

## CHAPTER

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Studying the motions of distant celestial objects, as well as the distributions of mass within multiparticle systems such as globular clusters and galaxies, provides direct evidence that gravity extends throughout the entire visible universe.

## SUMMARY

Although no one knows what gravity is or why it exists, we can accurately describe how gravity affects the motions of objects. The same laws of motion work on Earth and in the heavens. Newton's universal law of gravitation states that a gravitational attraction exists between every pair of objects and is given by

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

where  $m_1$  and  $m_2$  are the masses of the two objects,  $r$  is the distance between their centers, and  $G$  is the gravitational constant. The value of  $G$  was first determined by Cavendish and is believed to be constant with time and space.

The higher a satellite's orbit, the longer it takes to complete one orbit. A satellite with a period of 1 day and positioned above the equator would appear to remain fixed in the sky. The Moon, a natural satellite, takes 27.3 days to complete one orbit around Earth.

The force of gravity can be considered constant when the motion occurs over short distances near Earth's surface. However, small variations occur in the acceleration due to gravity with latitude, elevation, and the types of surface material. At larger distances the force decreases as the square of the distance. Stars in binary systems revolving around each other and the motion of stars within galaxies support this idea.

The value of the gravitational field at any point in space is equal to the force experienced by a 1-kilogram mass placed at that point.

## KEY TERMS

**field:** A region of space that has a number or a vector assigned to every point.

**gravitational field:** The gravitational force experienced by a 1-kilogram mass placed at a point in space.

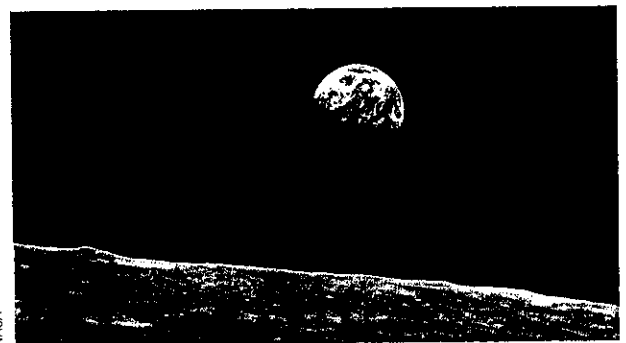
**inverse-square:** A relationship in which a quantity is related to the reciprocal of the square of a second quantity. An example is the law of universal gravitation; the force is inversely propor-

tional to the square of the distance. If the distance is doubled, the force decreases by a factor of 4.

**law of universal gravitation:** All masses exert forces on all other masses. The force  $F$  between any two objects is given by  $F = Gm_1m_2/r^2$ , where  $G$  is a universal constant,  $m_1$  and  $m_2$  are the masses of the two objects, and  $r$  is the distance between their centers.

## CONCEPTUAL QUESTIONS

1. What force (if any) drives the planets along their orbits?
2. What force (if any) causes the planets to execute (nearly) circular orbits?
3. Is the size of the gravitational force that Earth exerts on the Moon smaller than, larger than, or the same size as the force the Moon exerts on Earth? Why?
4. Earth exerts a gravitational force of 10,000 newtons on a satellite. What force does the satellite exert on Earth?
5. How does the average acceleration of the Moon about the Sun compare with that of Earth about the Sun?

