Universal Gravitation 3.3

Figure 1
The details of the night sky are enhanced when the surroundings are dark and a telescope is used. The force of gravity has an important influence on all the objects in the universe.

People have always enjoyed viewing stars and planets on clear, dark nights (**Figure 1**). It is not only the beauty and variety of objects in the sky that is so fascinating, but also the search for answers to questions related to the patterns and motions of those objects.

Until the late 1700s, Jupiter and Saturn were the only outer planets identified in our solar system because they were visible to the naked eye. Combined with the inner planets (Mercury, Venus, Earth, and Mars), the solar system was believed to consist of the Sun and six planets, as well as other smaller bodies such as moons. Then in 1781, British astronomer William Herschel (1738–1822), after making careful observations on what other astronomers thought was a star, announced that the "star" appeared to move relative to the background stars over a long period. This wandering star turned out to be the seventh planet, which Herschel named Uranus, after the Greek god of the sky and ruler of the universe. Astronomers studied the motion of Uranus over many years and discovered that its path was not quite as smooth as expected. Some distant hidden object appeared to be "tugging" on Uranus causing a slightly uneven orbit. Using detailed mathematical analysis, they predicted where this hidden object should be, searched for it for many years, and in 1846 discovered Neptune (**Figure 2**). Neptune is so far from the Sun that it takes almost 165 Earth years to complete one orbit; in other words, it will soon complete its first orbit since being discovered.

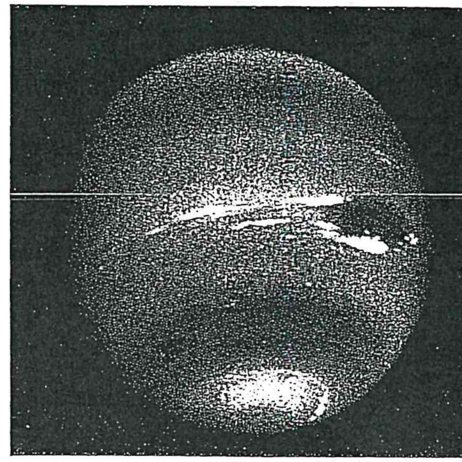

Figure 2
Neptune, the most distant of the gas giant planets, was named after the Roman god of water. Although earthbound telescopes disclose little detail, photographs taken by the space probe *Voyager 2* in 1989 reveal bright blue and white clouds, and a dark area that may be a large storm.

The force that keeps the planets in their orbits around the Sun and our Moon in its orbit around Earth is the same force tugging on Uranus to perturb its motion—the force of gravity. This force exists everywhere in the universe where matter exists. Sir Isaac Newton first analyzed the effects of gravity throughout the universe. Neptune was discovered by applying Newton's analysis of gravity.

LEARNING TIP

Perturbations
In physics, a perturbation is a slight alteration in the action of a system that is caused by a secondary influence. Perturbations occur in the orbits of planets, moons, comets, and other heavenly bodies. When astronomers analyze the perturbations in the orbits of heavenly bodies, they search for the secondary influence and sometimes discover another body too small to find by chance.

Newton's Law of Universal Gravitation

In his *Principia,* published in 1687, Newton described how he used known data about objects in the solar system, notably the Moon's orbit around Earth, to discover the factors that affect the force of gravity throughout the universe. The relationships involved are summarized in his *law of universal gravitation.*

DID YOU KNOW?

Caroline Herschel: An Underrated Astronomer

Uranus was the first planet discovered by telescope. William Herschel, the astronomer who made the discovery, designed and built his own instruments with the assistance of another astronomer, his sister. Caroline Herschel (1750–1848) spent long hours grinding and polishing the concave mirrors used to make reflecting telescopes. With some of those telescopes, she made many discoveries of her own, including nebulae (clouds of dust or gas in interstellar space) and comets. She also helped William develop a mathematical approach to astronomy, and contributed greatly to permanently valuable catalogues of astronomical data. She was the first woman to be granted a membership in the Royal Astronomical Society in London, UK.

Newton's Law of Universal Gravitation

The force of gravitational attraction between any two objects is directly proportional to the product of the masses of the objects, and inversely proportional to the square of the distance between their centres.

To express this law in equation form, we use the following symbols for the magnitudes of the variables involved: F_G is the force of gravitational attraction between any two objects; m_1 is the mass of one object; m_2 is the mass of a second object; and r is the distance *between the centres* of the two objects, which are assumed to be spherical.

Newton discovered the following proportionalities:

If m_2 and r are constant, $F_G \propto m_1$ (direct variation).

If m_1 and r are constant, $F_G \propto m_2$ (direct variation).

If m_1 and m_2 are constant, $F_G \propto \frac{1}{r^2}$ (inverse square variation).

Combining these statements, we obtain a joint variation:

$$F_G \propto \frac{m_1 m_2}{r^2}$$

Finally, we can write the equation for the law of universal gravitation:

$$F_G = \frac{G m_1 m_2}{r^2}$$

where G is the universal gravitation constant.

