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.

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

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.

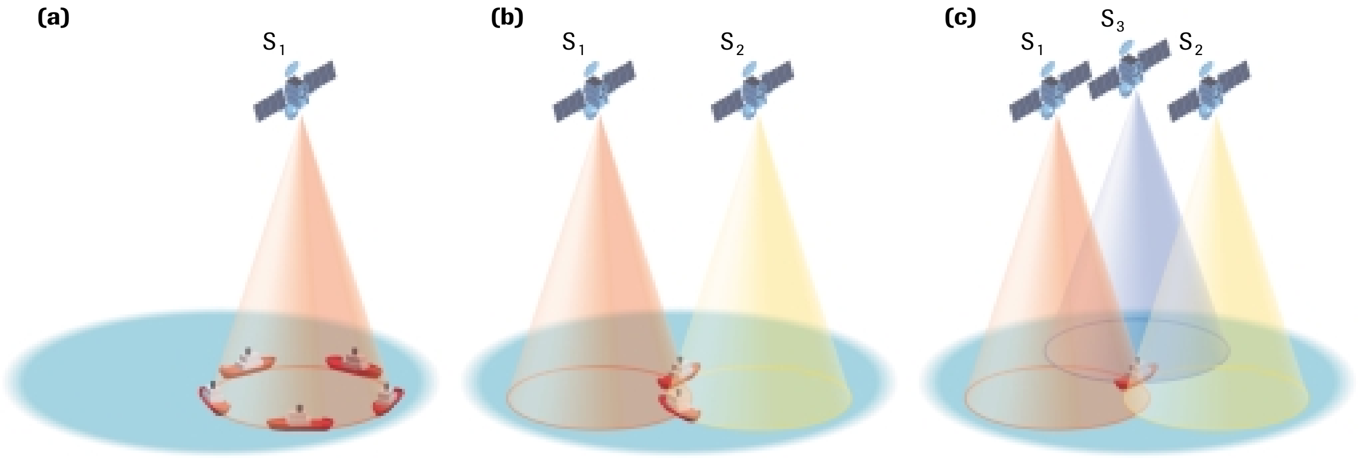


Figure 1
GPS satellites can determine the location of an object, in this case a boat.
(a) With one satellite, the location is known to be somewhere along the circumference of a circle.
(b) With two satellites consulted simultaneously, the location is found to be at one of two intersection spots.
(c) 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 force of gravity toward Earth follows a curved path. Since Earth's surface is curved, the

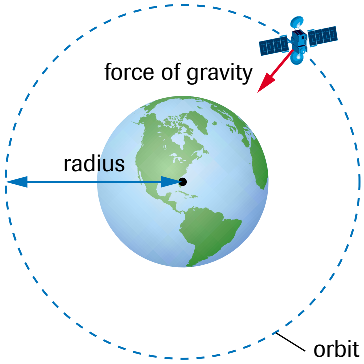


Figure 2
A satellite in a circular orbit around Earth experiences constant free fall as its path follows the curvature of Earth's surface.

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.

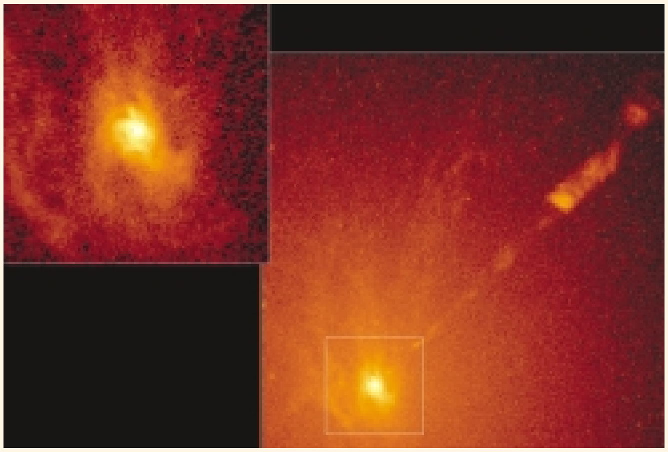


Figure 4
This image of the centre of galaxy M87 was obtained by the HST. The square identifies the area at the core of the galaxy where a black hole is believed to exist.