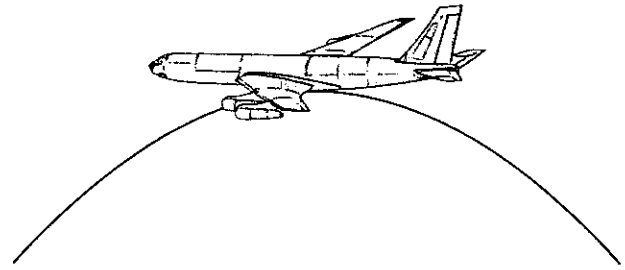


NASA

Question 3

6. If an apple were placed in orbit at the same distance from Earth as the Moon, what acceleration would the apple have?
7. What happens to the surface area of a cube when the length of each side is doubled? How does this compare to what happens to the surface area of a sphere when you double its radius?
8. What happens to the volume of a cube if the length of each side is doubled? How does this compare to what happens to the volume of a sphere when you double its radius?
9. A future space traveler, Skip Parsec, lands on the planet MSU3, which has the same mass as Earth but twice the radius. If Skip weighs 800 newtons on Earth's surface, how much does he weigh on MSU3's surface?
- \*10. Astronaut Skip visits planet MSU8, which is composed of the same materials as Earth, but has twice the radius. If Skip weighs 800 newtons on Earth's surface, how much does he weigh on MSU8's surface?
11. Why didn't Newton have to know the mass of the Moon to obtain the law of universal gravitation?
12. Comment on the following statement made by a TV newscaster during an Apollo flight to the Moon: "The spacecraft has now left the gravitational force of Earth."
13. In a parallel universe, there is a planet with the same mass and radius as Earth. However, when an apple is dropped on this planet, it falls with acceleration of 20 (meters per second) per second. What is the value of  $G$  in this parallel universe?
14. For simplicity we use 10 (meters per second) per second for  $g$  instead of the more accurate 9.8 (meters per second) per second. If Cavendish had made the same approximation, would his estimate for Earth's mass have been too high or too low?
15. If a satellite in a circular orbit above Earth is continually "falling," why doesn't it quickly return to Earth?
16. As a satellite orbits Earth, the gravitational force is constantly pulling the satellite inward. What counters this force?
17. Astronaut Story Musgrave has spent a total of 1281 hours, 59 minutes, and 22 seconds in space on his six space shuttle missions. If Story's mass is 80 kilograms, then the gravitational force acting on him in orbit is approximately 730 newtons. Why did he feel weightless?
18. You are standing on a bathroom scale in an elevator when suddenly the cable breaks and the elevator begins to fall freely down the shaft. How does the reading on the scale change from just before to just after the cable breaks? How does the force of gravity that Earth exerts on you change over the same time interval?
19. NASA uses the famous "Vomit Comet," a KC-135 cargo plane, to provide astronauts and scientists a simulated zero-gravity environment. The plane flies a series of

parabolic arcs, as shown in the figure. Explain why the passengers feel "weightless" when the plane is near the top of its arc.

