GRAVITATIONAL WAVES DETECTED 100 YEARS AFTER EINSTEIN'S PREDICTION
LIGO Opens New Window on the Universe with Observation of Gravitational Waves from Colliding Black Holes
IUCAA physicists make fundamental contributions in the discovery

For the first time, scientists have observed ripples in the fabric of spacetime called gravitational waves, arriving at the earth from a cataclysmic event in the distant universe. This confirms a major prediction of Albert Einstein's 1915 general theory of relativity and opens an unprecedented new window onto the cosmos.

Gravitational waves carry information about their dramatic origins and about the nature of gravity that cannot otherwise be obtained. Physicists have concluded that the detected gravitational waves were produced during the final fraction of a second of the merger of two black holes to produce a single, more massive spinning black hole. This collision of two black holes had been predicted but never observed.

The gravitational waves were detected on September 14, 2015 at 5:51 a.m. Eastern Daylight Time (9:51 UTC) by both of the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors, located in Livingston, Louisiana, and Hanford, Washington, USA. The LIGO Observatories are funded by the National Science Foundation (NSF), and were conceived, built, and are operated by Caltech and MIT. The discovery, accepted for publication in the journal *Physical Review Letters*, was made by the LIGO Scientific Collaboration (which includes the GEO Collaboration and the Australian Consortium for Interferometric Gravitational Astronomy) and the Virgo Collaboration using data from the two LIGO detectors.

Gravitational wave research at IUCAA, Pune, India

Physicists at the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, an autonomous institution of the University Grants Commission, India, made significant contributions to this discovery. They are Professors Sukanta Bose, Sanjeev Dhurandhar (Emeritus), Sanjit Mitra, Tarun Souradeep, postdoctoral fellow Anuradha Gupta, PhD students Anirban Ain, Bhooshan Gadre, Nikhil Mukund, and visiting scientists Jayanti Prasad and Sharad Gaonkar. They are all active members of the LIGO Scientific Collaboration (LSC).

Describing this discovery as a major breakthrough, IUCAA director Professor Somak Raychaudhury said, "IUCAA has been at the core of building a gravitational wave research community in India ever since it was founded, over a quarter century ago. Therefore, it is heartening to see my colleagues not only contribute directly to this discovery with a breadth of expertise but also facilitate several LSC collaborators in other Indian institutions to contribute to it in a significant way." Professor (Emeritus) Dhurandhar has been at the forefront of this effort, and has done pioneering work in formulating methods for detecting gravitational wave signals in detector noise.

Founding IUCAA director, Professor (Emeritus) Jayant Narlikar, echoed Raychaudhury, "From the very beginning IUCAA has been emphasizing the importance of detecting gravitational waves towards a more complete understanding of the cosmos. To this end IUCAA has created many researchers who have contributed to this effort worldwide. We expect to continue our contribution in the coming years." Former IUCAA director, Professor (Emeritus) Ajit Kembhavi added, "It gives me immense satisfaction that IUCAA also nurtured the national consortium of scientists called the Indian Initiative in Gravitational wave Observations (IndIGO) right from its inception in August 2009. Its members have now done us proud." At this time IUCAA provides logistical support to IndIGO under a Memorandum of Understanding.

IUCAA's involvement in the discovery spanned across a wide range of areas of this multi-disciplinary search, beginning with the basic idea used in finding the weak and short-lived gravitational wave signal in the very noisy data of the LIGO detectors. That idea, due to Dhurandhar and B. Sathyaprakash (then a postdoctoral fellow at IUCAA, now in Cardiff) from 1991, was of matching thousands of wave patterns expected from black hole binaries, as derived from Einstein's theory, with the data from the detectors. This maiden detection relies on this fundamental work.

