Section 3.5

The Earth, Moon, and Sun

One of Newton's most remarkable discoveries was that celestial objects obey the same laws of motion that govern objects on earth. Until that discovery, the universe seemed to have two separate components: the earth and the heavens. With his discovery, Newton united two formerly independent realms under a single set of rules. The dynamics of the planets and stars became knowable, predictable, and understandable.

Questions To Think About: *Why do the planets appear to move relative to the fixed stars? What causes the seasons? Why does the moon have phases? Why doesn't the moon fall into the earth or the earth into the sun? What suspends satellites as they travel around the earth?*

Experiments To Think About: *Most of us are destined to spend our days on the earth's surface. For us, astronomy is a passive activity of observation. However, there is a useful experiment, first imagined by Newton, that relates the motions of the planets to motion on earth. Find a level table with nothing in front of it and push a rubber ball slowly off its edge. The ball falls, hitting the ground just beyond the table. Now push the ball off the table with a substantial forward velocity. The ball falls in an arc, striking the floor some distance from the table. The faster the ball is traveling when it rolls off the table, the broader its arc and the farther it travels before hitting the ground. Now imagine giving the ball such a huge horizontal velocity that it travels beyond the earth's horizon before it has time to fall very far. The spherical earth curves downward and the ball doesn't reach the earth's surface. Though the ball continues to fall downward, the earth's surface curves endlessly away from the falling ball. The ball is orbiting the earth.*

The Solar System

The study of the solar system dates back to ancient times when people first discovered heavenly objects that moved relative to the fixed stars. Except for the sun, the true stars in the night sky are so distant that it's virtually impossible to detect their motion. They form a pattern of lights that is essentially fixed, night after night, like a huge picture painted on the sphere of the sky. Against this backdrop of motionless stars, the planets move slowly across the sky.

Early on, people noticed that the fixed stars circle the earth a little more than once a day. We now know that this "motion" is actually due to the rotation of the earth, not to any movement of the stars themselves. If it were not for the planets, people might have assumed the night sky really was nothing more than a picture. But when observers looked more carefully at the sky, they noticed that the planets drift slowly past one group of stars after another along a ring that goes all the way around the sky. The five easily visible planets, Mercury, Venus, Mars, Jupiter, and Saturn, as well as the sun and the moon, were seen to travel endlessly around this circular racetrack at different rates, sometimes passing one another and sometimes almost standing still. The band of stars that makes up this celestial circuit was called the zodiac and was divided into 12 equal sections according to the seasons and the 12 months. Each of these sections was named after a *constellation* of stars that coincided with it. The Greek scientist Ptolomy named the constellations around 150 AD. Since then, a slow motion of the earth's rotational axis, called the *precession of the equinoxes,* has caused the 12 sections of the zodiac to drift westward. Although these sections no longer coincide with the constellations for which they were named, those names remain in use.

Originally, people believed that the stars, the planets, the moon, and the sun simply traveled around the earth, which remained motionless. The erratic motions of the planets as they circled the earth were attributed to some complicated machinery that drove these heavenly bodies. It was not until the writings of Polish astronomer Nicolaus Copernicus (1473–1543) that anyone considered the possibility that the earth actually participates in the celestial motion. Copernicus suggested that the sun is actually the center of the universe and that the earth travels around the sun. Later, German astronomer Johannes Kepler (1571–1630) used the careful measurements of his former master Tycho Brahe (1546–1601) to prove Copernicus's theories correct and to deduce three important laws of planetary motion. These **empirical laws**—based on observation rather than physical principles—were later proven correct by the work of Sir Isaac Newton.

Perhaps the most important observation of Kepler was that the planets all follow elliptical trajectories as they travel around the sun. Ellipses are a class of geometric curves that can be described roughly as circles and ovals. The trajectories of the planets are called **orbits**. Most of the planets follow elliptical orbits that are almost perfectly circular.