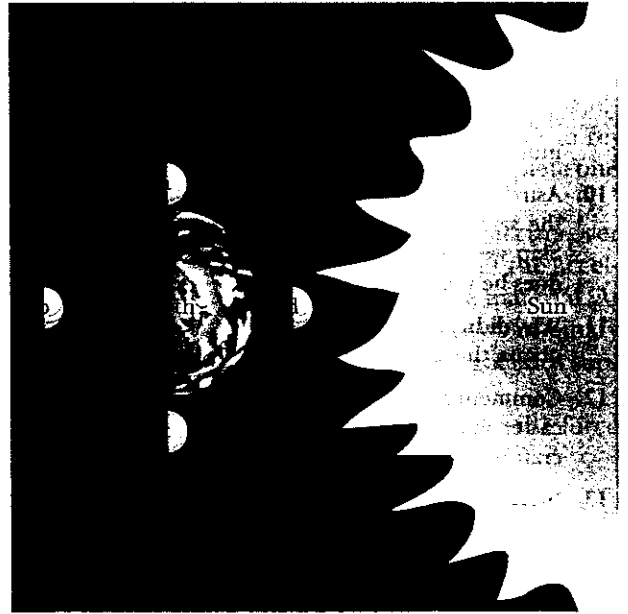


20. You have no doubt seen pictures of the astronauts floating around inside the space shuttle as it orbits some 300 kilometers above Earth's surface. Would the force of gravity Earth exerts on an astronaut be the same, a little less, or much less than the force that the astronaut would experience on Earth's surface? Why?
- \*21. If Earth were hollow but still had the same mass and radius, would your weight be different? Why?
22. Astronomers believe that when Earth first formed, its composition was uniform. Over time, the heavier materials sunk to the middle to create a dense iron core, with the less dense materials toward the outside. How did the value of  $g$  at Earth's surface change while this process was occurring?
23. The gravitational force between two books sitting on a table does not cause them to accelerate toward each other because of frictional forces. If these same two books were floating near each other in deep space, they would still not appear to accelerate toward each other. Why not?
24. Why do we use the form  $W = mg$  for the gravitational force on an object near Earth, but the form  $F = Gm_1m_2/r^2$  when the object is far from Earth?
25. Skylab caused quite a commotion when it returned to Earth in July 1979. Why would it suddenly return to Earth after it had been in orbit for many years?



26. When the Hubble Space Telescope (HST) was originally launched by the space shuttle *Discovery*, its approximately circular orbit was at an altitude of about 600 kilometers. However, over the next several years, the altitude decreased so that subsequent servicing missions were required to lift the HST back into the higher orbit. What is responsible for the orbital decay?
27. How could we determine the mass of a planet such as Venus, which has no moon?
28. Why can we not determine the mass of the Moon by noting that it orbits Earth in a nearly circular orbit? What can we do to determine the Moon's mass?
29. Would you expect the value of  $g$  to be larger or smaller than normal over a large deposit of uranium ore? Why?
30. You are steaming across the Atlantic Ocean in a large cruise ship. What happens to your weight as the ship leaves the deep waters of the North Atlantic and enters the shallow coastal waters of the United States?
31. What changes would occur in the solar system if the gravitational constant  $G$  were slowly getting larger?
32. What do you think would happen to the Moon's orbit if the gravitational attraction between the Moon and Earth were slowly growing stronger?
33. Is it possible for an Earth satellite to remain "stationary" over Paris? Why or why not?
34. During the Gulf War with Iraq in 1991, a newspaper story reported that American spy satellites were in stationary orbits over Iraq, providing continuous intelligence information. Explain why this is impossible.
- \*35. Assume that NASA fails in its attempt to put a communications satellite into geosynchronous orbit. If the orbit is too big, what apparent motion will the satellite have as seen from the rotating Earth?
36. Some of NASA's Earth satellites remain above a single location on Earth. Why don't these geosynchronous satellites fall to Earth under the influence of gravity?
37. Newton's third law says that the gravitational force exerted on Earth by the Moon is equal to that exerted on the Moon by Earth. Why is it, then, that Earth doesn't appear to orbit the Moon?
38. The Sun has a profound influence on Earth's motion. Does Earth influence the Sun's motion? Explain.
39. When the tide is high along the American western seaboard, is the tide in Japan nearer high tide or low tide? Japan is approximately 90 degrees west of San Francisco.
40. When it is high tide off the coast of Ecuador, is the tide off the coast of Indonesia, which is 180 degrees around the globe from Ecuador, nearer high tide or low tide?

41. If Earth rotated once every 12 hours, how long would it be between high tides?
- \*42. The Moon is observed to keep the same side facing Earth at all times. If the Moon had oceans, how much time would elapse between its high tides?
43. Which position in the figure corresponds to the new moon? This is when the Moon is above the horizon but cannot be seen because the lit side faces away from Earth. Why are high tides higher than normal during this phase?

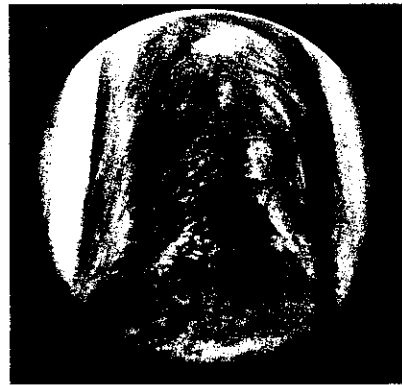


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44. Which position in the figure corresponds to the full moon, which is when the Moon appears as a fully lit disk? Why are high tides higher than normal during this phase?
45. A classmate asserts that when the Moon is in position b in the figure, the gravitational effects of the Sun and Moon tend to cancel, producing lower than normal high tides. What is wrong with this reasoning?
46. Which positions of the Moon in the figure correspond to the smallest difference between high tide and low tide?
- \*47. In *The Jupiter Effect*, authors John Gribbin and Stephen Plagemann claim that the additional tidal force produced when all the planets lie along one line might be enough to trigger an earthquake along the San Andreas Fault in California. What do you think about the possibility?
- \*48. Why would the inertia and friction of water cause the tides to occur after the Moon passes overhead?
49. How does the magnitude of Earth's gravitational field change with increasing distance?

