NEW COSMIC

The gravitational waves detected by the LIGO observatories in the United States on September 14, 2015, while validating Einstein's theory of general relativity were, in a literal sense, cosmic messengers that brought first-hand information on a cataclysmic collision that occurred in a remote corner of the universe at a time when earth was just spawning first multicellular life.

BY **ABHAY ASHTEKAR**

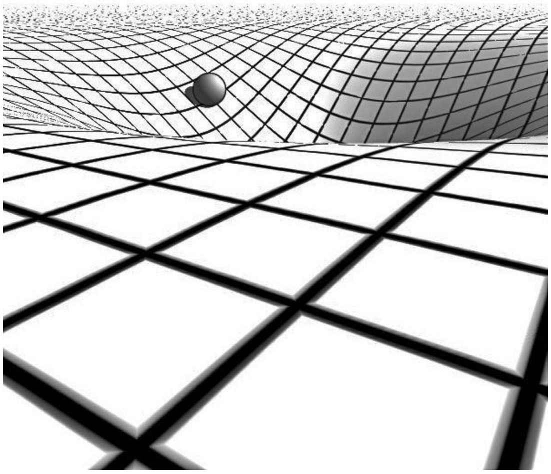

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FIGURE 1: Rubber sheet analogy. Artist's depiction of a planet moving in the curved geometry of the sun.

IT all began a century ago. In November of 1915, Albert Einstein sent his final formulation of the general theory of relativity for publication. It revolutionised our notions of space, time and gravity by overthrowing the Newtonian paradigm that constituted the foundation of physics and astronomy for over 200 years.

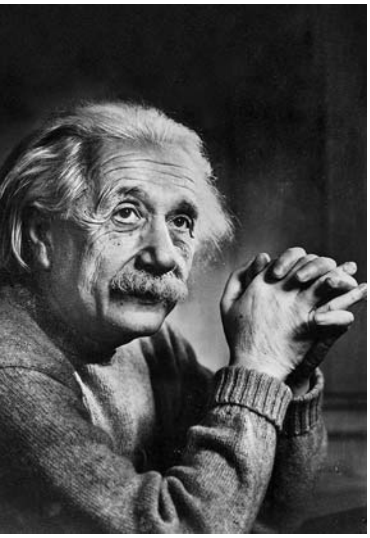
In general relativity, space and time fuse to form a four-dimensional *space-time* continuum. Furthermore, this continuum is curved and gravitational field is coded in this curvature. Space-time is not an inert entity. It acts on matter and can be acted upon. As the American physicist John Wheeler put it: *Matter tells space-time how to bend, and space-time tells matter how to move.* In the Newtonian world view, space and time are like a backdrop, a stage on which the drama of physical interactions unfolds. The actors are the stars and planets, light and gravity, you and me. In general relativity, space-time itself becomes a physical entity, capable of acting on familiar objects and reacting to them. The stage itself joins the troupe of actors! There are no longer any spectators in the cosmic dance.

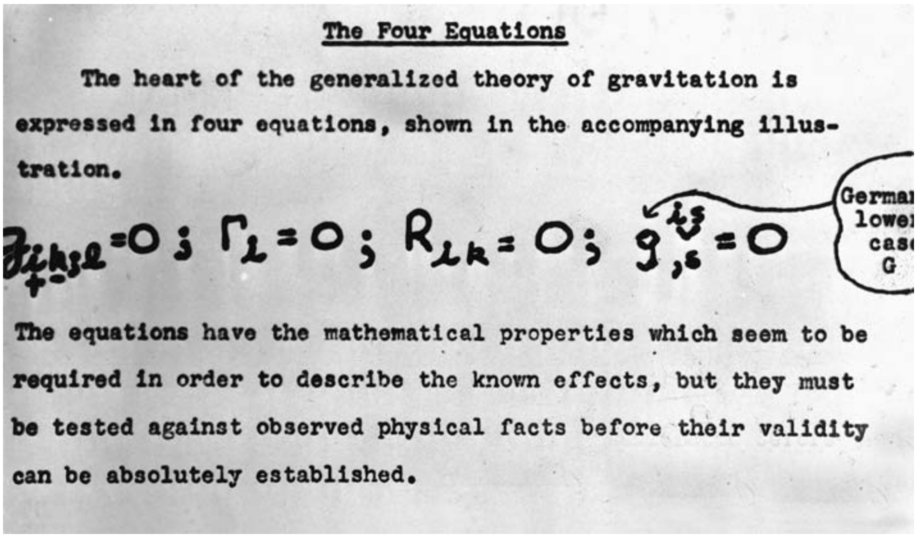
The magic of general relativity is that, through elegant mathematics, it transforms this deep idea into concrete equations and uses them to make astonishing predictions about the nature of physical reality. It predicts that clocks should tick faster on the majestic mountains of Himalaya than they do in the coastal plains. It predicts that galactic nuclei would act as giant (gravitational) lenses and provide spectacular, multiple images of distant quasars. Over the last 30 years, astute measurements have been performed to test if these and other even more exotic predictions are correct. Each time, general relativity has triumphed. This is why the legendary astrophysicist S. Chandrasekhar was moved to compare general relativity to the greatest sculptures which reveal new beauty at every scale at which one examines them.

