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Extracting Physics from Gravitational Waves

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POPULAR-SCIENCE SUMMARY (EN)

Description of planetary motion throughout time

Humans have been watching the sky for thousands of years. In early times, humans tracked the motion of the Sun and the Moon to make calendars and to associate it with Earthly events such as tides and seasons. By tracking the motion of celestial objects, the early notion of the orbit of the Sun, the Moon and the planets started to form. Building on earlier work developed by Greek astronomers, Claudius Ptolemy (90–168) introduced an accurate model of the planetary orbits by including the notion of a smaller circular orbit (epicycle) augmenting the primary circular orbit.

During the Renaissance, our knowledge of the sky started to change. Johannes Kepler (1571–1630) introduced three laws that described the planetary orbits as ellipses with the Sun at the focus. Later, Isaac Newton (1642–1727) showed that Kepler’s laws of planetary motion can be derived from a law that not only describes the motion of planets, but also describes how all objects are attracted to each other. Newton’s law of universal gravitation states that all objects “pull” on each other through the gravitational force, and the strength of this force is determined by the masses of the two objects.

Despite the success of Newton’s law of universal gravitation, it could not account for the shift in Mercury’s perihelion, the point in Mercury’s orbit that is closest to the Sun. It was Albert Einstein (1879–1955) who refined Newton’s law of universal gravitation by introducing the general theory of relativity. Einstein’s general theory of relativity states that the curvature of space and time dictates the way in which matter flows through it, and conversely, matter curves space and time around it. Einstein’s theory explained the shift in Mercury’s perihelion, and so far seems to be the correct description of the motion of planets, stars and even galaxies.

Gravitational waves: a new window into the Universe

The general theory of relativity does more than just predicting the motion of objects. It also predicts a new type of radiation, known as gravitational radiation or gravitational waves. Gravitational waves are ripples in the curvature of space and time, which propagate at the speed of light. The effect of gravitational waves is the periodic expansion and contraction

of space and time. The existence of gravitational waves has only been inferred indirectly through the motion of two stars orbiting each other.

Large-scale physics experiments such as the United States-based LIGO and the Italy-based Virgo aim to, for the first time in the history of mankind, detect the influences of gravitational waves directly. LIGO and Virgo are set up to measure tiny changes in distances of about one thousandth of the diameter of a proton. The characteristics of the gravitational waves are intimately connected to the motion of the source. Where, traditionally, astronomers needed telescopes to determine the motion of planets, stars and galaxies, the measurement of gravitational waves can provide an additional window from which we can explore the secrets of the Universe.

Testing Einstein's general theory of relativity

From Ptolemy to Newton and from Newton to Einstein, history has taught us that our laws of physics need continual refinement to describe Nature to ever increasing accuracy. No exception should be made for Einstein's general theory of relativity. In fact, Einstein's theory has never been tested in the vicinity of extremely dense objects such as neutron stars and black holes. Neutron stars are stellar remnants that mainly consist of electrically-neutral subatomic particles called neutrons. Neutron stars are so dense that they pack the mass of the Sun in about the size of a city. Black holes are even more extreme objects. They are stellar remnants that were once so dense that these stars could not counteract their own gravitational pull and imploded into themselves. Black holes are given their distinct name because their gravitational pull is so strong that not even light can escape if it comes too close.

This thesis describes the Test Infrastructure for GEneral Relativity (TIGER) framework, which provides a theoretical framework and a data-analysis algorithm to test the general theory of relativity in a way that does not require any knowledge of a possible alternative theory. TIGER compares the motion of two orbiting neutron stars to the prediction made by the general theory of relativity and assigns a degree of plausibility to the question: "Are the orbits consistent with the predictions from the general theory of relativity?" Such a test is analogous to precisely measuring the orbit of planets, and comparing it to the prediction made by Newton's law of universal gravitation.

