6 Read the following article and answer the questions that follow.

Gravitational Waves

In 1916, Albert Einstein predicted the existence of gravitational waves.

Charged particles that are accelerating emit electromagnetic waves. Einstein thought that masses that are accelerating would emit gravitational waves. The Laser Interferometer Gravitational-wave Observatory (LIGO) detectors in the Louisiana and Washington states of America have recently confirmed the existence of these waves. These two detectors are 3002 km apart.

As a gravitational wave passes through the universe, it stretches and compresses space so that it is stretched in one direction and compressed in a perpendicular direction. As a gravitational wave passes through an object, the object will change shape from the viewpoint of an outside observer.

Gravitational forces are very weak. Only the gravitational waves emitted by very massive bodies, such as black holes and neutron stars, are currently detectable.

The first gravitational waves detected were emitted during the collision of two black holes, about 1.3×10^9 light-years from Earth. The black holes had masses of 29 and 36 solar masses, respectively. The two black holes collided to form one single black hole of 62 solar masses in a time of 20 ms.

A LIGO detector is an interferometer built away from human activity. It consists of two straight vacuum tubes, each about 4.0 km long, arranged as shown in Fig. 6.1.

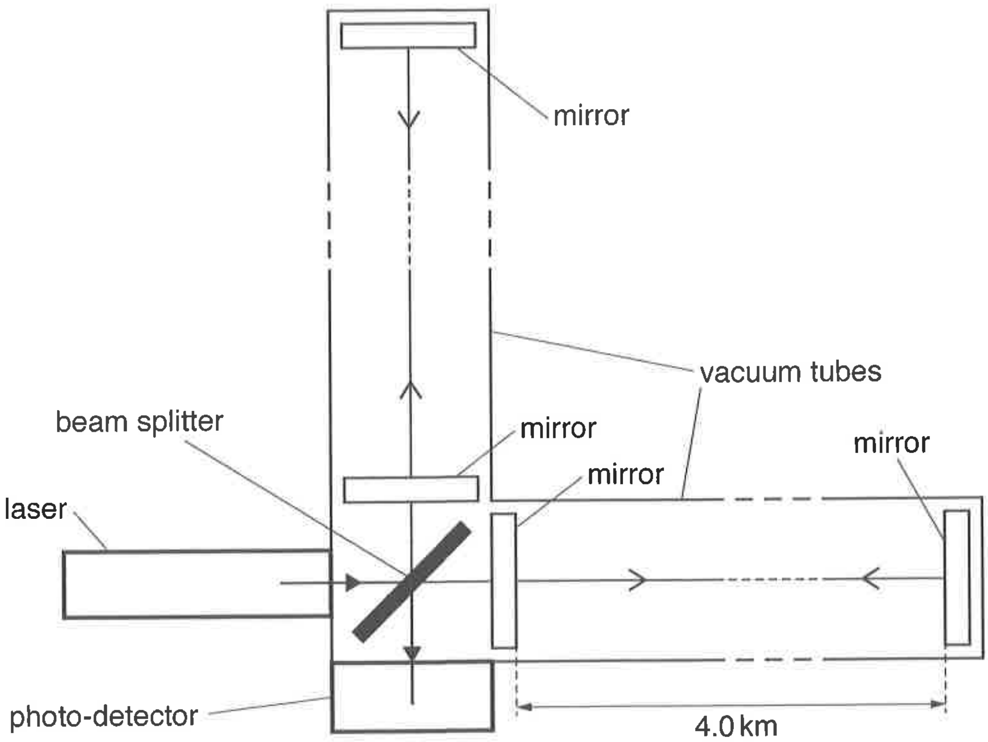


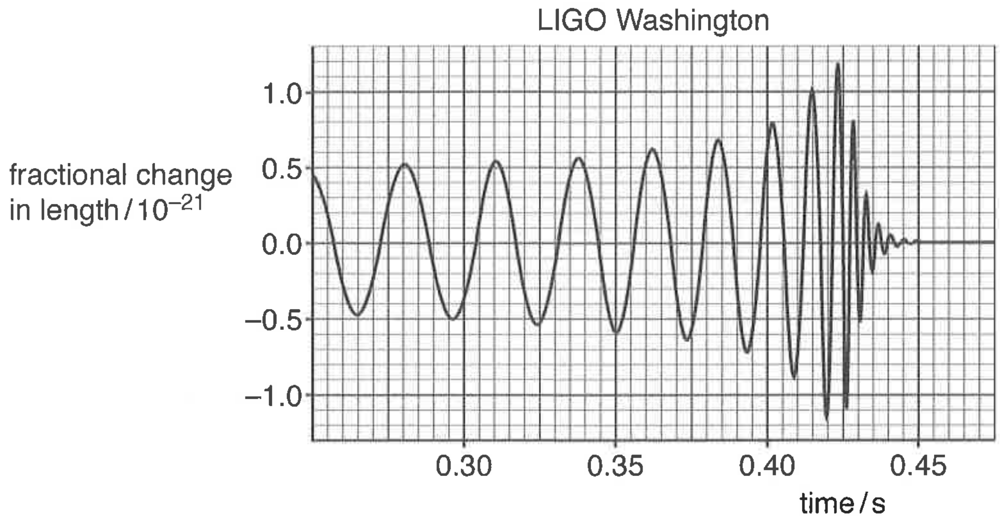
Fig. 6.1 (not to scale)

A beam of laser light, wavelength 1064 nm and power 200 W, is split into two coherent beams. Each beam is directed along a different tube of the interferometer. The two beams have a phase difference of π radians.