In applying the law of universal gravitation, it is important to consider the following observations:

- There are two equal, but opposite forces present. For example, Earth pulls on you and you pull on Earth with a force of equal magnitude.
- For the force of attraction to be noticeable, at least one of the objects must be very large.
- The inverse square relationship between F_G and r means that the force of attraction diminishes rapidly as the two objects move apart. On the other hand, there is no value of r, no matter how large, that would reduce the force of attraction to zero. Every object in the universe exerts a force of attraction on every other object.
- The equation for the law of universal gravitation applies only to two spherical objects (such as Earth and the Sun), to two objects whose sizes are much smaller than their separation distance (for example, you and a friend separated by 1.0 km), or to a small object and a very large sphere (such as you and Earth).

SAMPLE problem 1

Earth's gravitational pull on a spacecraft some distance away is 1.2×10^2 N in magnitude. What will the magnitude of the force of gravity be on a second spacecraft with 1.5 times the mass of the first spacecraft, at a distance from Earth's centre that is 0.45 times as great?

Solution

Let m_E represent the mass of Earth, and the subscripts 1 and 2 represent the first and second spacecraft, respectively.

$F_1 = 1.2 \times 10^2$ N

$m_2 = 1.5m_1$

$r_2 = 0.45r_1$

$F_2 = ?$

By ratio and proportion:

$$\frac{F_2}{F_1} = \frac{\left(\dfrac{Gm_Em_2}{r_2^2}\right)}{\left(\dfrac{Gm_Em_1}{r_1^2}\right)}$$

$$\begin{aligned} F_2 &= F_1\left(\frac{m_2}{r_2^2}\right)\left(\frac{r_1^2}{m_1}\right) \\ &= F_1\left(\frac{1.5m_1}{(0.45r_1)^2}\right)\left(\frac{r_1^2}{m_1}\right) \\ &= 1.2 \times 10^2 \text{ N}\left(\frac{1.5}{(0.45)^2}\right) \\ F_2 &= 8.9 \times 10^2 \text{ N} \end{aligned}$$

The force of gravity on the spacecraft is 8.9×10^2 N in magnitude.

Practice

Understanding Concepts

1. Relate Newton's third law of motion to his law of universal gravitation.
2. What is the direction of the gravitational force of attraction of object A on object B?
3. The magnitude of the force of gravitational attraction between two uniform spherical masses is 36 N. What would the magnitude of the force be if one mass were doubled, and the distance between the objects tripled?
4. Mars has a radius and mass 0.54 and 0.11 times the radius and mass of Earth. If the force of gravity on your body is 6.0×10^2 N in magnitude on Earth, what would it be on Mars?
5. The magnitude of the force of gravity between two uniform spherical masses is 14 N when their centres are 8.5 m apart. When the distance between the masses is changed, the force becomes 58 N. How far apart are the centres of the masses?

Applying Inquiry Skills

6. Sketch a graph showing the relationship between the magnitude of the gravitational force and the distance separating the centres of two uniform spherical objects.

Making Connections

7. In the past, Pluto has been known as the ninth planet in the solar system. Recently, however, it has been suggested that Pluto should be classified as a body other than a planet. Research and write a brief report on Pluto's discovery, and also the reasons for the recent controversy over Pluto's planetary status.

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Answers

3. 8.0 N
4. 2.3×10^2 N
5. 4.2 m

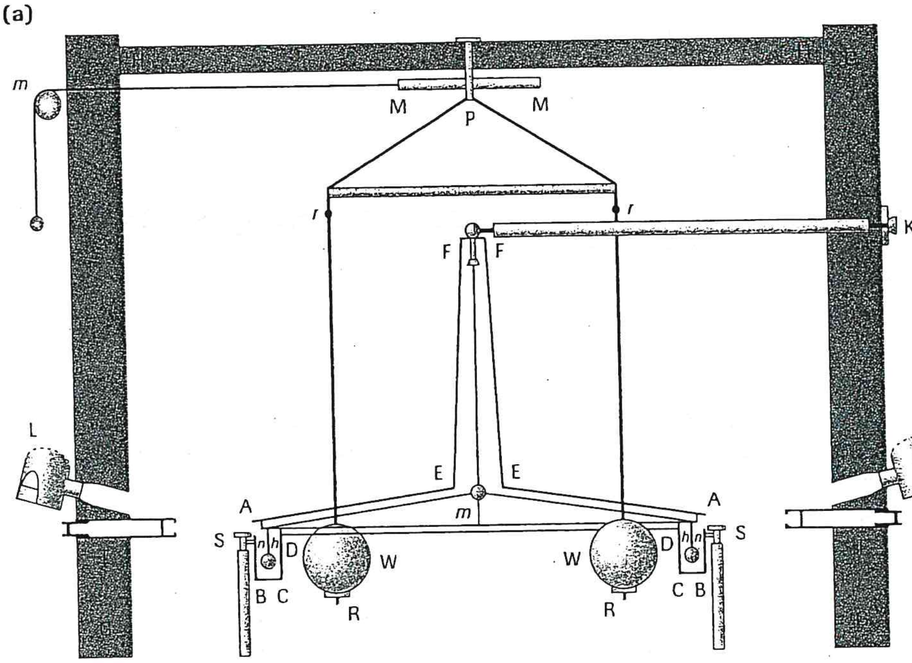
Universal Laws

Newton's law of universal gravitation was among the first of the "universal truths," or laws of nature that could be applied everywhere. Scientists in the 18th and 19th centuries introduced an analytical and scientific approach to searching for answers to questions in other fields. By the turn of the 20th century, however, scientific investigation showed that nature was not as exact and predictable as everyone had believed. For example, as you will see in Unit 5, the tiny physical world of the atom does not obey strict, predictive laws.

