

General Introduction

Version 1

Einstein's general theory of relativity is the modern description of gravity. It is based on the concept of a curved four-dimensional spacetime, and predicts the existence of black holes and gravitational waves. Black holes are thought to be common in the Universe. In fact, most galaxies, including the Milky Way, seem to harbour gigantic black holes in their cores. Yet we do not have the means to probe black holes directly. We expect this to change with the advent of gravitational-wave astronomy. Binary black hole systems provide particularly exciting sources of gravitational radiation. Their detection would confirm Einstein's theory and would provide a detailed fingerprint of a black hole. Recent advances in numerical simulations have led to reliable models of the inspiral and subsequent merger of black-hole binaries.

At the same time, the first generation gravitational wave detectors like LIGO in the US, Virgo in Italy and GEO600 in Germany are presently being upgraded to the second generation by applying the newest components and technology. When the instruments go back online, their sensitivity and frequency range will be significantly enhanced.

Version 2

Much of what astronomers detect and measure about the universe is a consequence of gravity: Gas collapses to form stars and galaxies. Smaller galaxies collide and merge to form larger galaxies. When their nuclear fuel is exhausted, stars explode in supernovae and the remnants collapse to make white dwarf stars, neutron stars and black holes.

By detecting and tracking gravitational waves, Gravitational wave detectors will enable astronomers to see the most violent gravitational events. For example, a single pair of merging black holes will emit ten times the energy of all the stars in all the galaxies in the visible universe – all of it in the form of gravitational waves and none of it observable by conventional astronomical observations.

What are gravitational waves?

Version 1

Gravitational waves are time-varying distortions in spacetime – technically a 'strain' in the fabric of the cosmos - that move throughout the universe. Compact massive objects like black holes, neutron stars and white dwarfs, typically generate these waves, but other highly energetic processes may also generate them. Gravitational waves can be directly detected by measuring minute changes in the apparent separation of otherwise undisturbed objects.

Version 2

Gravitational waves are ripples in the fabric of space and time produced by violent events in the distant universe, for example by the collision of two black holes or by the cores of supernova explosions. Gravitational waves are emitted by accelerating masses much in the same way as radio waves are produced by accelerating charges – for example, such as electrons in antennas. These ripples in the space-time fabric travel to Earth, bringing with

them information about their violent origins and about the nature of gravity that cannot be obtained by other astronomical tools.

Albert Einstein predicted the existence of these gravitational waves in 1916 in his general theory of relativity, but only since the 1990s has technology become powerful enough to permit detecting them and harnessing them for science. Although they have not yet been detected directly, the influence of gravitational waves on a binary pulsar system (two neutron stars orbiting each other) has been measured accurately and is in excellent agreement with the predictions. Scientists therefore have great confidence that gravitational waves exist. But a direct detection will confirm Einstein's vision of the waves, and allow a fascinating and unique view of cataclysms in the cosmos.

Version 3

Gravitational waves are ripples in the fabric of space and time produced by violent events in the distant universe--for example, by the collision of two black holes or by the cores of supernova explosions. Gravitational waves are emitted by accelerating masses much in the same way as radio waves are produced by accelerating charges-- such as electrons in antennas.

Version 4 – short

Gravitational waves -- tiny deformations of space-time -- had been predicted by Albert Einstein, but their direct verification is still one of the most tantalising open issues of modern science. Einstein himself did not believe that they could ever be measured. An indirect proof of their existence has already been obtained by the American astronomers Russell Hulse and Joseph Taylor Jr. This won them the 1993 Nobel Prize in physics.

Why gravitational wave astronomy?

When in 1916 Albert Einstein predicted the existence of gravitational waves as an outcome of his General Theory of Relativity, he was convinced that these minute changes in the fabric of space-time would never be measurable. And still the direct detection of gravitational waves belongs to the most important open questions of modern science. Their direct observation will open the era of gravitational wave astronomy and will thus allow totally new insights into our universe – including clues as to its very beginning.