The light going along each tube is reflected 140 times from each mirror. The mirrors are 4.0 km apart. The distance between the mirrors in each tube is measured to a precision of one thousandth of a mm. These mirrors are designed to be isolated from vibrations and to minimise the effect of the light radiation pressure on them. Hence, the distance between the mirrors is only sensitive to changes caused by gravitational waves.

The light travels 280 times along each tube before being recombined at a photo-detector. Under normal conditions, the resultant signal upon recombination has zero amplitude. In the presence of a gravitational wave, one tube of the interferometer lengthens and shortens, and the other tube shortens and lengthens. The tubes will change length in this way for as long as it takes the wave to pass. This results in a further difference in phase between the two light beams and a corresponding change of amplitude at the photo-detector where the two beams are recombined. LIGO detectors can detect a change in tube length as small as 10^{-19} m.

The variations with time of the fractional change in length of one of the tubes of each of the LIGO detectors in Washington and Louisiana are shown in Fig. 6.2. The graphs are simplified.



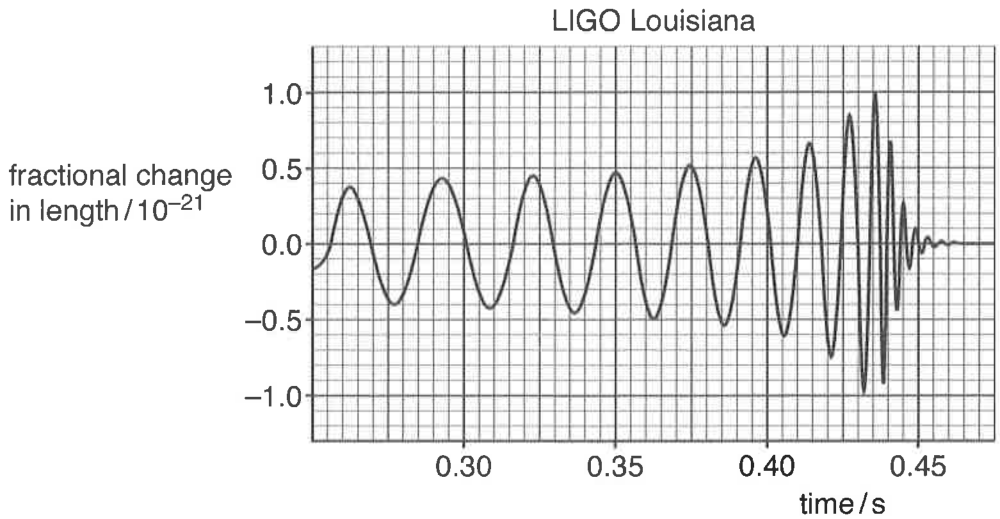


Fig. 6.2

(a) Suggest why gravitational waves have **not** been observed from a source in the Solar System.

....

.... [1]

(b) (i) Use data from Fig. 6.2 to estimate the maximum change of length of one of the vacuum tubes in the LIGO detector.

maximum change of length = ... m [1]

(ii) With reference to your answer in **(b)(i)** explain why the light beams need to be reflected many times.

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....

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.... [2]

(iii) Explain why the LIGO photo-detector theoretically receives a signal of zero amplitude in the absence of gravitational waves.

....

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.... [2]

(c) (i) Once split, each laser beam has a power of 100 W. Calculate the number N of photons passing a point in the 100 W beam in each second.

N = ... [3]

(ii) Use your answer in **(c)(i)** to calculate the average force exerted by the light beam on one mirror when the beam is completely reflected back along its original path.

force = ... N [3]

(iii) In reality, some photons are absorbed by the mirror and are not reflected. State and explain the change, if any, this would make to your answer in **(c)(ii)**.

....

.... [1]

(d) (i) Calculate the energy released in the collision of the two black holes.

1.0 solar mass = 2.0×10^{30} kg

energy = ... J [2]

(ii) Assume that all of the energy released in the collision was in the form of gravitational waves that travel uniformly in all directions.

Calculate the power per unit area received on Earth due to the gravitational waves.

1.0 light-year = 9.5×10^{15} m

power per unit area = ... $W m^{-2}$ [4]

(e) (i) Use Fig. 6.2 to determine the time between the detection of the gravitational wave at the two LIGO detectors.

time = ... s [1]

(ii) Use your answer in **(e)(i)** and the distance between the detectors to obtain a value for the speed of the gravitational waves.

speed = ... $m\,s^{-1}$ [1]

(iii) It has been shown that gravitational waves travel at the speed of light in free space.

Suggest a reason for the difference between this and your answer in **(e)(ii)**.

....

.... [1]

(f) It is proposed that three LIGO detectors are built in space. Suggest two advantages of building these detectors in space.

1. ....

....

2. ....

....

[2]

[Total: 24]