Determining the Universal Gravitation Constant

The numerical value of the universal gravitation constant G is extremely small; experimental determination of the value did not occur until more than a century after Newton formulated his law of universal gravitation. In 1798, British scientist Henry Cavendish (1731–1810), using the apparatus illustrated in **Figure 3**, succeeded in measuring the gravitational attraction between two small spheres that hung on a rod approximately 2 m long and two larger spheres mounted independently. Using this equipment, he derived a value of G that is fairly close to today's accepted value of $6.67 \times 10^{-11}\ \mathrm{N{\cdot}m^2/kg^2}$. His experiment showed that gravitational force exists even for relatively small objects and, by establishing the value of the constant of proportionality G, he made it possible to use the law of universal gravitation in calculations. Cavendish's experimental determination of G was a great scientific triumph. Astronomers believe that its magnitude may influence the rate at which the universe is expanding.

(a)



(b)

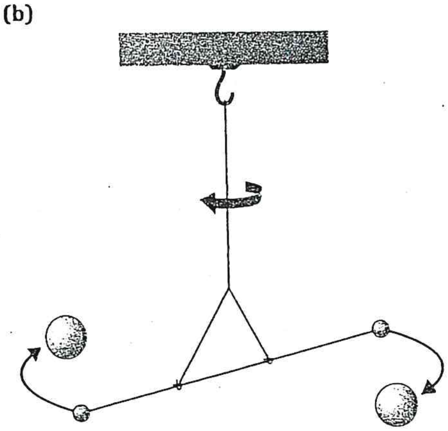


Figure 3
Cavendish's experimental setup
(a) This sketch of the apparatus appeared in his original paper. The device is mounted in a large case G, with outside controls to move the masses and adjust the horizontal rod. Scales near the end of the rod are illuminated by lamps L and observed through the telescope T.
(b) A simplified view of the apparatus

SAMPLE problem 2

Determine the magnitude of the force of attraction between two uniform metal balls, of mass 4.00 kg, used in women's shot-putting, when the centres are separated by 45.0 cm.

Solution

$G = 6.67 \times 10^{-11}$ N·m²/kg² $\qquad r = 0.450$ m

$m_1 = m_2 = 4.00$ kg $\qquad F_G = ?$

$$F_G = \frac{Gm_1m_2}{r^2}$$

$$= \frac{(6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2)(4.00\ \text{kg})(4.00\ \text{kg})}{(0.450\ \text{m})^2}$$

$$F_G = 5.27 \times 10^{-9}\ \text{N}$$

The magnitude of the force of attraction is 5.27×10^{-9} N, an extremely small value.

Practice

Understanding Concepts

8. What is the magnitude of the force of gravitational attraction between two 1.8×10^8-kg spherical oil tanks with their centres 94 m apart?
9. A 50.0-kg student stands 6.38×10^6 m from Earth's centre. The mass of Earth is 5.98×10^{24} kg. What is the magnitude of the force of gravity on the student?
10. Jupiter has a mass of 1.90×10^{27} kg and a radius of 7.15×10^7 m. Calculate the magnitude of the acceleration due to gravity on Jupiter.
11. A space vehicle, of mass 555 kg, experiences a gravitational pull from Earth of 255 N. The mass of Earth is 5.98×10^{24} kg. How far is the vehicle (a) from the centre of Earth and (b) above the surface of Earth?
12. Four masses are located on a plane, as in **Figure 4**. What is the magnitude of the net gravitational force on m_1 due to the other three masses?

Making Connections

13. The mass of Earth can be calculated by applying the fact that an object's weight is equal to the force of gravity between Earth and the object. The radius of Earth is 6.38×10^6 m.
    (a) Determine the mass of Earth.
    (b) At what stage in the historical development of science would physicists first have been able to calculate Earth's mass accurately? Explain your answer.
    (c) What effect on society is evident now that we accurately know Earth's mass?

Answers

8. 2.4×10^2 N
9. 4.90×10^2 N
10. 24.8 m/s²
11. (a) 2.95×10^7 m
    (b) 2.31×10^7 m
12. 6.8×10^{-10} N
13. (a) 5.98×10^{24} kg

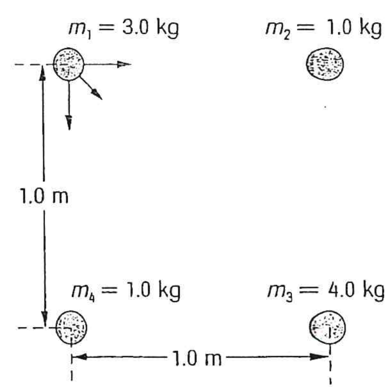


Figure 4
For question 12

SUMMARY Universal Gravitation

- Newton's law of universal gravitation states that the force of gravitational attraction between any two objects is directly proportional to the product of the masses of the objects and inversely proportional to the square of the distance between their centres.
- The universal gravitation constant, $G = 6.67 \times 10^{-11}$ N·m²/kg², was first determined experimentally by Henry Cavendish in 1798.
- The law of universal gravitation is applied in analyzing the motions of bodies in the universe, such as planets in the solar system. (This analysis can lead to the discovery of other celestial bodies.)