GRAVITATIONAL WAVES

A few months later, in 1916, Einstein published another paper in which he worked out in detail some of the striking consequences of general relativity. One of them was the existence of gravitational waves, which are inconceivable in Newton's universe. It is simplest to visualise them using an analogy. One can think of the space-time continuum of general relativity as a malleable rubber sheet. It is bent by heavy bodies such as stars, as depicted in Figure 1. The heavier the body, the more is the space-time continuum bent, and the greater is its curvature. Black holes bend it maximally. Now imagine two

MESSENGERS





The Four Equations

The heart of the generalized theory of gravitation is expressed in four equations, shown in the accompanying illustration.

$$\mathfrak{g}_{\underset{+}{i}\underset{-}{k};l}=0;\quad \Gamma_{i}=0;\quad R_{ik}=0;\quad \mathfrak{g}^{\underset{\vee}{is}}{}_{,s}=0$$

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The equations have the mathematical properties which seem to be required in order to describe the known effects, but they must be tested against observed physical facts before their validity can be absolutely established.

THE HINDU ARCHIVES

ALBERT EINSTEIN'S (left) equations on the "generalised theory of gravitation" attempts to interrelate all known physical phenomena. At that time the new theory was thought to rank with the original publication of theory of relativity as a milestone of scientific achievement. Intended to bring relativity and the quantum theory into a single system, it was impossible to say at that time whether the theory would be successful. Preliminary indications were favourable.

such bodies moving towards each other, and finally colliding. On a rubber sheet, two colliding heavy balls would send out ripples as they approach each other. The same thing happens in general relativity. *Gravitational waves are these ripples in the very geometry of space-time.* The ripples are tiny when the bodies are far away but gain strength as the bodies approach one other. When they collide, the ripples can have cataclysmic strength. If the two bodies are black holes, space-time is shaken so violently that there is a veritable tsunami in the very fabric of space-time. In a tiny fraction of a second, more energy is emitted than one would obtain by "burning" a few suns, converting their entire mass into energy! Such breathtaking possibilities can be envisaged only because general relativity shattered the Newtonian precepts of space and time as pristine entities, aloof and indifferent to the actions of physical bodies. In general relativity, not only stars and black holes bend space-time, but they can also shake it, and do so violently. As the celebrated mathematician and physicist Hermann Weyl said: *it is as if a wall that separated us from the truth has collapsed. Wider expanses and greater depths are now exposed to the searching eye of knowledge, regions of which we had not even an inkling.*

THE LONG ROAD TO DETECTION

Early on, Einstein and others took up the question of whether any of the extraordinary predictions of general relativity can be observationally verified. Their calculations showed that a star such as our sun curves space-time sufficiently for certain effects to be measurable. A famous expedition led by the English astronomer Arthur Eddington during the 1919 total solar eclipse revealed that light arriving at earth from distant stars does bend because it experiences the curvature in the sun's neighbourhood. General relativity passed the test with flying colours and almost overnight Einstein became a household name. But for gravitational waves the situation turned out to be entirely different. Calculations showed that to create *measurable ripples* in space-time curvature, one needs heavenly bodies that are vastly denser than our sun. That is why decades passed before researchers could seriously contemplate the possibility of detecting gravitational waves.