Kepler also found that the larger the planet's orbit, the more time it takes the planet to complete a full circuit around the sun, the **orbital period**. He found that, for a circular orbit, the orbital period is proportional to the **orbital radius** to the 3/2 power:

$$\text{orbital period} \propto \text{orbital radius}^{3/2}. \tag{3.5.1}$$

This relationship indicates that doubling the radius of the earth's orbit around the sun would increase the time needed to complete that orbit by a factor of $2^{3/2}$ (about 2.8) so that it would require about 2.8 of our present years to complete a full orbit around the sun.

We are now prepared to understand why the planets appear to drift across the stars of the Zodiac. Let's follow the motion of two planets, the earth and Mars, over a period of several months (Fig. 3.5.1). At the start of this time, an observer on the earth looks for Mars and finds that it's located in front of a particular group of stars. A month and a half later, the earth has moved 12.5% of the way around its orbit while Mars has moved only 6.6% of the way around its orbit. Mars has a larger orbital radius than the earth and its orbital period is

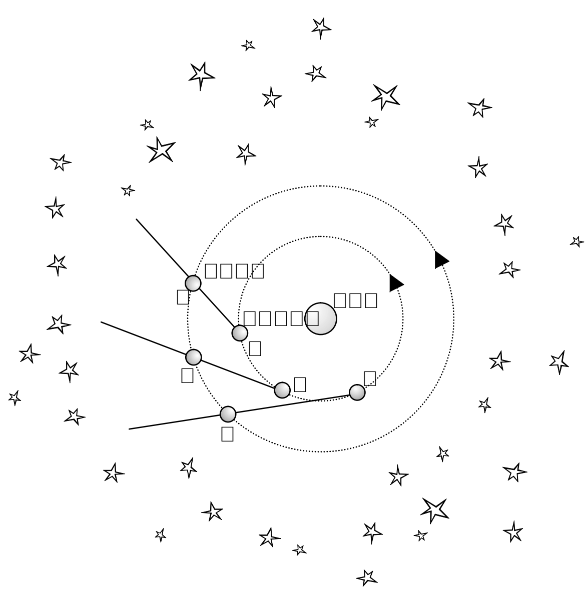

Fig. 3.5.1 - The planets of the solar system orbit the sun at different rates. The earth orbits the sun once per year while Mars, with its larger orbital radius, takes 1.88 years to complete the circuit. To an observer on the earth, Mars appears first in front of one group of stars, then another, then another.

1.88 years. The observer on the earth finds that Mars has drifted in front of a different group of stars. Another month and a half later, Mars appears in front of yet another group of stars. Thus, each planet's position relative to the fixed stars depends on where that planet and the earth are in their orbits around the sun.

The sun also appears to move against the fixed stars. Since the earth orbits the sun once each year, the sun seems to pass in front of the whole zodiacal ring of fixed stars once per year.

The earth's moon is a somewhat different case. As we shall soon see, the moon orbits the nearby earth and follows the latter on its journey around the sun. Since the moon goes completely around the earth once every 27.3 days, it appears to move across the zodiac very quickly.

CHECK YOUR UNDERSTANDING #1: Equal but Opposite

At any time, we only see one side of the sun from earth. Suppose scientists wanted to observe the other side of the sun continuously. They decide to put a satellite in a circular orbit around the sun, so that it's always on the other side of the sun. What should that satellite's orbital radius be?

Orbits

But why do the planets follow elliptical orbits around the sun? For the moment, let's imagine that the solar system consists only of the earth and the sun. The earth and the sun exert gravitational forces on one another so that the earth accelerates toward the sun and the sun accelerates toward the earth. But the sun is 333,000 times more massive than the earth and barely accelerates at all. Thus the earth does virtually all of the moving.