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.

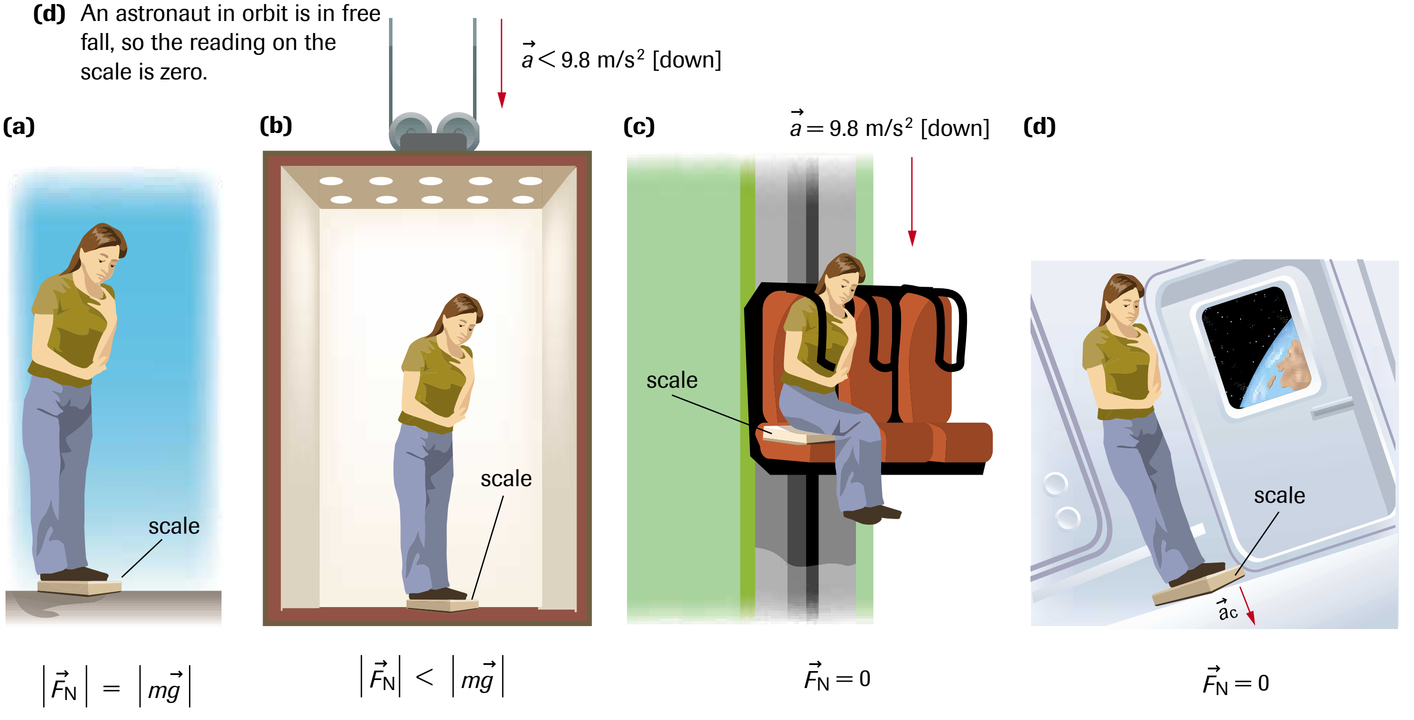


Figure 5
(a) The reading on a bathroom scale is equal to the magnitude of your weight, *mg*.
(b) The reading on the bathroom scale becomes less than *mg* if you weigh yourself on an elevator accelerating downward.
(c) The reading is zero in vertical free fall at an amusement park.
(d) An astronaut in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

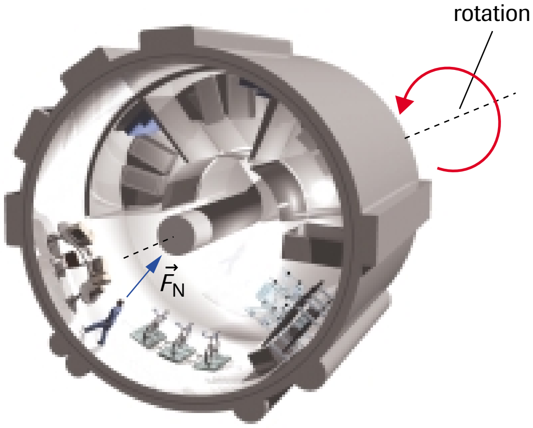


Figure 7
Any object on the inside surface of a rotating spacecraft experiences a normal force toward the centre of the craft. This normal force causes the centripetal acceleration of the objects in circular motion.

