4.3: Astronomical Objects in Motion

Learning Objectives

- You will be able to distinguish between rotation and orbit
- You will know what orbits around what
- You will know that everything is in motion in some frame of reference
- You will know that acceleration is change in motion

What Do You Think: Motions of Earth

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One of the most obvious aspects of our world is that things move, or in other words, that their positions tend to change with time. This is apparent when we look out a window and see birds and insects fly past, cars drive by on a nearby roadway, or people walk across our view. We can even see clouds float across the sky. The one thing that seems as if it does not move is Earth itself. Apparently Earth and objects like buildings that are attached to it do not ever move. However, this apparently obvious truth is not the truth at all.

4.3.1: The Motions of Earth

We realize that the seeming immobility of Earth is a result of our perspective. If we could leave Earth and hover in space close to the Solar System, we would see that Earth travels in orbit around the Sun once every year. It also rotates once every 24 hours. So what seems to be solid and unmoving when we stand on it is actually moving through space while spinning like a top! Earth's rotation and the orbits of the planets around Sun are depicted in Animated Figure 4.4.

a.

Video of the Earth rotating (original link)

b.

Animated Figure 4.4 (a) Earth’s rotation, (b) Planets orbiting the Sun (original link).

Earth’s Rotational and Orbital Speeds

Worked Example:

Earth rotates on its axis once in a day. If you are standing on the equator, how fast (in km/hr and mi/hr) do you have to be moving to complete this trip?

- Find: speed v
- Given: time t, distance d

To answer the question, you must know the distance you travel and the time required.

The time, we know, is t = 24 hours.

What about the distance?

Earth is roughly spherical, and it has a radius of about 6,400 km. Since the circumference of a sphere is given by C = 2πr, just as for a circle, we can write:

$$C = 2\pi(6400\,\text{km}) = 40,200\,\text{km}$$

This is the distance we would travel on the equator as Earth rotates once.

- Concept: v = d/t
- Solve: v = 40,200 km / 24 hr = 1700 km/hr
- Converting to miles per hour: 1700 ~~km~~/hr × (0.62 mi /1 ~~km~~) = about 1,000 miles/hr.

Questions

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4.3.2: The Motions of the Sun, Stars, and Galaxies

The Sun, too, is in motion. It spins on its axis, much as Earth does, taking about a month to make one complete rotation at its equator. It also travels in a huge, roughly circular orbit that takes it once around the Galaxy in about 230 million years. This corresponds to a speed of about 500,000 mi/hr. Objects closer to the center of the Galaxy also orbit around the center, but they take less time. And objects farther than the Sun from the center take longer to go around. Our entire Galaxy is rotating. The inner parts complete their orbits in less time than the outer parts (see Figure 4.5 and Animated Figure 4.6). This motion makes the patterns of stars in the sky change very slowly over millions of years. In addition to this average motion, the stars in the Galaxy can also have random velocities in local areas. The relative speed between nearby stars is typically about 10 km/s, or 20,000 mi/hr. This seems very fast, but it would still take a long time to notice the change because the distances separating the stars from one another are so large.

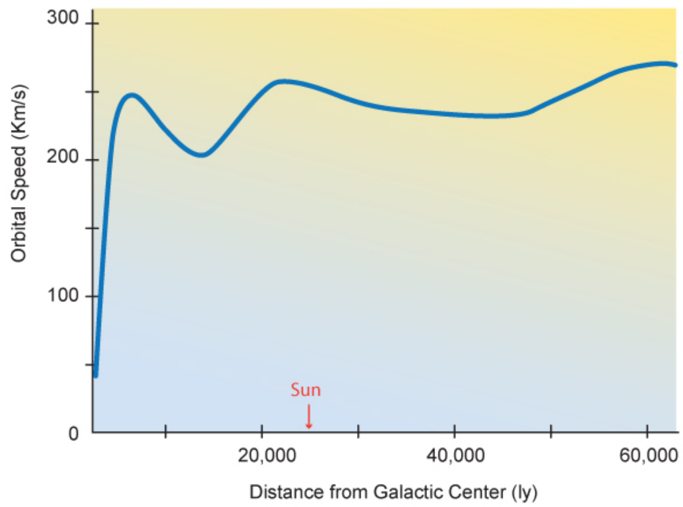

Figure 4.5: The actual measured orbital speeds of stars within a typical galaxy as a function of their distance from the center of the galaxy (in light-years). Credit: NASA/SSU/Aurore Simonnet.

Animated Figure 4.6 Galactic rotation.