We might expect the earth to accelerate quickly, reach an enormous velocity, and smash catastrophically into the sun. Fortunately, the earth and the sun didn't start out at rest or that is exactly what would have happened (Fig. 3.5.2*a*). Actually, the earth really does accelerate directly toward the sun but it has an initial sideways velocity that prevents it from hitting the sun (Fig. 3.5.2*b*). This sideways velocity would carry the earth away from the sun were it not for gravity. The earth accelerates toward the sun, so its velocity shifts toward the sun.

The gravitational force the sun exerts on the earth is centripetal, always toward the nearly stationary sun. The earth's acceleration is also centripetal. The earth's velocity continues to change and the planet's path is bent around in a huge elliptical arc through space. This arc eventually closes on itself after a period of one year to form an almost circular ellipse. This ellipse is the earth's **orbital path** through space.

Because the earth's orbital path is almost circular, the earth undergoes uniform circular motion about the sun. It experiences an inward gravitational force from the sun and an outward fictitious force due to this centripetal acceleration. The real force of gravity and this outward fictitious force balance so that the earth's apparent weight is zero. For objects located at the earth's surface, the cancellation may not be quite perfect. Small imbalance between the sun's gravity and the centrifugal "force" of orbiting the sun contribute to the ocean tides, as discussed in Section 7.3.

It's as though the tiny earth swings around the gigantic sun on cord, following a nearly circular path. The cord is actually the force of gravity. As long as the earth continues to travel sideways, gravity can't pull the earth any closer to the sun. Because the force of gravity grows weaker as a planet moves farther from the sun, a larger orbit must take longer than a smaller orbit. Planets close to the

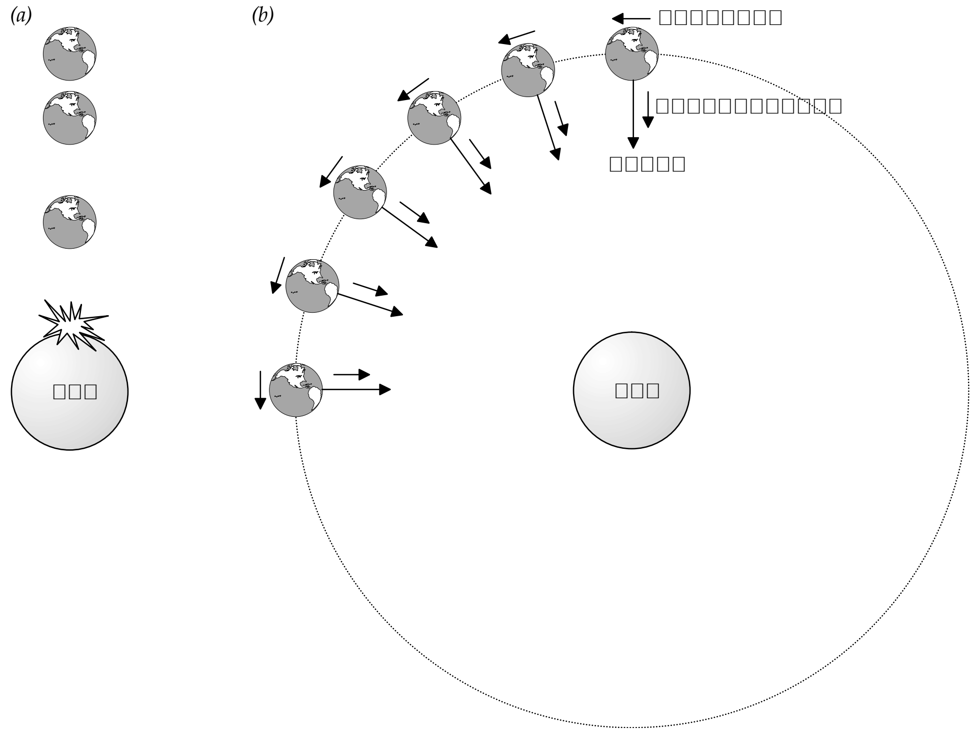

Fig. 3.5.2 - The gravitational attraction between the earth and the sun causes both objects to accelerate directly toward one another. The less massive earth does most of the accelerating. (*a*) If the earth had started out stationary, then it would have accelerated directly toward the sun, picked up speed, and smashed into the sun's surface. (*b*) However, the earth has a large velocity relative to the sun, at right angles to the line separating them. The earth accelerates directly toward the sun, but it misses the sun as it heads toward the lower left corner of this figure and circles the sun in an elliptical orbit. The earth always accelerates directly toward the sun but its sideways velocity prevents it from hitting the sun.