In this respect, gravitational waves are very different from the more familiar electromagnetic waves, which are

created by moving charges, rather than moving masses. Gravitational waves with appreciable strength are so much more difficult to produce because the gravitational force is much weaker than the electromagnetic force. For example, there is gravitational attraction between a proton and an electron because they both have mass, and also an electromagnetic attraction between them because they have charge. But the gravitational attraction is smaller by 40 orders of magnitude—that is, 40 powers of 10—an inconceivably small number. Therefore, while we routinely produce measurable electromagnetic waves on earth—radio stations produce them all over India—the situation with gravitational waves is very different. Even though planets, for example, have huge masses, the gravitational waves they produce as they orbit the sun are so incredibly weak that there is no chance *at all* to detect them on earth. To produce appreciable gravitational radiation, one needs heavy and *extremely* compact heavenly bodies orbiting around each other at speeds only a few orders of magnitude below the speed of light.

Until relatively recently, no one dreamed that such bodies exist in our universe. Today, of course, we have all heard of black holes. But even at the mathematical level, the question of whether general relativity allows them at all was debated until the late 1950s. And after the issue was settled in the affirmative, it took another 20 years for black holes to enter mainstream astronomy literature. Similarly, the known stars were all fairly "tame", like our sun. Nature does admit *much more* dense, compact bodies, *neutron stars*, which are heavier than our sun but whose mass is compressed in a ball of radius of just 10 kilometres. Consequently, their density is a billion, million times greater than that of water. But such exotic objects were also unheard of until the late 1960s.

Then, in the 1970s it was found that neutron stars also feature in binaries. The first such binary system was discovered by Russell Hulse and Joseph Taylor in 1973. Finally, some six decades after Einstein's theoretical prediction, a system was located that could produce significant ripples in the space-time around it. Einstein's 1916 calculations showed that these gravitational waves carry away enough energy to have an appreciable effect on the orbits of the two stars. For, since total energy is conserved, the stars must compensate for the energy loss by steadily falling towards each other, following an ever-shrinking orbit. The shrinkage is tiny. But, fortunately, the neutron star in this binary system is a pulsar, that is, a "lighthouse", whose signal is beamed towards us. These signals arrive in the form of pulses that carry a wealth of information. Hulse and Taylor monitored these pulses carefully over the next two decades and, by decoding them, conclusively showed that the orbit is shrinking exactly as predicted by general relativity. Thus, finally, there was a proof that gravitational waves do exist in nature; they are physical and capable of carrying energy. For this discovery, Hulse and Taylor were awarded the

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THE LASER INTERFEROMETER Gravitational-wave Observatory in Livingston, Louisiana, United States.

Physics Nobel Prize in 1993, the first and so far the only Nobel Prize associated with general relativity. But this is now about to change.

FINALLY, SEPTEMBER 14, 2015!

Spectacular as the Hulse-Taylor discovery is, the evidence it provides for the existence of gravitational waves is indirect. The sensational discovery announced two weeks ago by the LIGO/VIRGO collaboration is the first direct detection, made on September 14, 2015 (see article by R. Ramachandran).

Why has it taken so long? As gravitational waves travel through space, their strength diminishes inversely with the distance from the source. The emission in the Hulse-Taylor binary is sufficiently strong near that system to measurably affect orbits, but by the time they arrive on earth they are extremely weak to be detected here. What is needed was a truly cataclysmic event that caused not just an appreciable ripple, but a *veritable storm* in the fabric of space-time in the vicinage of the source. Only then is the strength of the ripple measurable on earth. The cataclysmic event that caused that particular event was a collision between two black holes, each with about 33 times the mass of the sun. The violent event forced the two black holes to merge and the result was a black hole of about 63 solar masses. So in this event, energy contained in the mass equivalent of *three suns* was converted to gravitational waves in a fraction of a second. This is the type of tsunami that I referred to earlier. In the last fraction of a second of the collision, more power was packed into gravitational waves than that carried by light emitted by *all stars in the entire universe!* Interestingly, the event took place long ago, very long ago. About a billion years ago, when the universe was much, much younger and the earth was just spawning first multicellular life. In a very literal sense, then, the gravitational waves detected by the LIGO observatories in the United States on September 14, 2015, were cosmic messengers that brought to us first-hand information on a cataclysmic collision that occurred in a remote corner of the universe far, far away.