Section 3.1 Questions

Understanding Concepts

1. Do you agree with the statement, "There is no location anywhere in the universe where a body can exist with no force acting on it"? Explain.
2. The force of attraction between masses m_1 and m_2 is 26 N in magnitude. What will the magnitude of the force become if m_2 is tripled, and the distance between m_2 and m_1 is halved?
3. You are an astronaut. At what altitude above the surface of Earth is your weight one-half your weight on the surface? Express your answer as a multiple of Earth's radius r_E.
4. Calculate the magnitude of the gravitational attraction between a proton of mass 1.67×10^{-27} kg and an electron of mass 9.11×10^{-31} kg if they are 5.0×10^{-11} m apart (as they are in a hydrogen atom).
5. Uniform spheres A, B, and C have the following masses and centre-to-centre separations: $m_A = 55$ kg, $m_B = 75$ kg, $m_C = 95$ kg; $r_{AB} = 0.68$ m, $r_{BC} = 0.95$ m. If the only forces acting on B are the forces of gravity due to A and C, determine the net force acting on B with the spheres arranged as in **Figures 5(a)** and **(b)**.

(a) **(b)**

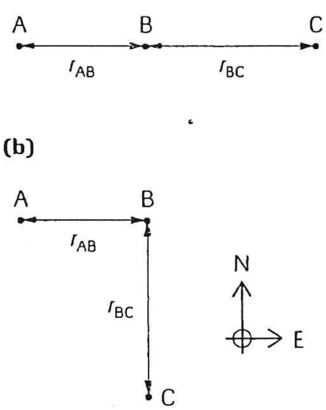


Figure 5

6. At a certain point between Earth and the Moon, the net gravitational force exerted on an object by Earth and the Moon is zero. The Earth-Moon centre-to-centre separation is 3.84×10^5 km. The mass of the Moon is 1.2% the mass of Earth.
   (a) Where is this point located? Are there any other such points? (*Hint:* Apply the quadratic formula after setting up the related equations.)
   (b) What is the physical meaning of the root of the quadratic equation whose value exceeds the Earth-Moon distance? (An FBD of the object in this circumstance will enhance your answer.)

Applying Inquiry Skills

7. Using **Figure 6**, you can illustrate what happens to the magnitude of the gravitational force of attraction on an object as it recedes from Earth. Make a larger version of the graph and complete it for the force of gravity acting on you as you move from the surface of Earth to 7.0 Earth radii from the centre of Earth.

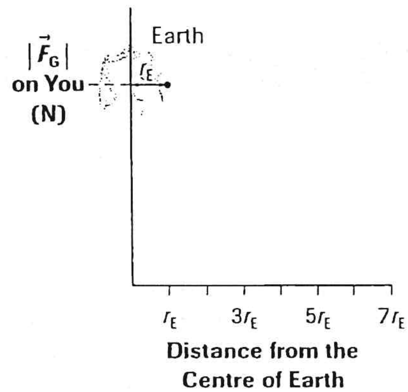


Figure 6

Making Connections

8. A geosynchronous satellite must remain at the same location above Earth's equator as it orbits Earth.
   (a) What period of revolution must a geosynchronous satellite have?
   (b) Set up an equation to express the distance of the satellite from the centre of Earth in terms of the universal gravitation constant, the mass of Earth, and the period of revolution around Earth.
   (c) Determine the value of the distance required in (b). (Refer to Appendix C for data.)
   (d) Why must the satellite remain in a fixed location (relative to an observer on Earth's surface)?
   (e) Research the implications of having too many geosynchronous satellites in the space available above the equator. Summarize your findings in a brief report.

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Satellites and Space Stations 3.4

A **satellite** is an object or a body that revolves around another object, which is usually much larger in mass. Natural satellites include the planets, which revolve around the Sun, and moons that revolve around the planets, such as Earth's Moon. Artificial satellites are human-made objects that travel in orbits around Earth or another body in the solar system.

A common example of an artificial satellite is the network of 24 satellites that make up the Global Positioning System, or GPS. This system is used to determine the position of an object on Earth's surface to within 15 m of its true position. The boat shown in Figure 1 has a computer-controlled GPS receiver that detects signals from each of three satellites. These signals help to determine the distance between the boat and the satellite, using the speed of the signal and the time it takes for the signal to reach the boat.

satellite object or body that revolves around another body

space station an artificial satellite that can support a human crew and remains in orbit around Earth for long periods

