Introduction

The Laser Interferometer Space Antenna (LISA) is a joint space mission between the NASA and the ESA which is to be launched in 2025. Its purpose is to detect gravitational waves, a proposed phenomenon relating to general relativity which has never before been detected. NASA describes the project as “one of two large space missions to be implemented in this decade.”

The mission will consist of three identical spacecraft which will be oriented in an equilateral triangle. Each spacecraft will direct two powerful laser beams at test masses on the other spacecraft, separated by a distance of 5 million kilometres. These lasers act as the light beams in an interferometer apparatus, while the test masses act as mirrors. Since there are three beams, two independent interference patterns can be observed.

Gravitational waves incident on this interferometer will alter the path lengths of the beams periodically by a very tiny amount. The smallest measurable precision is 4x10^{-11} m, averaged over 1 second. Thus, there will be produced a very tiny – but measurable – periodic shift between the two interference patterns. The observable frequency is in the order of 10^{-4} to 10^{-1} Hz.

What are Gravitational Waves?

Gravitational Waves (GWs) are a phenomenon which was first proposed in 1905 by Jules Henri Poincaré as a simple analogy to electromagnetic waves. He proposed that GWs were necessary for two masses to communicate the force of gravity with one another, just as electromagnetic waves are necessary for two charges to communicate electromagnetic forces over some distance.

GWs were predicted and described in detail ten years later by Einstein’s General Theory of Relativity. The theory describes gravity as a curvature of space-time around bodies with mass, and also allows for ripples in the curvature of space-time as masses accelerate in an asymmetrical way. These ripples could manifest themselves as fluctuating tidal forces on masses in the path of the wave.

Gravitational waves are highly penetrating, meaning that they retain much of their energy during matter interactions. This leads to the energy deposited by a GW onto any laboratory-sized detector being very small. This, coupled with the fact that the tidal oscillations produced by GWs are also very small, leads to great difficulty in detection.

The analogy between gravitational waves and electromagnetism breaks down when considered rigorously. Gravitational waves are quadrupole in nature, while electromagnetic waves are monopole in nature.
are dipole. This means that while a charge must move with some non-zero acceleration to produce electromagnetic waves, a mass must undergo an asymmetrical acceleration referred to as “jerking” (with the time derivative of acceleration non-zero) to produce gravitational waves.[1]

Quantisation of gravitational waves came in the 1930s with the proposal of the graviton as the vector boson of gravity. The major unique feature of the graviton is that it has a spin of 2, while photons have spin 1[9]. This means that while photons interact with matter but not with one another, gravitons will also interact with other gravitons. Another way to understand this point is to say that gravitons themselves have mass, and so can themselves emit other gravitons. It is this complicated quantum nature which leads to GWs being quadrupole.

There are many astronomical objects that are proposed to emit gravitational waves, though no GWs have actually been detected from any of them. A few examples are unstable binary star systems and binary black holes, stars being absorbed by black holes, electromagnetic to gravitational wave conversion in the cosmic media, “evaporation” of small black holes with fast rotation, and primordial gravitational waves from fluctuations in the early universe.

Interferometer Detection:

The first GW detectors were developed by Joseph Weber in 1963, His “Weber Bars” were designed to measure oscillations in a suspended aluminium cylinder due to the tidal forces caused by GWs. Since then, many different and more sophisticated detection mechanisms have been employed, though none have yet been successful in observing gravitational waves.

Since then, many different detection techniques have been developed such as measuring light polarisation shift in circular waveguides over many periods of an incident GW; measuring the relative shift in resonance frequency between coupled electromagnetic cavities as a GW changes their dimensions; anticipating GW-EM wave conversion with an electromagnetic sense beam; and indirect measurement via a pulsar timing array. None of these techniques have yet been successful in detecting gravitational waves, though there has been significant theoretical evidence for their existence.[7][2]

Interferometry remains the most promising technique for the possible detection of GWs. These detectors rely on alterations in the relative path lengths of a Michelson interferometer to detect gravitational waves. The first ground-based interferometer detector was operational in 1983. These detectors have also undergone much development since their initial use, becoming larger and more sensitive with each subsequent generation.