STILL, WHY SO MUCH EXCITEMENT?

Yes, the detection brought out, yet again, the sheer audacity of the human race. We dared to undertake the task of peering into the distant reaches of the universe and uncovered a catastrophic explosion of the type that was not imagined even by the likes of Einstein. Is that what all the excitement is about?

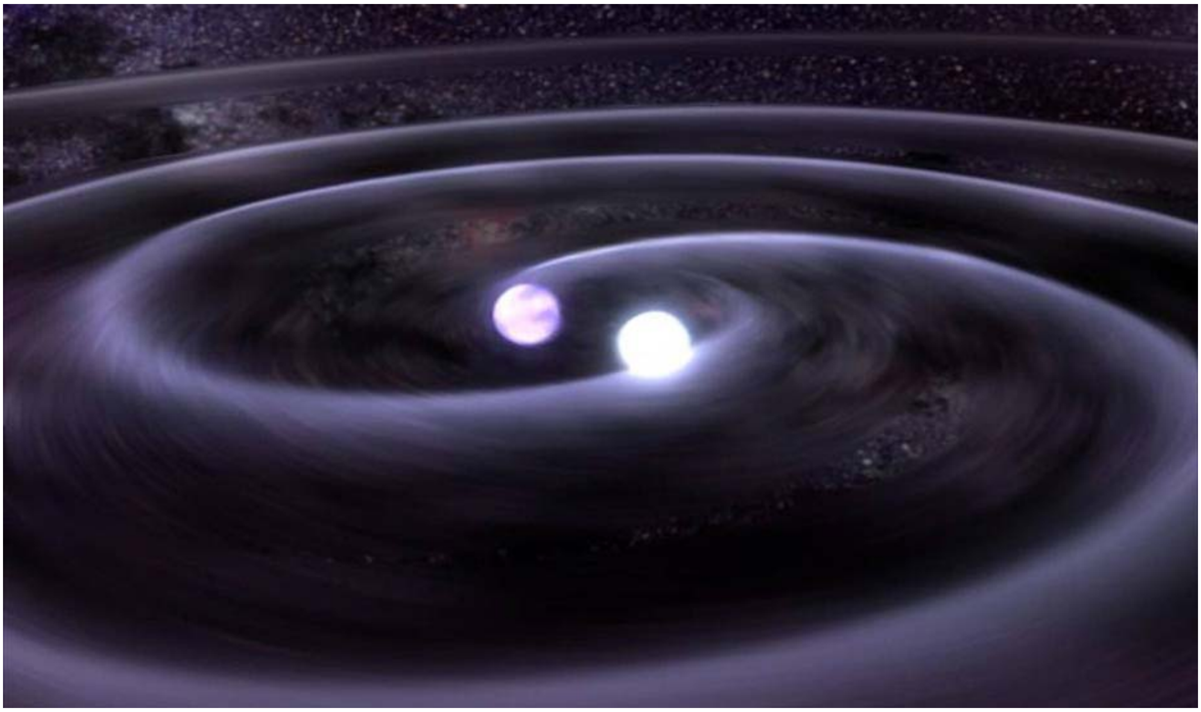
No. The real excitement comes from the fact that the direct detection of gravitational waves by the LIGO observatories has opened *a brand new window on the universe*. Over 400 years ago, Galileo turned the telescope to the skies and set us on the course to an untold number of discoveries about the marvels the universe holds. We now have the potential to do something equally grand.

Ever since the human race started gazing at the night sky and pondering about the nature of heavenly bodies, all our information about the universe has come in the form of electromagnetic waves. Until the middle of the last century, we only knew what was revealed to us in visible light. By and large, the universe appeared to be rather calm. But then we broadened the frequency bands and looked at the universe using radio waves, through infrared light, through X-rays and through gamma rays. The universe seen at these frequencies, we found, was dramatically different. Brand new phenomena were seen to unfold. There were huge bursts of energy in the form of jets. There were radio bursts. We saw brand new processes heavenly bodies engage in that had not been even imagined before. As a result, our view of the universe today is *very* different from what it was half a century ago. The novel and exotic phenomena of yesterday are now part of the standard picture. They were always there. But we were blind to them in spite of centuries of careful observations simply because we did not have the appropriate detectors to receive the messengers that the cosmos has been sending. Gravitational waves are a whole new genre of cosmic messengers, entirely different from our electromagnetic channels. Starting now, we will be blessed with novel, unforeseen opportunities. It is as if a curtain is being drawn back, exposing us to new aspects of the cosmos we inhabit.