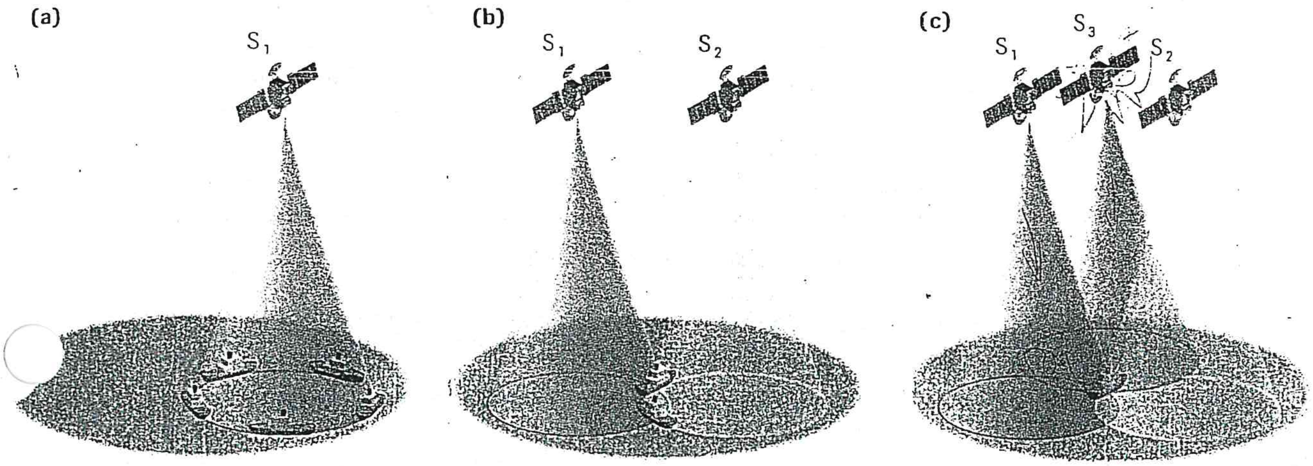


Figure 1
GPS satellites can determine the location of an object, in this case a boat.
(a) With one satellite, the location is known to be somewhere along the circumference of a circle.
(b) With two satellites consulted simultaneously, the location is found to be at one of two intersection spots.
(c) With three satellites consulted simultaneously, the intersection of three circles gives the exact location of the boat.

Another example of an artificial satellite is a **space station**, a spacecraft in which people live and work. Currently, the only space station in operation is the International Space Station, or ISS. Like satellites travelling with uniform circular motion, the ISS travels in an orbit of approximately fixed radius. The ISS is a permanent orbiting laboratory in which research projects, including testing how humans react to space travel, are conducted. In the future, the knowledge gained from this research will be applied to design and operate a spacecraft that can transport people great distances to some destination in the solar system, such as Mars.

Satellites in Circular Orbit

When Isaac Newton developed his idea of universal gravitation, he surmised that the same force that pulled an apple downward as it fell from a tree was responsible for keeping the Moon in its orbit around Earth. But there is a big difference: the Moon does not hit the ground. The Moon travels at the appropriate speed that keeps it at approximately the same distance, called the orbital radius, from Earth's centre. As the Moon circles Earth, it is undergoing constant free fall toward Earth; all artificial satellites in circular motion around Earth undergo the same motion. A satellite pulled by the f…f gravity toward Earth follows a curved path. Since Earth's surface is curved, the

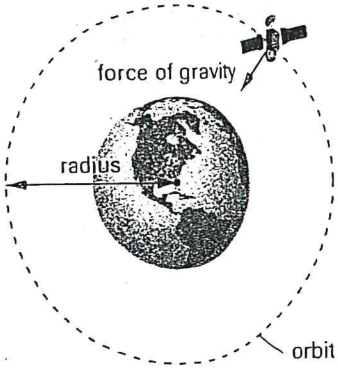


Figure 2
A satellite in a circular orbit around Earth experiences constant free fall as its path follows the curvature of Earth's surface.

satellite falls downward at the same rate as Earth's curvature. If the orbiting, free-falling satellite has the proper speed for its orbital radius as it falls toward Earth, it will never land (**Figure 2**).

To analyze the motion of a satellite in uniform circular motion, we combine Newton's law of universal gravitation with the equation for centripetal acceleration involving the satellite's speed. Using the magnitudes of the forces only, we have:

$$\sum F = \frac{Gm_S m_E}{r^2} = \frac{m_S v^2}{r}$$

where G is the universal gravitation constant, m_S is the mass of the satellite, m_E is the mass of Earth, v is the speed of the satellite, and r is the distance from the centre of Earth to the satellite. Solving for the speed of the satellite and using only the positive square root:

$$v = \sqrt{\frac{Gm_E}{r}}$$

This equation indicates that for a satellite to maintain an orbit of radius r, its speed must be constant. Since the Moon's orbital radius is approximately constant, its speed is also approximately constant. A typical artificial satellite with a constant orbital radius is a geosynchronous satellite used for communication. Such a satellite is placed in a 24-hour orbit above the equator so that the satellite's period of revolution coincides with Earth's daily period of rotation.

The equations for centripetal acceleration in terms of the orbital period and frequency can also be applied to analyze the motion of a satellite in uniform circular motion depending on the information given in a problem.

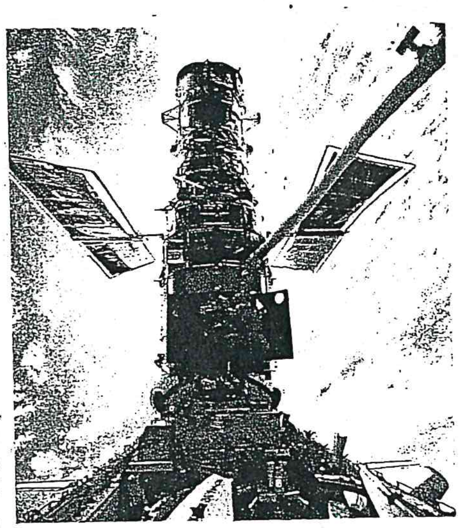


Figure 3
The Hubble Space Telescope (HST) being deployed from the cargo bay of a space shuttle

SAMPLE problem 1

The Hubble Space Telescope (HST), shown in **Figure 3**, follows an essentially circular orbit, at an average altitude of 598 km above the surface of Earth.