A Michelson interferometer combines two coherent light beams that have travelled different distances to produce an interference pattern. The interference pattern produced is highly dependant on the path difference between the two beams. Gravitational waves incident on the apparatus (in a direction normal to the plane of the arms) would alter the relative path lengths of the arms periodically by a very tiny amount, and this alteration in path length would lead to a detectable shift in the interference pattern.
In a laser interferometric detector, a light beam is split to form two coherent beams, which are each "stored" between two suspended test masses acting as mirrors. A gravitational wave altering the length of the light storage arm would then alter the path length by a larger amount, as the light beam is passing through this space multiple times. After a fixed number of reflections in the light storage arms, the beams are then recombined to form the required interference pattern, and any shift in path length due to a gravitational wave can be observed, and the frequency and amplitude of the incident GW could be determined from the observed path length alterations.

**Laser Interferometric Detector**

![Diagram of a laser interferometer GW detector](source)

Fig. 1. Schematic of a laser interferometer GW detector. Source: [4]

A space-based interferometer detector such as LISA was proposed to eliminate noise due to human and seismic activity on Earth, and to allow for higher vacuum conditions over much larger distances than ground based detectors. The largest ground based detectors are called LIGO (Laser Interferometer Gravitational wave Observatories), and have perpendicular evacuated arms of length 2 - 4km. This would be far exceeded by LISA's 5 million km arm length. A greater arm length gives an interferometer better sensitivity to low frequency GWs.

**LISA Mission Plan**

The proposed launch date for LISA is between 2018 and 2025, this depends on how NASA and ESA chooses to distribute their resources.

A single launcher will be directed into a solar orbit behind the Earth, then the three craft which will form the interferometer will each be propelled away from this launcher with ion engines. They will come into formation of an equilateral triangle with side length 5 million km. This triangular formation will be in a stable orbit around the sun, about 50 million km (20 degrees) behind the Earth. The target length for the mission is ten years, including just over one year for the launch and orientation of the satellites.
The three spacecraft will be identical, the current design is for each to be a short cylinder of size 2.8 x 0.76 meters\(^6\). Each spacecraft will have solar panels for power, ion engines, a laser source and beam-splitter, and two suspended test masses, as well as antennae for communication with Earth. The entire apparatus across all three spacecraft acts as two independent interferometers, with the fixed test masses acting as the mirrors. With regard to fig. 1, each spacecraft will contain the laser, beamsplitter, photodetector and two test masses of the interferometer detector, while the light storage arms occupy the space between the three spacecraft.

![Fig. 2. LISA orientation of satellites and position with respect to Earth, with a gravitational wave source. [4]](image)

**LISA’s disadvantages**

There are some disadvantages to the interferometer space antenna over other gravitational wave detectors:

Firstly, thermal noise from light source prevents low frequency detection, and shot noise from the production of photons prevents high frequency detection. These provide an effective frequency range over which any interferometer design can detect gravitational waves. LISA's frequency range is about \(10^{-4}\) to \(10^{-1}\) Hz\(^6\). Thus, LISA will be used to target gravitational waves in this specific part of the spectrum, proposed to originate from objects such as black holes and binary star systems, while other detectors will focus on other GW sources.
Interferometers must be made very large to allow for reasonable path-length shifts from GWs, and are hence very difficult and expensive to build and maintain. Other detectors which rely on resonance over many periods of a GW can be made much smaller, though are often still expensive.

A space design interferometer must be placed at a distance from local gravitational sources. The large distance makes repairs and upgrades difficult to perform.

**The Outcome of LISA’s mission**

If LISA is successful in detecting gravitational waves, then the simple proof of their existence opens up many possibilities for scientific advancement:

Firstly, the existence of GWs would strengthen the theory of relativity by providing direct experimental evidence.

With better detectors, gravitational wave astronomy may prove to be a very enlightening field for astronomical discovery. New GW sources could be discovered leading to a better understanding of the universe. Also, GWs are more penetrating than EM waves, so can be used to observe events through visual blockages, they could even be used to observe the early universe past the dust cloud near the time of the Big Bang.\(^{[1]}\) GWs could be used to observe the interactions of black holes directly, providing direct evidence for their existence.

It has also been proposed that GWs could provide a means of propulsion of spacecraft, not relying on fuel expulsion. The craft would essentially “surf” on the gravitational wave.\(^{[1]}\) High frequency GWs could also be used for communications in future space missions over very large distances.\(^{[1]}\)
There is always the possibility, however, that LISA will fail to detect any gravitational waves. In the event that GWs are not detected, this may force the proposal of a new model of gravity which does not include gravitational waves. This could mean that Einstein's theory of relativity itself may have to be reconsidered. If this is indeed the case, the next few decades will prove to be a very interesting time for the study of physics.

References