## EXERCISES

1. Earth's speed in its orbit about the Sun is about 30 km/s. What is Earth's acceleration?
2. The Moon's speed in its orbit is approximately 1 km/s, and the Earth–Moon distance is 380,000 km. Show that these numbers yield an acceleration for the Moon that is very close to that given in the text.
3. What is the acceleration due to gravity at a distance of 2 Earth radii above Earth's surface?
4. If you were located halfway between Earth and the Moon, what acceleration would you have toward Earth? (Ignore the gravitational force of the Moon because it is much less than Earth's.)
5. A solid lead sphere of radius 10 m (about 66 ft across!) has a mass of about 57 million kg. If two of these spheres are floating in deep space with their centers 20 m apart, the gravitational attraction between the spheres is only 540 N (about 120 lb). How large would this gravitational force be if the distance between the centers of the two spheres were tripled?
6. Two spacecraft in outer space attract each other with a force of 20 N. What would the attractive force be if they were one-half as far apart?
7. How would the Sun's gravitational force on Earth change if Earth had one-half its present mass? Would Earth's acceleration change?
8. The gravitational force between two very large metal spheres in outer space is 50 N. How large would this force be if the mass of each sphere were cut in half?
9. What is the ratio of the gravitational force on you when you are 6400 km above Earth's surface versus when you are standing on the surface? (Earth's radius is 6400 km.)
10. How does Earth's gravitational force on you differ when you are standing on Earth and when you are riding in a space shuttle 400 km above Earth's surface? (Earth's radius is 6400 km.)
11. A 320-kg satellite experiences a gravitational force of 800 N. What is the radius of the satellite's orbit? What is its altitude?
12. A 600-kg geosynchronous satellite has an orbital radius of 6.6 Earth radii. What gravitational force does Earth exert on the satellite?
13. What is the gravitational force between two 20-kg iron balls separated by a distance of 0.5 m? How does this compare with the weight of either ball?
14. The masses of the Moon and Earth are  $7.4 \times 10^{22}$  kg and  $6 \times 10^{24}$  kg, respectively. The Earth–Moon distance is  $3.8 \times 10^8$  m. What is the size of the gravitational force between Earth and the Moon? Does the acceleration of the Moon produced by this force agree with the value given in the text?
15. If an astronaut in full gear has a weight of 1200 N on Earth, how much will the astronaut weigh on the Moon?
16. The acceleration due to gravity on Titan, Saturn's largest moon, is about  $1.4 \text{ m/s}^2$ . What would a 50-kg scientific instrument weigh on Titan?
17. Mercury has a radius of about 0.38 Earth radii and a mass of only 0.055 Earth masses. Estimate the acceleration due to gravity on Mercury.
18. Mars has a radius of about 0.53 Earth radii and a mass of only 0.11 Earth masses. Estimate the acceleration due to gravity on Mars.
19. A geosynchronous satellite orbits at a distance from Earth's center of about 6.6 Earth radii and takes 24 h to go around once. What distance (in meters) does the satellite travel in one day? What is its orbital velocity (in m/s)?
20. An 80-kg satellite orbits a distant planet with a radius of 4000 km and a period of 280 min. From the radius and period, you calculate the satellite's acceleration to be  $0.56 \text{ m/s}^2$ . What is the gravitational force on the satellite?
21. The radius of Venus's orbit is 0.72 times that of Earth's orbit. How much stronger is the Sun's gravitational field at Venus than at Earth?
22. By what factor is Earth's gravitational field reduced at a distance of 5 Earth radii from the center of Earth?



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