Elementary Astronomy

by

James N. Pierce

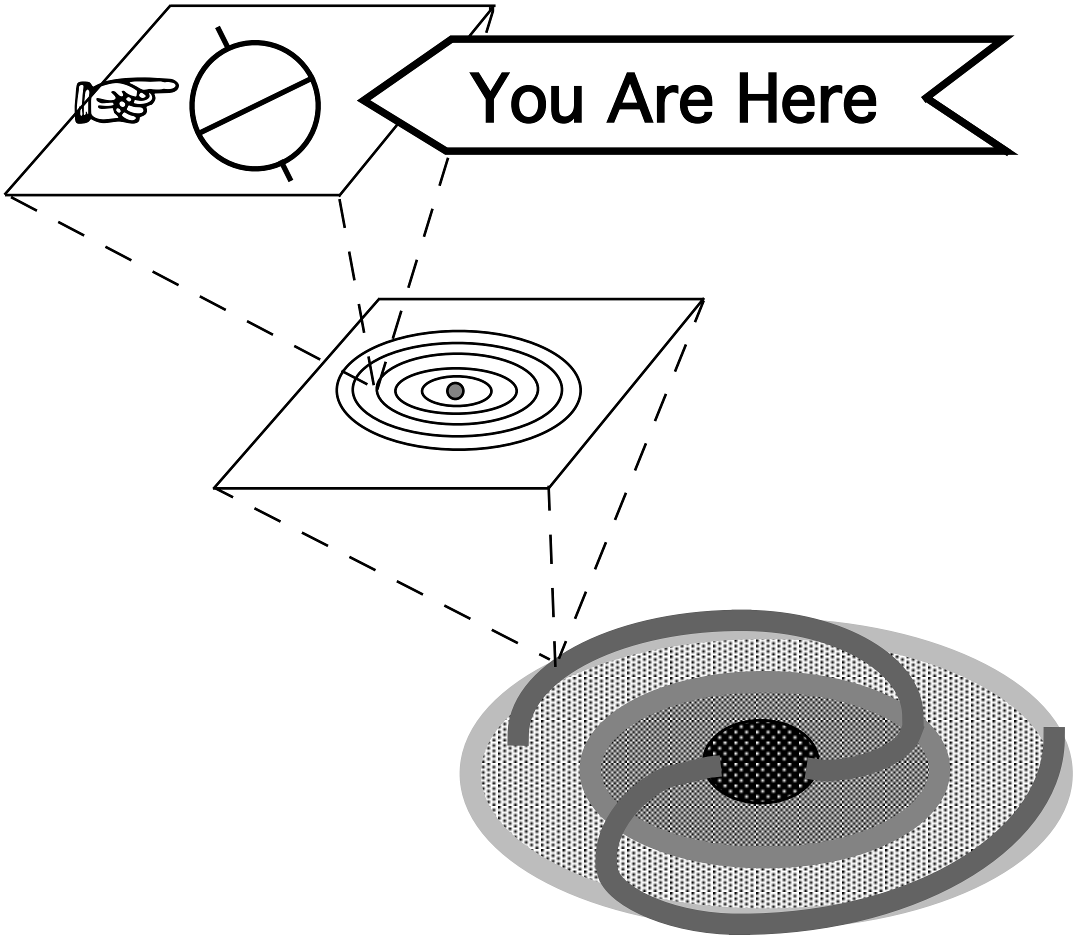
Dedication

To my wife, Rebecca

Edition 3.0

Table of Contents

Chapter 1: Introduction



This is a book about **astronomy**, the study of the Sun, Moon, planets, stars, galaxies and other objects found in the sky. It is *not* a book about astronauts, rockets, and space travel, although these interesting topics are occasionally mentioned. Nor is it a book about astrology and horoscopes, written to collect money for its entertainment value. This book is a crash course in basic astronomy, written for those who have never found the opportunity to learn any astronomy before now – especially elementary and middle school teachers, and parents of children in these grades. The book is intended as a source of information on the basic astronomical topics that are part of a strong science curriculum. Astronomy is the perfect introductory science: it is interesting, it is fun, and it doesn't get your hands dirty.

Why should anyone study astronomy? What practical use is it to us? Many people realize that astronomy is the basis for such activities as time-keeping, navigation, and picking out constellations while camping under the stars. But astronomy is important for another reason: it fascinates people – even those who know very little about it. Children especially, are eager to learn about planets and stars, worlds much different from their own, which give their imaginations a flying start. They are amazed by the huge numbers, distances, and sizes that are encountered with every new topic. And they like being able to make predictions of moon phases, eclipses, and other events in the sky – predictions that can then be verified by observations. In a school setting, astronomy is a natural cross-curricular topic; it develops and exercises mathematical and scientific thinking processes and stimulates the imagination. Integrating curriculum strands is easy with astronomy, as it provides topics for learning activities in language arts, social studies, math, and science.

