched in, and the region of the sky responsible for the GW event and GRB was narrowed down to a small region. Optical telescopes around the world scanned each and every galaxy in this region and, lo and behold, there indeed was a bright optical object, not seen before, near a galaxy called NGC 4993.

The rest, as they say, is history. Soon, infra-red and ultraviolet emissions were seen from this source. Nine days later, an X-ray source was detected, and fifteen days later, radio emission was also observed. From such vast multi-wavelength data, the physics of colliding and merging neutron stars were studied in depth. An exciting find is that the material ejected in the event is rich in heavy elements, so much so that, colliding neutron stars can account for the entire supply of precious metals, like gold, platinum and silver, in the universe. Production of these elements have been difficult to understand, and now the source has been found!

The story of GW170817 bears testimony to the amazing outcome possible when all the world's best instruments are combined for a single purpose. The collaborative efforts of a number of teams worldwide lends an added credibility to this exciting and substantial discovery and ushers in a new era in multi-messenger, time-domain astronomy!

Scientific curiosity: never satiated

The GW detectors are taking a year off to return with an improved sensitivity. Neutron star merger events and the accompanying `kilonova' should be fairly common observations during the next run. There should be more of black hole merger events as well. Scientists are already dreaming about the rich future harvests:

Can we get any tell-tale signatures of black hole mergers to identify where they are coming from? Perhaps more sensitive all sky detectors would help with an answer.

Can these events be used as a tool for distance measurement to refine cosmology? A massive collaboration between GW theorists and kilonova observers should be able to do it.

Can we learn anything about the regions close to black hole? Possible.

Are there some strange stars among the neutron stars? Certainly more such objects will tell us.

Finally, has Mother Nature more surprises up her sleeve? Only the future will tell us!

What next? Significant next steps will involve making detectors more sensitive, improving localisation capability and most importantly, continued collaboration of observatories worldwide spanning all electromagnetic bands, neutrinos and gravitational waves.

In the Indian space science context, the capability of CZTI would certainly be improved through better algorithms and simulations: it should be possible to independently confirm and localise gamma-ray events for future GW associations. Perhaps, even a much improved CZTI like all sky monitor could be designed and flown!

*Multi-messenger studies of GW170817 incorporating the contribution of AstroSat CZTI are published in the journals **Science** and **Astrophysical Journal Letters**.*