Observation of gravitational waves would have, aside from verifying the General Theory of Relativity, far-reaching consequences: For the first time it would become possible to cast an eye on the “childhood” of our universe. Up to now the observation of the sky is limited to the electromagnetic spectrum (e.g., radio and X-ray telescopes and astronomy in visible light). The information thus available to us will reach back into the past only to an era as much as 380,000 years after the Big Bang. Epochs dating back even further have thus far remained hidden, as only at that time the universe became transparent for electromagnetic radiation. The various theories on the early universe have therefore remained unverified experimentally. The direct measurement of gravitational waves would open totally new possibilities, as gravitation is not subject to these limitations. Via gravitational wave astronomy, totally new areas of science will become accessible.

Measuring Gravitational waves

Gravitational wave detectors like the British-German GEO600-, die US American LIGO- and the French-Italian-Dutch Virgo-detector are L-shaped laser interferometers for high precision measurements. Each detector uses a laser split into two beams which travel back and forth down long arms in evacuated beam tubes. The beams are used to monitor the distance between precisely figured mirrors. According to Albert Einstein's 1916 theory of general relativity, the relative distance of the mirrors changes very slightly when a gravitational wave--a distortion in space-time produced by massive accelerating objects that propagates outward through the universe--passes by. The interferometers are constructed in such a way that they can detect a change of less than a thousandth the diameter of an atomic nucleus in the lengths of the arms relative to each other.

The first generation gravitational wave detectors like LIGO, Virgo and GEO600 are presently being upgraded to the second generation by applying the newest components and technology. When the instruments go back online, their sensitivity and frequency range will be significantly enhanced.

Research is carried out by the LIGO Scientific Collaboration, a group of about 600 scientists from twelve countries. The LIGO Scientific Collaboration interferometer network includes the MPG/STFC funded GEO600 interferometer located in Hannover, Germany designed operated by scientists from the Max Planck Institute for Gravitational Physics, Germany, and partners in the UK.

Space- and groundbased observation

The Laser Interferometer Space Antenna LISA, a future gravitational wave detector in space and the ground-based gravitational wave observatories are complementary. LIGO for instance observes a higher frequency range (10-1,500 hertz) and LISA observes a lower range (0.0001 to 0.1 hertz). These ranges are as different from each other as gamma rays are from visible light in the electromagnetic spectrum. Consequently, the two detectors perceive very different sources of gravitational waves.

The ground-based detectors will provide useful information on mergers of binaries containing neutron stars and black holes weighing roughly 10 solar masses. LISA will be able to provide new information about the initial formation and growth of supermassive black holes found in the centers of galaxies. These massive black holes may initially form weighing hundreds of solar masses and grow as large as ten billion solar masses. LISA is most sensitive to merging systems where the total mass ranges from thousands to tens of millions of solar masses. By tracing mergers in this range, LISA can help astrophysicists learn about the interaction of such massive black holes with the galaxy formation back to the birth of the earliest galaxies.

Advanced LIGO & possible quote:

The Advanced LIGO Project is an upgrade in sensitivity for LIGO (Laser Interferometer Gravitational-wave Observatories). The National Science Foundation funds the \$205.12 million, seven-year project, starting with \$32.75 million in 2008.

This major upgrade will increase the sensitivity of the LIGO instruments by a factor of 10, giving a one thousand-fold increase in the number of astrophysical candidates for gravitational wave signals. The new instrument will see gravitational wave sources possibly on a daily basis, with excellent signal strengths, allowing details of the waveforms to be observed and compared with theories of neutron stars, black holes, and other astrophysical objects moving near the speed of light.

The Advanced LIGO detector, to be installed at the LIGO Observatories in Hanford, Washington, and Livingston, Louisiana, using the existing infrastructure, will replace the present detector, and will transform gravitational wave science into a real observational tool. The improvement of sensitivity will allow the data set generated after one year of initial operations to be equaled in just several hours.