(a) Determine the speed needed by the HST to maintain its orbit. Express the speed both in metres per second and in kilometres per hour.

(b) What is the orbital period of the HST?

Solution

(a) $G = 6.67 \times 10^{-11}\ \text{N·m}^2/\text{kg}^2$ $\quad r = 6.38 \times 10^6\ \text{m} + 5.98 \times 10^5\ \text{m} = 6.98 \times 10^6\ \text{m}$

$m_E = 5.98 \times 10^{24}\ \text{kg}$ $\quad v = ?$

Since gravity causes the centripetal acceleration,

$$\frac{Gm_S m_E}{r^2} = \frac{m_S v^2}{r}$$

Solving for v:

$$v = \sqrt{\frac{Gm_E}{r}}$$

$$= \sqrt{\frac{(6.67 \times 10^{-11}\ \text{N·m}^2/\text{kg}^2)(5.98 \times 10^{24}\ \text{kg})}{6.98 \times 10^6\ \text{m}}}$$

$$= 7.56 \times 10^3\ \text{m/s}$$

$$v = 2.72 \times 10^4\ \text{km/h}$$

The required speed of the HST is 7.56×10^3 m/s, or 2.72×10^4 km/h.

(b) $v = 2.72 \times 10^4$ km/h
$d = 2\pi r = 2\pi(6.98 \times 10^3 \text{ km})$
$T = ?$

$$T = \frac{2\pi r}{v}$$
$$= \frac{2\pi(6.98 \times 10^3 \text{ km})}{2.72 \times 10^4 \text{ km/h}}$$
$$T = 1.61 \text{ h}$$

The orbital period of the HST is 1.61 h.

Practice

Understanding Concepts

1. (a) As the altitude of an Earth satellite in circular orbit increases, does the speed of the satellite increase, decrease, or remain the same? Why?
   (b) Check your answer by comparing the speed of the HST (discussed in Sample Problem 1) with the speed of the Moon. The orbital radius of the Moon is 3.84×10^5 km.
2. The ISS follows an orbit that is, on average, 450 km above the surface of Earth. Determine (a) the speed of ISS and (b) the time for one orbit.
3. Derive an expression for the radius of a satellite's orbit around Earth in terms of the period of revolution, the universal gravitation constant, and Earth's mass.
4. Satellite-broadcast television is an alternative to cable. A "digital TV" satellite follows a geosynchronous orbit.
   (a) State the period of revolution of the satellite in seconds.
   (b) Determine the altitude of the orbit above the surface of Earth.

Applying Inquiry Skills

5. Sketch graphs showing the relationship between the speed of a satellite in uniform circular motion and
   (a) the mass of the body around which the satellite is orbiting
   (b) the orbital radius

Making Connections

6. Astronomers have identified a black hole at the centre of galaxy M87 (**Figure 4**). From the properties of the light observed, they have measured material at a distance of 5.7×10^{17} m from the centre of the black hole, travelling at an estimated speed of 7.5×10^5 m/s.

Figure 4
This image of the centre of galaxy M87 was obtained by the HST. The square identifies the area at the core of the galaxy where a black hole is believed to exist.

Did You Know?

Analyzing Black Holes
A black hole is created when a star, having exhausted the nuclear fuel from its core, and having a core mass about twice as great as the mass of the Sun, collapses. The gravitational force of a black hole is so strong that nothing—not even light—can escape. A black hole is observed indirectly as material from a nearby star falls toward it, resulting in the emission of X rays, some of which can be detected on Earth. Measurements of the material in circular motion around a black hole can reveal the speed of the material and the distance it is from the centre of its orbital path. The equations developed for satellite motion can then be used to determine the mass of the black hole.

Answers

1. (b) $v_M = 1.02 \times 10^3$ m/s
2. (a) 7.64×10^3 m/s
   (b) 1.56 h
3. $r = \sqrt[3]{\frac{T^2 G m_E}{4\pi^2}}$
4. (a) 8.64×10^4 s
   (b) 3.59×10^4 km
6. (a) 4.8×10^{39} kg
   (b) 2.4×10^9:1

(a) Determine the mass of this black hole, making the assumption that the observed material is in a circular orbit.
(b) What is the ratio of the mass of the black hole to the mass of the Sun (1.99×10^{30} kg)? What does this ratio suggest about the origin and makeup of a black hole found at the centre of a galaxy?
(c) It has been suggested that "dark body" is a better term than "black hole." Do you agree? Why or why not?

apparent weight the net force exerted on an accelerating object in a noninertial frame of reference

Apparent Weight and Artificial Gravity

When you stand on a bathroom scale, you feel a normal force pushing upward on your body. That normal force makes you aware of your weight, which has a magnitude of *mg*. If you were standing on that same scale in an elevator accelerating downward, the normal force pushing up on you would be less, so the weight you would feel would be less than *mg*. This force, called the **apparent weight**, is the net force exerted on an accelerating object in its noninertial frame of reference. If you were standing on that same scale on a free-falling amusement park ride, there would be no normal force and the scale would read zero. If you were to travel on the ISS, you would be in constant free fall, so there would be no normal force acting on you. **Figure 5** illustrates these four situations.