sun can orbit it rapidly, as though held by a strong rope. Planets far from the sun must travel very slowly around it, as though held by a fine, delicate thread.

That the earth's orbit closes on itself perfectly after one trip around the sun is a remarkable result. It occurs because the force of gravity is exactly proportional to one divided by the square of the distance between the sun and the earth, an observation that we'll cover in Section 5.3. Any other type of centripetal force would still create orbits, but these orbits wouldn't necessarily close on themselves after one complete trip around the center. For example, if you attach a ball to a rubber band and swing it around with your hand, the ball will follow a complicated orbital path that never quite closes on itself. That's because the rubber band's centripetal force isn't proportional to 1 divided by the square of the distance between your hand and the ball.

The sun also accelerates toward the earth, but its enormous mass prevents it from picking up much speed. Instead, the sun only wobbles ever so slightly as the tiny earth circles around it. To be precise, the two objects orbit together about their combined center of mass. Because the mass of the sun dominates the combined system, their center of mass is almost exactly at the center of the sun. The other planets orbit the sun in the same manner as the earth. The giant planets, Jupiter, Saturn, Uranus, and Neptune, are more massive than the earth and make the sun wobble more than the earth does. Still, for most purposes we can imagine that the objects in the solar system merely circle about a stationary sun.

The planets are too far apart from one another for their gravitational attractions to be very noticeable. The earth does attract Mars (and vice versa), but so weakly that this gravitational force is nearly impossible to detect. However, the planet Pluto was found in 1930 because people observed that some unseen object was distorting the planet Neptune's orbit around the sun.

CHECK YOUR UNDERSTANDING #2: Out of Round We Go

The scientists want to move their sun-orbiting satellite in closer to get a better view of the sun's surface. The satellite is currently orbiting the sun at the earth's orbital radius. They still want the satellite to orbit the sun once per year. What will happen if they move their satellite in close to the sun and give it just enough sideways speed to complete one circular orbit per year?

The Moon

While the planets seem largely unaffected by one another's presence in the solar system, that isn't true of their moons. For example, the earth's moon is so close to the earth—400 times closer than the sun—that it's strongly affected by the earth's gravity. The earth and the moon move together as a pair. The earth is about 80 times as massive as the moon, so the moon does most of the moving. The moon accelerates toward earth and orbits it, just as the earth orbits the sun. Because of the small size of the earth-moon system, the moon completes its near-circular orbit in only 27.3 days.

This 27.3 day cycle approximately coincides with the phases of the moon. Sometimes the moon appears to be a complete white disk and other times it is only a thin crescent. What causes these phases?

The phases occur because we can only see the portion of the moon that is illuminated by the sun (Fig. 3.5.3). As the moon orbits the earth, the lighted side of the moon is sometimes facing toward the earth and sometimes facing away from the earth. When the moon is as far away from the sun as its orbit allows, the moon's lighted side is facing toward us. We then see the complete lighted disk of a full moon. When the moon is as close to the sun as its orbit allows, the moon's lighted side is facing away from us. We can't see the moon at all and call this the new moon. In between, we see portions of the lighted half of the moon. These portions appear as crescent moons, half moons, or gibbous moons.