For further confirmation of the common astrophysical origin of the signals, a multi-detector consistency test was applied. The theoretical foundation for it was laid by Bose and Dhurandhar, alongwith Archana Pai (then a PhD student at IUCAA, now at IISER Thiruvananthapuram). More recently, the duo, along with Mitra, Gupta and Mukund, carried out extensive studies towards understanding the LIGO detectors' data and found ways of discerning astrophysical signals from transient terrestrial noise in the data. IUCAA scientists also contributed towards developing a set of analysis tools that were used in this discovery. The High Performance Computing facility at the IUCAA Data Center provided valuable support.

Bose, who has been in the LSC since 2000, reminisced, "In 1991 the possibility of making a direct detection of gravitational waves looked remote. But multi-detector observations got a shot in the arm in 1994, with the construction of the two LIGO detectors beginning in the US. It needed a leap of faith for us to begin working in a research area in the nineties that was just getting started." Dhurandhar agreed, "It is a fantastic feeling to see this substantial body of work, to which IUCAA has contributed in a major way, come to fruition with this discovery finally."

Astronomers at IUCAA, led by Varun Bhalerao, Javed Rana, and Akshat Singhal, joined forces with their international partners to search for an afterglow soon after the gravitational wave signal was picked up by LIGO on September 14, 2015 and relayed to them subsequently. In collaboration with multiple other institutions in India and abroad, IUCAA is leading the effort for setting up necessary mechanisms in India for electromagnetic follow-up of gravitational wave events, especially, because both kinds of signals, whenever emitted, can teach us much more about these violent phenomena in the universe than what any single kind can.

"This is why we need a third LIGO like detector, far away from the ones in the US. A three-detector network will be able to localize a gravitational wave source much more accurately," says Tarun Souradeep, who is the spokesperson of IndIGO. Since it is much simpler and quicker for telescopes to scan a small area of the sky for an electromagnetic counterpart, a third detector is critical in transforming this discovery into the launch of Gravitational wave Astronomy.

An international collaboration

LIGO was originally proposed as a means of detecting these gravitational waves in the 1980s by Rainer Weiss, professor of physics, emeritus, from MIT; Kip Thorne, Caltech's Richard P. Feynman Professor of Theoretical Physics, emeritus; and Ronald Drever, professor of physics, emeritus, also from Caltech.

LIGO research is carried out by the LIGO Scientific Collaboration (LSC), a group of more than 1000 scientists from universities around the United States and in 14 other countries. More than 90 universities and research institutes in the LSC develop detector technology and analyze data; approximately 250 students are strong contributing members of the collaboration. The LSC detector network includes the LIGO interferometers and the GEO600 detector. The GEO team includes scientists at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, AEI), Leibniz Universität Hannover, along with partners at the University of Glasgow, Cardiff University, the University of Birmingham, other universities in the United Kingdom, and the University of the Balearic Islands in Spain.

Virgo research is carried out by the Virgo Collaboration, consisting of more than 250 physicists and engineers belonging to 19 different European research groups: 6 from Centre National de la Recherche Scientifique (CNRS) in France; 8 from the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; 2 in The Netherlands with Nikhef; the Wigner RCP in Hungary; the POLGRAW group in Poland and the European Gravitational Observatory (EGO), the laboratory hosting the Virgo detector near Pisa in Italy.

The discovery was made possible by the enhanced capabilities of Advanced LIGO, a major upgrade that increases the sensitivity of the instruments compared to the first generation LIGO detectors, enabling a large increase in the volume of the universe probed—and the discovery of gravitational waves during its first observation run. The US National Science Foundation leads in financial support for Advanced LIGO. Funding organizations in Germany (Max Planck Society), the U.K. (Science and Technology Facilities Council, STFC) and Australia (Australian Research Council) also have made significant commitments to the project. Several of the key technologies that made Advanced LIGO so much more sensitive have been developed and tested by the German UK GEO collaboration. Significant computer resources have been contributed by the AEI Hannover Atlas Cluster, the LIGO Laboratory, Syracuse University, and the University of Wisconsin-Milwaukee. Several universities designed, built, and tested key components for Advanced LIGO: The Australian National University, the University of Adelaide, the University of Florida, Stanford University, Columbia University in the City of New York, and Louisiana State University.

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