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.

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

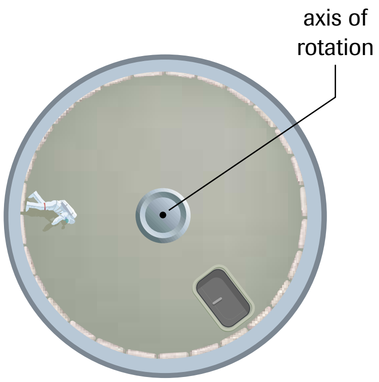
ACTIVITY 3.4.1

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?

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.

(a)



(b)

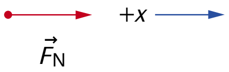


Figure 8
(a) The system diagram of the astronaut and the space station for Sample Problem 2
(b) The FBD of the astronaut

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

Applying Inquiry Skills

11. You are an astronaut on a mission to Mars. You want to determine whether the frequency of rotation of your spacecraft is providing an apparent weight equal in magnitude to your Earth-bound weight. What experiment(s) could you perform?

Making Connections

12. Astronauts on a rotating spacecraft travelling to Mars, like present-day astronauts on the nonrotating ISS, need to minimize problems with muscles, bones, and body fluids. In what ways would an exercise program for astronauts bound for Mars resemble, and in what ways would it differ from, an exercise program for astronauts on the ISS?

SUMMARY Satellites and Space Stations

- Satellites can be natural (such as moons of planets) or artificial (such as the Hubble Space Telescope).
- The speed of a satellite in uniform circular motion around a central body is a function of the mass of that central body and the radius of the orbit. The speed is constant for a given radius.
- Any interplanetary space travel for humans in the future must involve artificial gravity aboard a spacecraft.

Section 3.4 Questions

Understanding Concepts

1. Describe a situation in which a space station is a satellite and a situation in which a space station is not a satellite.
2. Arrange the following satellites in decreasing order of speed: the Moon, the ISS, a geosynchronous satellite, and a weather-watch satellite. (Weather-watch satellites are closer to Earth than the ISS.)
3. The Moon's mass is 1.23% of Earth's mass and its radius is 27.2% of Earth's radius. Determine the ratio of the speed of an artificial satellite in orbit around Earth to the speed of a similar satellite in orbit around the Moon, assuming that the orbital radii are the same.
4. Mars travels around the Sun in 1.88 Earth years in an approximately circular orbit with a radius of 2.28×10^8 km. Determine (a) the orbital speed of Mars (relative to the Sun) and (b) the mass of the Sun.
5. Each satellite in the Global Positioning System travels at 1.05×10^4 km/h. Determine, in kilometres, each satellite's (a) orbital radius and (b) distance from the surface of Earth. (Refer to Appendix C for data.)
6. As a spacecraft of diameter 2.8 km approaches Mars, the astronauts want to experience what their Mars-bound weight will be. What should (a) the period and (b) the frequency of rotation be to simulate an acceleration due to gravity of magnitude 3.8 m/s^2?

Applying Inquiry Skills

7. (a) Choose a toy that involves motion and describe how you think its operation on the ISS would differ from its operation on Earth.
   (b) Research which toys have been taken into space for physics experiments. Describe some results of these experiments.

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Making Connections

8. Although Earth's orbit around the Sun is not perfectly circular, it can still be analyzed by applying the principles and equations of circular motion. Consider that Earth's orbital speed is slightly greater during our winters than during our summers.
   (a) In which month, June or December, is Earth closer to the Sun?
   (b) Does your answer to (a) explain why June in the Northern Hemisphere is so much warmer than December? Why or why not?