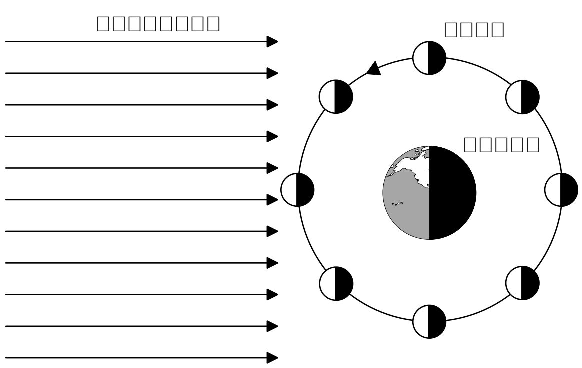

Fig. 3.5.3 - The phases of the moon arise because we only see the lighted portion of the moon. When the moon is farther from the sun than is the earth, most of the half that we can see is illuminated by the sun and we see a full or gibbous moon. When the moon is closer to the sun than is the earth, we see a large amount of unilluminated moon and it appears as a new or crescent moon.

Occasionally, the earth gets in the way of light illuminating the moon. During those times, the moon is in the earth's shadow and a **lunar eclipse** occurs. A person on earth, looking at the moon, sees a huge round shadow drift slowly across the moon's surface. For a time, this shadow may completely cover the moon's surface. Because the moon is as far as possible from the sun, the moon appears full just before and after the lunar eclipse.

Similarly, there are rare occasions when the moon blocks the sunlight on its way to the earth's surface. A person standing on the earth will see the dark lunar sphere pass in front of the sun and block its light, and a **solar eclipse** occurs. The moon is fairly small and is just barely able to obscure the entire sun from view for people at the right location on earth. That is why solar eclipses are so much rarer than lunar eclipses. Because the moon is as close as possible to the sun, the moon appears new just before and after the solar eclipse.

CHECK YOUR UNDERSTANDING #3: Down in Front!
The sun-orbiting satellite observing the opposite side of the sun is programmed to take a picture of the earth. This request turns out to be impossible. What is wrong?

The Day

To a person standing on the surface of the earth, the sun appears to rise in the east every morning and set in the west every evening. Of course, people long ago realized that this daily schedule doesn't reflect any movement of the sun, but rather the rotation of the earth. The earth rotates on its axis slightly more than once a day so that every object in the sky appears to circle the earth in approximately that same amount of time.

The earth keeps on spinning because it has an incredible amount of angular momentum. It obtained this angular momentum during its formation and has retained this angular momentum because there are few torques exerted on it. The sun and the moon exert small torques on the earth as they drive the ocean tides, but for the most part, the earth just keeps on rotating at a very steady rate determined only by its total angular momentum and its moment of inertia. For about half a day, any point on the earth's surface is facing the sun and for about half a day, that same point is rotated away from the sun.

But how long is a day on the moon? To figure that out, we'll start by noting that the moon orbits the earth with the same half of its surface always pointing toward the earth. This locking of its rotation to its orbit occurred long ago as the result of tidal effects (see Section 7.3) that deformed the moon so that it isn't perfectly spherical. Because the moon's rotation is locked to its orbit, the moon turns on its axis only once every 27.3 earth days. As a result, a person on the moon will notice that the sun appears to rise and set once every orbit of the moon around the earth. The "day" on the moon is 27.3 earth days long.

We can't see the other half of the moon from the earth, since it always faces away from the earth. The far side of the moon is only visible from spacecraft that travel to that side. People mistakenly interchange the expressions "far side of the moon" and "dark side of the moon." The far side of the moon is the one not visible from earth and is always the same region of the moon's surface. The region of the moon that is dark changes throughout the moon's 656 hour "day."

CHECK YOUR UNDERSTANDING #4: Slow Motion
Scientists on the earth can only observe the sun half the time because of the earth's rotation. Their satellite observes the sun continuously through its telescope. What is the satellite's rate of rotation?

