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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.
Indian scientists part of 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.

"This is a momentous discovery. From the dawn of time humankind has observed the universe using light. Now a completely new way, using gravitational waves instead, has opened up. Who know what mysteries of the universe will be uncovered using it?", wondered Sandip Trivedi, director of the Tata Institute of Fundamental Research (TIFR).

According to general relativity, a pair of black holes orbiting around each other lose energy through the emission of gravitational waves, causing them to gradually approach each other over billions of years, and then much more quickly in the final minutes. During the final fraction of a second, the two black holes collide into each other at nearly half the speed of light and form a single more massive black hole, converting a portion of the combined black holes' mass to energy, according to Einstein's formula $E=mc^2$. This energy is emitted as a final strong burst of gravitational waves. It is these gravitational waves that LIGO has observed. *"LIGO observation of gravitational waves emitted during the merger of two black holes is an extraordinarily exciting event indeed. It opens up a new avenue to the understanding of these strange but beautiful objects,"* said C. V. Vishveshwara, the Indian theoretical physicist who made important contributions to our understanding of the final state of such events by his theoretical calculations on the stability of black holes predicted by Einstein's theory.

Based on the observed signals, LIGO scientists estimate that the black holes for this event were about 29 and 36 times the mass of the sun, and the event took place 1.3 billion years ago. The merger produced a black hole with mass 62 times the mass of the sun that spins at a rate 67% of the maximum possible spin of black holes. About 3 times the mass of the sun was converted into gravitational waves in a fraction of a second — with a peak power output about 50 times that of the whole visible universe.

"*The direct observation of gravity waves by LIGO is a turning point in the history of astronomy. Gravitational wave astronomy will explore hitherto unseen dramatic events in the universe. Unlike light waves, gravity waves can travel to us from the time of the birth of the universe. The LIGO discovery makes the observation of primordial gravity waves a realistic dream for the future,*" said Spenta Wadia, professor emeritus and founder director of the International Centre for Theoretical Sciences (ICTS), TIFR.

LIGO SCIENCE AT ICTS-TIFR

The Indian scientific community has made seminal contributions to gravitational-wave physics over the last twenty-five years. The group at RRI, Bangalore lead by Bala R. Iyer (currently at ICTS-TIFR) in collaboration with a group of French scientists pioneered the theoretical calculations used to model gravitational-wave signals from orbiting black holes. In parallel, the group of Sanjeev Dhurandhar at IUCAA, Pune did foundational work on developing the data-analysis techniques used to detect these weak signals buried in the detector noise. Over the last decade the Indian gravitational-wave community had expanded to a number of institutions. The Indian participation in the LIGO Scientific Collaboration, under the umbrella of the Indian Initiative in Gravitational-Wave Observations (IndIGO), includes scientists from CMI Chennai, ICTS-TIFR Bangalore, IISER Kolkata, IISER Trivandrum, IIT Gandhinagar, IPR Gandhinagar, IUCAA Pune, RRCAT Indore and TIFR Mumbai. *"I am so grateful for the major contributions, by Indian scientists working in India and abroad, that helped make this discovery and future discoveries possible. These include contributions from experimenters who have contributed to the observational technology, by data analysts who have developed and implemented techniques for finding gravitational wave signals amidst noise, and by theorists who have computed to high accuracy the shapes of the gravitational wave signals that we seek,"* said Kip Thorne, eminent theoretical physicist and one of the founders of the LIGO project.

The ICTS-TIFR group made significant, direct contributions to obtaining estimates of the mass and spin of the final black hole, and the energy and peak power radiated by the binary in gravitational waves. These are obtained by applying fits to supercomputer simulations of binary black holes to the estimates of the binary's initial masses and spins. The group has also contributed to the astrophysical interpretation of the event.

This powerful astronomical event allows us to test Einstein's theory of general relativity in a hitherto unexplored regime. The ICTS-TIFR group designed and implemented one of the tests of general relativity that have shown that the current observation is completely consistent with a binary black hole collision in Einstein's theory. Specifically, this test checks consistency of the mass and spin of the final black hole estimated from two different parts of the observed signal (produced by the motion of the black holes before and after they merge). Yet another test of Einstein's theory performed on this merger event involves measuring the so-called "post-Newtonian coefficients" from the observed signal to see if these agree with the values predicted by the theory. This was proposed by a group of scientists, then based at RRI, and collaborators (several of them currently members and associates of ICTS-TIFR). Researchers from CMI Chennai, IISER Trivandrum and IISER Kolkata were actively involved in the implementation of this test.

"*Black Holes are one of the most remarkable predictions of Einstein's theory*", said Rajesh Gopakumar, director of ICTS. "*What amazes me about the LIGO discovery is that it has now opened a completely new window into learning how these mysterious objects behave. We can now test* *aspects of Einstein's theory in extreme regimes which were inaccessible hitherto. I am particularly elated that the ICTS-TIFR group has made brilliant contributions in this direction already*."

"Parameswaran Ajith's team at ICTS were critical in carrying out tests of the strong field dynamics of black holes in this system and in confirming the consistency of the signal with Einstein's General Theory of Relativity. It is heartening to see the involvement of many young scientists in India in this discovery", said B. S. Sathyaprakash, professor of physics and astronomy and leader of the gravitational-wave group at Cardiff University, UK.

ICTS scientists work on modeling the astrophysical sources of gravitational waves, on developing data-analysis techniques, and on the astrophysics of black holes and neutrons stars. The data-analysis work related to the test of Einstein's theory contributed by the ICTS group was entirely performed at the LIGO Tier-3 grid computing center at ICTS-TIFR. The research of the ICTS group is supported by the Tata Institute of Fundamental Research (an autonomous institution under the aegis of the Department of Atomic Energy, Govt of India) and Science and Engineering Research Board, Department of Science and Technology, Airbus Foundation, Simons Foundation, Infosys Foundation, and the Max Planck Society. *"I am proud that we have recently established a Max Planck Partner Group at ICTS. Their work tests Einstein's theory of general relativity using data from this black-hole merger and similar events. The ICTS is an ideal home, providing state-of-the-art computing resources and facilities for their distinguished faculty of scientists",* said Bruce Allen, director of the Max Planck Institute for Gravitational Physics in Hannover, Germany.

A WORLDWIDE 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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