We *cannot* see black hole collisions through any of the electromagnetic frequencies. The only messengers that can inform us of such phenomena are gravitational waves. Over the last quarter of a century, astronomers have pondered a great deal about black holes. But they have been unsure of whether our universe harbours black holes of tens of solar masses. The very first gravitational-wave signal has dispelled that doubt. Every time a new frequency band became accessible in the electromagnetic spectrum, new facets of the universe were uncovered, facets that we had not imagined before. Gravitational waves have opened an entirely new branch of astronomy, with various frequency bands of its own. They will reveal to us an untold number of new phenomena. Over the next quarter of a century, our view of the universe is likely to change dramatically.

LIGO INDIA

India is well poised to participate in this revolution that is waiting in the wings. Over several decades, Indian researchers at the Inter-University Centre for Astronomy and Astrophysics (IUCAA) in Pune and the Raman Research Institute in Bengaluru have been deeply involved in gravitational-wave science, making important theoretical contributions to diverse aspects of the problem, ranging from mathematical studies within general relativity to novel aspects of statistics and analysis of large data sets (see article by P. Ajith and K.G. Arun). Currently, under the umbrella of the IndIGO consortium, some 60 scientists from nine institutions are members of the LIGO Scientific Collaboration, and the paper reporting the first detection includes 35 authors from these institutions. Furthermore, thanks to the sustained effort by a handful of leading researchers over the last five years, prospects for the future are even brighter.



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AN ARTISTIC IMPRESSION of the ripples in space-time geometry produced by two orbiting compact bodies.

These researchers have proposed the creation of a Laser Interferometer Gravitational-wave Observatory in India itself, which will become an integral part of the international network of such observatories, including two in the U.S., one in Europe and one in Japan (see article by Bala Iyer and Tarun Souradeep). Through the IndIGO consortium, India is already represented on the Gravitational Wave International Committee. Funding for the LIGO-India proposal was included in the 12th Five Year plan in 2012 through the Department of Atomic Energy and the Department of Science and Technology. We heard recently that the Union Cabinet has now given its approval, clearing the way for the construction of this observatory. Through a bilateral agreement, the U.S. will provide an advanced detector valued approximately at $120 million and India will invest upwards of Rs.1,200 crore to create the observatory. In the current plan, the charge is divided among three lead institutions: the IUCAA, the Institute for Plasma Research in Bengaluru and the Raja Ramanna Centre for Advanced Technology in Indore.

This initiative represents a truly extraordinary opportunity for development of both fundamental science and technology. On the scientific front, the participating institutions will create human resources not only in physics and astronomy but also in statistics, computational science and data analysis. Through summer schools, workshops and visits to other institutions in the U.S. and Europe, young researchers will be trained in state-of-the-art techniques in all these areas. The opportunities to push forefront technology to new heights are truly immense. The observatory will feature 4-km-long tunnels in which laser beams bounce back and forth between suspended mirrors (see article by Stanley Whitcomb). This will be one of the most sensitive instruments on earth. The interference pattern between laser beams will be able to detect displacements of mirrors of 1/1000th size of a proton, over their 4-km separation! That is comparable to measuring the distance to Alpha Centauri, the nearest star system to our sun, to an accuracy of less than a human hair. Through the vacuum systems employed in the 4-km-long tunnels, through the powerful lasers used in the interferometer, and through the novel methods that go in the building of the required mirrors and the suspension system that holds them, research and development efforts have already improved technologies used in vacuum systems, optics and material science by several orders of magnitude. It is a true blessing for young researchers to be able to put together, use, and further develop such fine instruments. Through this participation, they will remain at the very cusp of technology in these areas for years to come.

The new cosmic messengers have brought not only news from the distant reaches of the universe, but also joy and exuberance to an untold number of young scientists and technologists in India. ☐

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