The Seasons

The earth rotates on its axis about once a day and orbits the sun once a year. Apart from changes in the sun's position against the fixed stars, it seems that every day should be identical to the day before. Why are there seasons? Why is a winter's day so much shorter than a summer's day?

The answers to these questions lie in the orientation of the earth's rotational axis relative to its orbit around the sun. The earth's orbit around the sun describes a huge, nearly circular ellipse that you could imagine as defining the edges of a gigantic glass disk. We call the geometrical surface represented by this glass disk the **orbital plane**. If the earth's rotational axis were straight up and down to a person standing upright on this orbital plane, then the earth's situation wouldn't change much as it followed its orbit and every day would be essentially the same.

But the earth's rotational axis is *not* straight up and down with respect to the orbital plane. The earth rotates about an axis that is tilted 23.45° away from straight up and down. And because the earth has so much angular momentum, the earth's rotational axis keeps pointing the same direction relative to the fixed stars, day after day, month after month, and year after year. It points almost directly toward a bright, solitary star—Polaris, the "north star."

For part of the year, the earth's northern hemisphere is tilted away from the sun (Fig. 3.5.4*a*) and for part of the year, the northern hemisphere is tilted away from the sun (Fig. 3.5.4*c*). When the northern hemisphere is tilted toward the sun, as it is around June 21 (Fig. 3.5.4*c*), the northern hemisphere experiences summer. The sun appears more nearly overhead at noon in the northern hemisphere and the day is much longer than the night. North of the *Arctic Circle*, a band located 23.45° south of the North Pole, the sun never sets at all during part of the summer. When the northern hemisphere is tilted away from the sun, as it is around December 22 (Fig. 3.5.4*a*), the northern hemisphere experiences winter. The sun never rises very high in the sky and the day is much shorter than the night. North of the Arctic Circle, the sun never rises at all for part of the winter.

In the southern hemisphere, the experiences are reversed. The southern hemisphere experiences the height of summer around December 22 and the depths of winter around June 21. South of the *Antarctic circle*, a band located 23.45° north of the south pole, the sun never sets during part of the summer and never rises during part of the winter.

People living on a certain band around the earth, near the equator, find that the sun passes directly overhead in the middle of the day. The location of this band moves with the seasons. It moves north as summer approaches and it move south as winter approaches. At the *autumnal* (September 21) and *vernal* (March 21) **equinoxes**, the earth's rotational axis is pointed neither toward nor away from the sun and the sun appears directly overhead to people living on the earth's equator. On June 21, the earth's northern hemisphere is tilted as much as possible toward the sun, its summer **solstice**, and the sun appears overhead to people living on the *Tropic of Cancer*, a band located 23.45° north of the equator. On December 22, the northern hemisphere is tilted as much as possible away