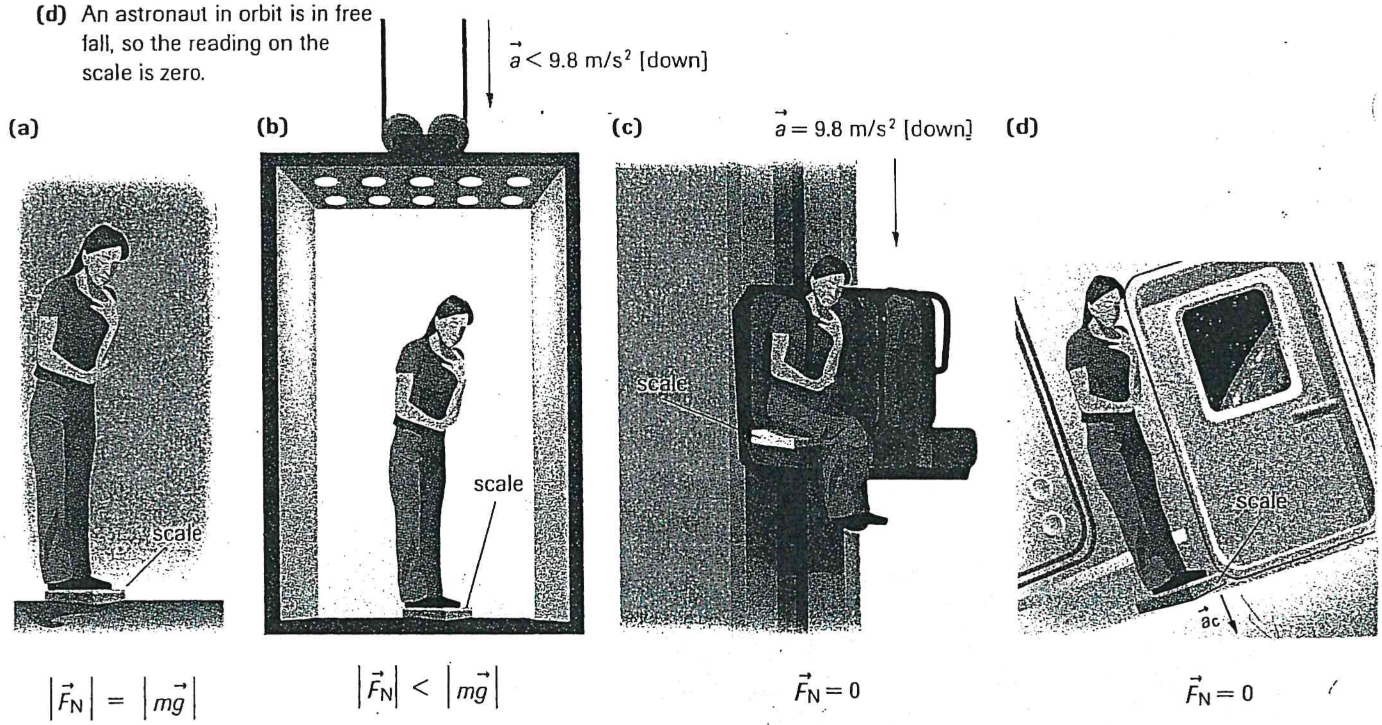


Figure 5
(a) The reading on a bathroom scale is equal to the magnitude of your weight, *mg*.
(b) The reading on the bathroom scale becomes less than *mg* if you weigh yourself on an elevator accelerating downward.
(c) The reading is zero in vertical free fall at an amusement park.
(d) An astronaut in orbit is in free fall, so the reading on the scale is zero.

Have you ever noticed how astronauts and other objects in orbiting spacecraft appear to be floating (**Figure 6**)? This condition arises as the spacecraft and everything in it undergo constant free fall. The apparent weight of all the objects is zero. (This condition of constant free fall has been given various names, including zero gravity, microgravity, and weightlessness. These terms will be avoided in this text because they are misleading.)

Since humans first became space travellers approximately four decades ago, researchers have investigated the effects of constant free fall on the human body. The absence of forces against the muscles causes the muscles to become smaller and the bones to become brittle as they lose calcium. Excess body fluids gather in the upper regions of the body causing the heart and blood vessels to swell, making the astronauts' faces look puffy and their legs look thinner. This imbalance of fluids also affects the kidneys, resulting in excess urination.

Today, vigorous exercise programs on space flights help astronauts reduce these negative effects on their bodies. Even with such precautions, however, the effects of constant free fall would be disastrous over the long periods needed to travel to other parts of the solar system, such as Mars. The most practical solution to this problem is to design interplanetary spacecrafts that have **artificial gravity**, where the apparent weight of an object is similar to its weight on Earth.

One way to produce artificial gravity during long space flights is to have the spacecraft constantly rotating (**Figure** 7). Adjusting the rate of rotation of the spacecraft to the appropriate frequency allows the astronauts' apparent weight to equal the magnitude of their Earth-bound weight.

Physics teachers often use water in a bucket swung quickly (and safely!) in a loop to simulate artificial gravity. You can perform a similar simulation in Activity 3.4.1 in the Lab Activities section at the end of this chapter.