The TIGER framework was tested through computer simulations that used thousands of computers spread all over the world. The results seem to suggest that the TIGER framework can detect arbitrary deviations in the motion of the orbiting neutron stars. Furthermore, the results show that by using the TIGER framework to analyse LIGO and Virgo data, one is able to test the influence of gravitation to precisions that have yet been achieved.

If the TIGER framework manages to find a deviation from Einstein's general theory of relativity, then it will mean a new revolution in our understanding of gravitation. Scientists will introduce new ideas to fill the gap left in our explanation of how all things in the Universe move. However, any potential new theory must be able to describe current and future observations. The circle of theoretical models predicting observations, and observations con-

firming theoretical models is likely to go on indefinitely, as humans continue to refine their ability to describe and to predict what happens in the Universe.

Inferring the large-scale behaviour of the Universe

Since the time of Ptolemy and Newton, we have come to know more about the glittering stars we see on the sky. For example, we have come to realise that the Milky Way is a large group of stars bound by their gravitational interaction, also known as a galaxy. Moreover, it turns out that some of the “stars” we see on the sky are actually galaxies. In fact, we now know that there are more than a hundred billion galaxies in our vast Universe. Remarkably, their collective motion, which seems to suggest that the Universe is undergoing an accelerated expansion, can be described by the general theory of relativity. The study of this large-scale behaviour of the Universe is called cosmology.

To determine the collective motion of galaxies, one needs to measure their distance from Earth and their relative motion with respect to Earth. However, the farther an object is, the more difficult it is to determine its distance. Scientists nowadays use a range of techniques to determine the distance of increasingly remote objects. Each of these techniques is calibrated to techniques used to determine the distance to closer objects. The series of different techniques is called the cosmic distance ladder, where each rung of the ladder represents a different distance-measurement technique. Such a setup is necessary because little is currently known about the properties of distant stars and galaxies. However, the cosmic distance ladder is rather error prone, as each rung depends on the results and accuracy of the previous rung. A tiny error in the first rung could have devastating consequences for the distance measurement of a remote object.

An alternative way of measuring cosmological distances that is less error prone than using the cosmic distance ladder, is by measuring the gravitational waves of two orbiting neutron stars or black holes. The general theory of relativity describes the way the intensity of gravitational waves becomes weaker as the observer is farther away, just as a light source appears to be fainter the farther you are from it. The ability to predict how the intensity of gravitational waves decays as the observer is farther allows scientists to measure the distance to an object directly, without the aid of the cosmic distance ladder.

This thesis explores the ability of future gravitational-wave detectors such as the Einstein Telescope, to measure the distance to remote objects. We focus on the gravitational-wave observations of two orbiting neutron stars or black holes. Those systems with at least one neutron star are believed to also emit a light signal as the two stars collide in the final stages of their dance around each other. We can measure the motion of the system relative to Earth by determining the wavelength composition of the light. By measuring hundreds of these orbiting neutron stars or black holes, scientists can map their collective behaviour.

Our results show that future gravitational wave detectors can map the large-scale behaviour of the Universe to the same accuracy as current and future telescopes. But the strength of using gravitational waves is that it is free from possible errors introduced by the cosmic distance ladder. Gravitational-wave measurements can provide an independent verification

of the current cosmological paradigm, or they may refute it.

Future of gravitational-wave astronomy

The topics covered in this thesis are merely the tip of the iceberg of what we can learn from direct gravitational-wave observations. From observations by telescopes we have clue of what we might expect. Yet, much about the Universe remains unknown. For example, the origin of about 96 percent of the content of the Universe is still unknown. All massive objects can emit gravitational waves, including those that do not emit light. This means that gravitational-wave observatories can study things that conventional telescopes cannot. This opens the possibility of detecting phenomena that have yet to be envisaged. The first detection of gravitational waves will usher in a new era of astronomy. Many scientists are working hard to prepare for the coming of this era. The author hopes that the work in this thesis will find a place in the scientific literature. Moreover, he hopes that in the near future, he can apply his work onto real gravitational-wave detections.

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