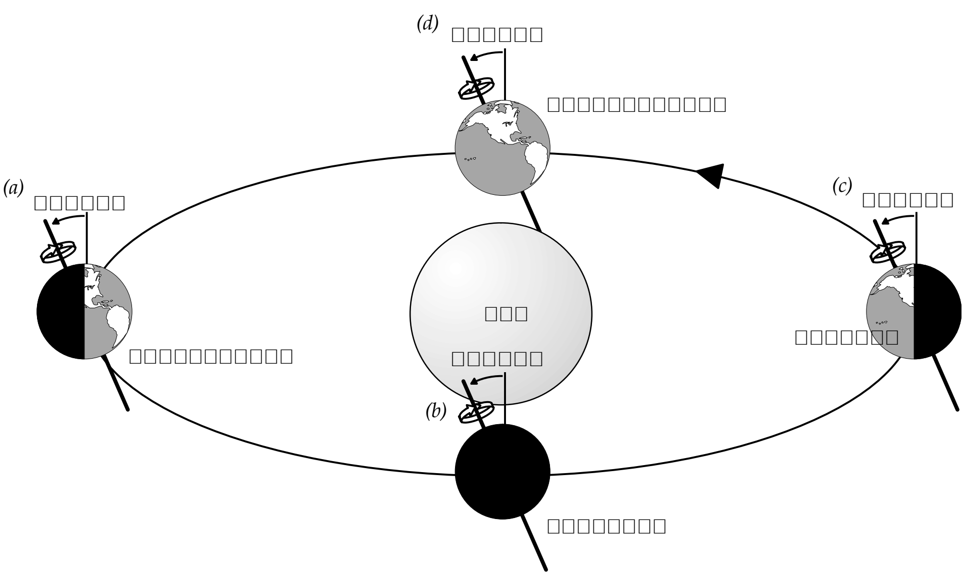

Fig. 3.5.4 - The seasons arise because the earth's rotational axis is tilted with respect to its orbital plane. For half the year, the earth's northern hemisphere is tilted toward the sun and for half the year, it's tilted away from the sun. The more the northern hemisphere is tilted toward the sun, the longer are its days and the shorter its nights.

from the sun, its winter solstice, and the sun appears overhead to people living on the *Tropic of Capricorn*, located 23.45° south of the equator.

Actually, the observation that the earth's rotational axis always points in the same direction isn't really true. The sun and moon exert small torques on the earth that cause the earth's rotational axis to turn ever so slowly about an axis that would appear vertical to a person standing on the earth's orbital plane. This slow movement of the earth's rotational axis, the precession of the equinoxes, completes one full cycle every 25,800 years. Because of it, the *tropical* or *civil year* (the time between successive vernal equinoxes) is a little shorter than the solar or *sidereal year* (the time in which the earth completes one full orbit of the sun relative to the fixed stars). The stars overhead at midnight on any particular day of the year are slowly changing because of this precession, which is why the constellations observed by Ptolomy two thousand years ago are no longer aligned with their regions of the zodiac.

There is one other interesting detail about the earth's orbit—the earth's orbit isn't a perfect circle, it's an ellipse. The earth is therefore not always the same distance from the sun. The earth makes its closest approach, its *perihelion* of 147,100,000 km (91,300,000 miles), on January 2 and reaches its farthest point from the sun, its *aphelion* of 152,100,000 km (94,400,000 miles), on July 4. So the northern hemisphere's summer has nothing to do with the closeness of the sun. The earth is actually farthest from the sun during the northern hemisphere's summer.

CHECK YOUR UNDERSTANDING #5: We're Getting Dizzy

At the end of its useful life, a brief failure of its propulsion system abruptly starts the sun-orbiting satellite spinning about an axis that points directly at the sun. Though disabled and inert, the satellite continues to orbit the sun. After three months, the satellite has traveled a quarter of the way around the sun. Which way is the satellite's rotational axis pointing?

Other Objects in the Solar System

The solar system has many other objects that are too small to be called planets but that are visible from the earth. There are many more objects that can't be seen until their paths cross that of the earth and they appear in our atmosphere as **meteors** or "falling stars." All of these objects travel in elliptical orbits around the sun. The **asteroids** are a group of objects that orbit the sun between the orbit of Mars and the orbit of Jupiter. The asteroids have nearly circular orbits and they are sometimes called minor planets.

In contrast, **comets** are objects that orbit the sun in highly non-circular elliptical orbits. They start very far from the sun and dive in close once per orbit. A typical comet is warmed by sunlight as it approaches the sun and becomes visible as gas evaporates from its surface and reflects the sun's light. A typical orbit of a comet appears in Fig. 3.5.5.