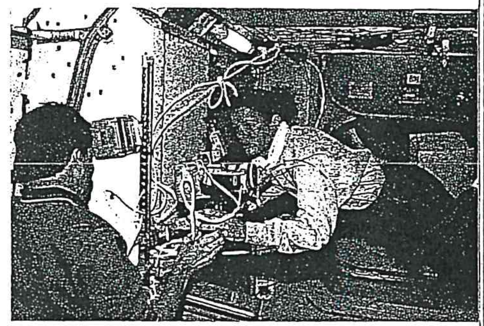


Figure 6
Canadian astronaut Julie Payette in free fall during duties on the space shuttle *Discovery* in 1999.

artificial gravity situation in which the apparent weight of an object is similar to its weight on Earth

ACTIVITY 3.4.1

Simulating Artificial Gravity (p. 154)
You can use a ball inside a bucket swung quickly in a vertical circle to simulate the situation in which an astronaut moves with uniform circular motion on the interior wall of a rotating space station. How does this model differ from the real-life rotating space station?

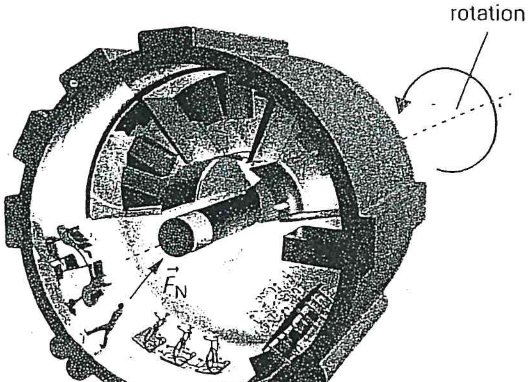


Figure 7
Any object on the inside surface of a rotating spacecraft experiences a normal force toward the centre of the craft. This normal force causes the centripetal acceleration of the objects in circular motion.

DID YOU KNOW?

Early Space Stations
The former Soviet Union and the United States operated experimental space stations intermittently from the 1970s onward. The most famous and long-lasting station before the ISS was the Soviet (later Russian) *Mir*, launched in 1986 and decommissioned in 2001.

SAMPLE problem 2

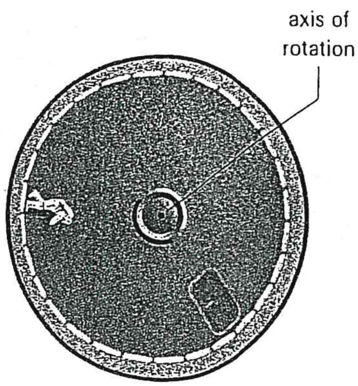
You are an astronaut on a rotating space station. Your station has an inside diameter of 3.0 km.

(a) Draw a system diagram and an FBD of your body as you stand on the interior surface of the station.

(b) Determine the speed you need to have if your apparent weight is to be equal in magnitude to your Earth-bound weight.

(c) Determine your frequency of rotation, both in hertz and in revolutions per minute.

(a)



(b)

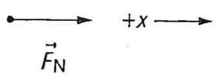


Figure 8
(a) The system diagram of the astronaut and the space station for Sample Problem 2
(b) The FBD of the astronaut

Solution

(a) **Figure 8** contains the required diagrams.

(b) The centripetal acceleration is caused by the normal force of the inside surface of the station on your body. Your weight on Earth is mg.

$r = 1.5 \text{ km} = 1.5 \times 10^3 \text{ m}$

$v = ?$

$$\sum F = ma_x$$
$$F_N = ma_c$$
$$F_N = \frac{mv^2}{r}$$
$$mg = \frac{mv^2}{r}$$
$$v^2 = gr$$
$$v = \sqrt{gr}$$
$$= \sqrt{(9.8 \text{ m/s}^2)(1.5 \times 10^3 \text{ m})}$$
$$v = 1.2 \times 10^2 \text{ m/s}$$

Your speed must be 1.2×10^2 m/s.

(c) $v = 1.2 \times 10^2$ m/s

$f = ?$

$$v = \frac{2\pi r}{T}$$
$$f = \frac{1}{T}$$
$$v = 2\pi rf$$
$$f = \frac{v}{2\pi r}$$
$$= \frac{1.2 \times 10^2 \text{ m/s}}{2\pi(1.5 \times 10^3 \text{ m})}$$
$$f = 1.3 \times 10^{-2} \text{ Hz, or } 0.77 \text{ rpm}$$

Your frequency of rotation is 1.3×10^{-2} Hz, or 0.77 rpm.

Practice

Understanding Concepts

7. Determine the magnitude of the apparent weight of a 56-kg student standing in an elevator when the elevator is experiencing an acceleration of (a) 3.2 m/s^2 downward and (b) 3.2 m/s^2 upward.

8. Describe why astronauts appear to float around the ISS even though the gravitational pull exerted on them by Earth is still relatively high.

9. The ISS travels at an altitude of 450 km above the surface of Earth.
(a) Determine the magnitude of the gravitational force on a 64-kg astronaut at that altitude.
(b) What percentage of the astronaut's Earth-bound weight is the force in (a)?

10. A cylindrical spacecraft travelling to Mars has an interior diameter of 3.24 km. The craft rotates around its axis at the rate required to give astronauts along the interior wall an apparent weight equal in magnitude to their Earth-bound weight. Determine (a) the speed of the astronauts relative to the centre of the spacecraft and (b) the period of rotation of the spacecraft.

Answers

7. (a) 3.7×10^2 N
(b) 7.3×10^2 N

9. (a) 5.5×10^2 N
(b) 87%

10. (a) 126 m/s
(b) 80.8 s