The motion does not end with our Galaxy spinning. As was discovered in the early part of the 20th century, all of the other galaxies we see are moving relative to our own, and most of them are moving away from us. So, does this make our Galaxy the center of the Universe, with all motion away from that center? As we will learn in later chapters, it does not. In fact, there is no center of the Universe. But this observation does give us some important insights about motion.

4.3.3: Relative Motion

Whenever we talk about motion, we mean that some object is changing its position relative to another object. On Earth, we generally measure position, and therefore motion, relative to the ground, but this is just for the sake of convenience. As we have already pointed out, Earth itself is in motion. Since we generally want to know where things are on Earth, using Earth as a reference is just fine most of the time. However, if we liked, we could measure motion and position relative to ourselves. In fact, this is what our senses generally do.

As an example, imagine yourself sitting in a car that moves down a straight section of the highway, moving at constant speed. You will notice the landscape rush past at 60 or 70 mph. You do not see yourself move across the ground at that speed; you see the landscape fly past. If not for the little bumps in the road that jostle you in your seat, you might conclude that the landscape really is rushing past and that you are yourself stationary. You might have this impression much more strongly if you are on a train or a boat, where the ride can be much smoother than in a car.

As you drive, you also see other drivers on the road. Most of them will be moving relative to yourself. Drivers traveling in your direction seem to be moving at very low speeds, usually only a few miles per hour. Some of them seem to move forward, others seem to move backward. On the other hand, drivers in the oncoming lanes seem to be moving at 120 mph or faster, either toward or away from you.

So, which is the correct viewpoint? Are the oncoming drivers moving at 60 or 70 mph or at 120 or 140 mph? Are we moving across the ground at 60 mph or is the ground moving past us with that speed in the opposite direction?

That question has no absolute answer. It depends on our point of view. As long as we are clear about which point of view we are using, the answer we give will also be clear. We are free to measure positions and speeds using any reference point we find to be convenient. The only caveat is that, once chosen, we must stick with that single reference point for all of our measurements. If we do not, we cannot compare them in any meaningful way. So, any of the descriptions of motion we used above would be fine as long as we make clear what the motion was measured against (us or the ground). This is one form of relativity, called Galilean relativity: We are free to measure motion (and position) using any convenient point of reference, but we always require some specific reference point to make any such measurement meaningful.

Relative Motion

In this activity, a cart will travel along some tracks. There is a person on the cart who will tell you at what speed she will throw a ball.

We will define the cart's speed to be negative when it is traveling from the right side of the screen toward the left. Likewise, left to right motion is defined so the speed is positive). The ball's velocity with respect to the cart will always be positive because the person will always throw the ball toward the right side of the screen.

Play Activity

Click the "Generate" button, and you will be given the speed of the cart and the speed of the ball in meters per second.

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Click on the “Generate” button to start another round. You may want to try a few combinations of negative and positive velocities to make sure you understand the concept.

In the last section, we imagined cars moving on the freeway or trains moving along a track at a straight section of track. This type of motion approximates uniform motion, which is just a shorthand way of saying that the objects move with a constant speed and constant direction. Of course, cars and trains do speed up and slow down, and they change direction, too. But we had imagined what we would see traveling at a constant speed and direction. If either of these conditions is not met, then the motion is not uniform, and its character changes fundamentally.

You might have noticed this effect yourself. Riding in a car feels very different when traveling straight down the road at a constant speed than it does when the car brakes rapidly or goes around a sharp curve. In these latter cases, we have strong departures from uniform motion, and we notice this departure because we feel as though we are thrust either forward or back, or side to side. Such motion is called accelerated. Note that acceleration for a physicist means that an object speeds up, slows down, or changes direction. This is an example of a word that has a slightly different, though still related, meaning in science than it does in our everyday language. Science is full of such words because scientists often require more precise meanings for things than we do in day-to-day conversation.

It turns out that uniform motion is an idealized view of motion. None of the moving objects we have mentioned are really in uniform motion at all. For instance, Earth is orbiting the Sun in a circular path, so it is constantly changing direction. It must be constantly accelerated. Earth is also spinning on its axis, so everything in and upon Earth must also be going around, being accelerated. These accelerations are small, and so we are not generally aware of them. This is why it took people a long time to realize that Earth moves at all. However, any acceleration can in principle be measured. Furthermore, the rate at which direction or speed changes can be measured in absolute terms, without reference to an arbitrary point of reference. In this way, accelerated motion differs profoundly from uniform motion. We will have more to say about accelerated motion when we discuss gravity in later modules.