The change of more than a factor of 10 in sensitivity comes also with a significant increase in the sensitive frequency range, and the ability to tune the instrument for specific astrophysical sources. This will allow Advanced LIGO to look at the last minutes of life of pairs of massive black holes as they spiral closer, coalesce into one larger black hole, and then vibrate much like two soap bubbles becoming one.

It will also allow the instrument to pinpoint periodic signals from the many known pulsars that radiate in the range from 500 to 1000 Hertz (frequencies which correspond to high notes on an organ). Recent results from the Wilkinson Microwave Anisotropy Probe have shown the rich information that comes from looking at the photon, or infrared cosmic background, which originated some 400,000 years after the Big Bang. Advanced LIGO can be optimized for the search for the gravitational cosmic background--allowing tests of theories about the development of the universe only 10-35 seconds after the Big Bang.

The LIGO Observatories were planned at the outset to support the continuing development of this new science, and the significant infrastructure of buildings and vacuum systems is left unchanged. The upgrade calls for changes in the lasers (180 watt highly stabilized systems), optics (40 kg fused silica "test mass" mirrors suspended by fused silica fibers), seismic isolation systems (using inertial sensing and feedback), and in how the microscopic motion (in the range of 10-20 meters) of the test masses is detected.

Several of these technologies are significant advances in their fields, and have promise for application in a wide range of precision measurement, state-of-the-art optics, and controls systems. A program of testing and practice installation will allow the new detectors to be brought online with a minimum of interruption in observation. The instruments will be ready to start scientific operation in 2014.

The design of the instrument has come from scientists throughout the 50-institution, 600-person LIGO Scientific Collaboration, an international group that carries out both instrument development and scientific data analysis for LIGO.

Possible quote (earlier used by Bernard Schutz in a press release about Advanced LIGO):

"Advanced LIGO will be one of the most important scientific instruments of the 21st century. For the first time, it will let us listen in on the sounds of the universe, as unseen explosions, collisions, and whirlpools shake the fabric of space-time and send out the ripples that

Advanced LIGO will measure. We in the German-British GEO project are excited that our long-standing partnership with LIGO allows us to contribute to Advanced LIGO some of the key technologies we have developed and tested in our GEO600 instrument.”

Several international partners have already approved funding for significant contributions of equipment, labor, and expertise:

- The UK contribution is the suspension assembly and some optics for the mirrors whose movements register the passage of the gravitational waves; this has been funded via Britain's Science and Technology Facilities Council (STFC).
- The German contribution is the high-power, high-stability laser whose light measures the actual movements of the mirrors; this has been funded via the Max Planck Society in Munich.
- The University of Florida and Columbia University are taking on specific responsibilities in the design and construction of Advanced LIGO.
- Other members of the LIGO Scientific Collaboration (LSC), with NSF or other funding, will participate in all phases of the effort.

LIGO Photos are available at:

http://www.ligo.caltech.edu/~beckett/LIGO/Images/HiResAerials/HiResHanford_5.jpg
http://www.ligo.caltech.edu/~beckett/LIGO/Images/HiResAerials/HiResHanford_3.jpg
http://www.ligo.caltech.edu/~beckett/LIGO/Images/HiResAerials/HiResLivingston_5.jpg
http://www.ligo.caltech.edu/~beckett/LIGO/Images/HiResAerials/HiResLivingston_6.jpg

GEO600 Photos:

<http://www.geo600.org/press-information/photos/geo600>

Additional information:

- The LIGO Laboratory: <http://www.ligo.caltech.edu>.
- Advanced LIGO: <http://www.ligo.caltech.edu/advLIGO/>
- The LIGO Scientific Collaboration: <http://www.ligo.org>.
- GEO600: <http://www.geo600.org/>
- LISA: <http://www.lisa-science.org/intro>