We can follow the comet through one orbit to see how it behaves. The

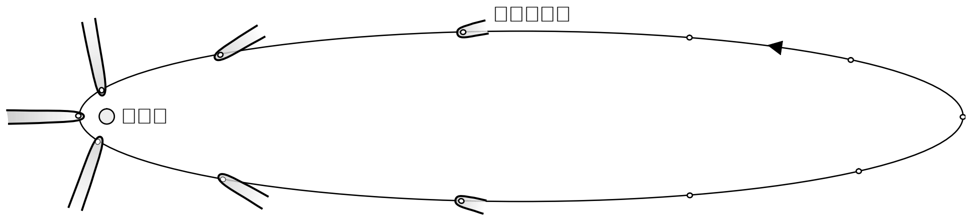

Fig. 3.5.5 - A comet orbits the sun in a very elongated or eccentric elliptical orbit. It moves slowly when it's far from the sun but speeds up as it approaches the sun. The comet's tail is actually gas that evaporates from the comet's nucleus and that is driven back, away from the sun, by the solar wind.

comet starts far from the sun, where it moves slowly and has relatively little kinetic energy. Since it's very small, it's essentially impossible to see even with a large telescope. However, its distance from the sun gives it a great deal of gravitational potential energy. The comet accelerates toward the sun but it doesn't have the sideways velocity needed to send it into a near-circular orbit, like the orbits of the planets. Instead, the comet dives almost directly toward the sun, picking up speed and kinetic energy at the expense of gravitational potential energy. As the comet approaches the sun, sunlight warms its surface and gas begins to evaporate from its nucleus. A steady spray of particles flowing away from the sun, the **solar wind**, blows this comet gas out and away from the sun like a gossamer streamer in the breeze from a fan. We see this gas because it's illuminated by sunlight.

The comet reaches its closest approach to the sun at a very high speed. It has converted most of its gravitational potential energy into kinetic energy and it sails quickly past the sun and begins to return to the distant reaches of the solar system. The streamer of gas recondenses on the cooling nucleus of the comet and the comet becomes harder and harder to see. It continues to accelerate toward the sun, but this time its acceleration slows its outward velocity. The comet is converting its kinetic energy back into potential energy. Eventually, it returns to its original position and the whole cycle begins again.

CHECK YOUR UNDERSTANDING #6: Out of Round

A small rocky object, a meteor, finally smashes into the sun-orbiting satellite at a fantastic velocity and breaks the satellite into many small fragments. What was the path of this meteor before it hit the satellite?

Satellites and Spacecraft

For the past several decades, people have used rockets to place satellites and spacecraft into orbit around the earth and other objects of the solar system. These artificial planets behave exactly as the original objects in the solar system do: they follow elliptical orbits.

A spacecraft that is in low earth orbit, not far above the earth's atmosphere, weighs almost as much as it did on the ground. The spacecraft accelerates directly toward the center of the earth. However, it has a huge sideways velocity of about 28,600 km / h (17,800 mph). Instead of crashing into the earth's surface, the spacecraft misses the earth and travels around it.

The astronauts riding in the spacecraft feel the sensations of falling all the time—they really are in free fall. Everything in the spacecraft falls together, accelerating toward the center of the earth but missing it because of the sideways velocity. Because everything moves together, the astronauts feel no tendency to accelerate toward the floor, walls, or ceiling of the spacecraft. Their apparent weights are zero and they feel weightless. They always feel as though they had jumped off the high diving board half a second ago and have not yet reached the water.

A spacecraft in low earth orbit takes about 90 minutes to complete its orbit. If the spacecraft tried to move any faster, it would fly outward, away from the earth. If it tried to move any slower, it would crash into the earth. For a spacecraft to take longer to complete its orbit, it must be farther from the earth. *Geosynchronous satellites* orbit the earth once per day at an altitude of 35,900 km (22,300 miles) above the surface of the earth. If a geosynchronous satellite orbits the earth eastward around the equator, it will be *geostationary*. A geostationary satellite always remains over the same spot on the earth's surface. Such a fixed orientation is very useful for communications satellites.

CHECK YOUR UNDERSTANDING #7: We're All In This Together

The fragments of the sun-orbiting satellite continue to orbit the sun. Although not attached to one another, they remain only a few meters apart for years. What forces hold them together?