The book presents a simplified view of astronomy. Equations have been minimized, numbers have been rounded, and the black-and-white diagrams can be easily reproduced on a chalkboard – which is where most of them originated. (Nice color images of planets, moons, and such do not appear here, as they can easily be found on the web.) Terms are explained in the chapters, as needed, and also collected in the glossary at the end of the book. Most of the topics are reasonably tame: they include sunrise and sunset, shadows and seasons, moon phases, planets, and such. Discussions of black holes, pulsars, quasars, supernovae, and other exotic objects are a bit premature at this level and will be omitted. Throughout most of the book we will stay fairly close to home; let us define what that means.

We live on the **Earth**, which is a **planet** – one of several that orbit our **Sun**. The Sun, together with the planets and their satellites, and the asteroids, comets, and other space debris that also orbit the Sun, make up the **solar system**. But the Sun is just a very close **star** – *our* star – and there are many, many stars in the sky. These *billions* of stars, together with their planetary systems, make up the huge stellar system we call a **galaxy**. And there are *billions* of galaxies out there populating the **universe**, which includes everything there is. Although astronomy covers the entire range of topics and objects from the Earth to the universe, we will not attempt such coverage in this book. We will not venture much outside our solar system; and yet we will discuss essentially all of the astronomy topics normally taught in the elementary grades.

Take your time and read carefully. Reread as often as necessary, until you are comfortable with each topic. Some information may seem to contradict what you thought was correct. (That's okay – that is why you are reading this book.) Some information may seem rather strange. (That's okay – some of it *is* strange, but only because you have not thought about it much before now.) Some passages may make you want to run out and look at the sky to see for yourself, and that is just fine. Astronomy is an observational science, and the more chances you have to experience it for yourself, the better you will understand. And the better you understand this material, the better you will be able to teach it.

NSES Content Standards

Most state education standards and frameworks are written based on the National Science Education Standards (NSES). These standards are presented by grade ranges: K–4, 5–8, and 9–12. Consequently, specific grade-level study topics vary considerably from state to state and district to district. The NSES content standards for space science presented here were published in 1996 and are available on the web (search *National Science Education Standards*). The science curriculum of a given school or district will most likely be written to reflect these content standards.

Grades K–4: Space Science

All students should develop an understanding of objects in the sky and changes in Earth and sky, based on regular observations of day and night skies. In K–4 emphasis is placed on developing observation and description skills, and explanations based on what students observe. They learn to identify the sequences of changes in what they observe over time, and to look for patterns in these changes. They observe the movement of an object's shadow during the course of a day, the positions of the Sun and Moon to find the patterns of movement, and record the Moon's shape on a calendar every evening over a period of weeks.

The fundamental astronomical concepts underlying the content standards are as follows:

- The properties, locations, and movements of the Sun, the Moon, and stars can be observed and described.
- The temperature of the Earth is maintained by the Sun's light and heat.
- Patterns of movement of objects in the sky can be observed. For example, although the Sun seems to move across the sky the same way every day, its path changes slowly over the seasons. The Moon's movement across the sky on a daily basis is much like that of the Sun. From day to day the observable shape of the Moon changes in a cycle that lasts about a month.

Grades 5–8: Space Science

In grades 5–8, content of earth and space science focuses on developing an understanding of the Earth and the Solar System and how closely they relate as systems. The observations made in grades K–4 are the basis for constructing models to explain the relationships among the Earth, Sun, Moon, and Solar System. Students will conclude through direct observation and satellite data that the Earth is a moving, spherical planet with features that distinguish it from other planets in the Solar System. Activities that explore trajectories and orbits with the Earth-Sun and Earth-Moon systems as examples help students understand that gravity holds all parts of the Solar System together. The primary energy source for processes on the Earth's surface is energy from the Sun transferred by light and other radiation.

The fundamental astronomical concepts underlying the content standards are as follows:

- The Solar System includes the Earth, the Moon, the Sun, a number of other planets and their moons, and smaller objects such as asteroids and comets. The Earth is the third planet from the Sun, which is an average star – the central and largest body in the Solar System.
- Most objects in the Solar System are in regular and predictable motion. Those motions explain such phenomena as the day, the year, phases of the Moon, and eclipses.
- The force that keeps planets in orbit around the Sun and governs the rest of the motion in the Solar System is gravity. It alone holds us to the Earth's surface and explains the phenomenon of tides.

- The Sun is the major source of energy for the Earth and the phenomena on the Earth's surface, such as plant growth, winds, ocean currents, and the water cycle. The tilt of the Earth's rotational axis causes variation in the length of days and in seasonal weather in different places on the Earth's surface over the course of a year.

Grades 9–12: Space Science

The study of astronomy in grades 9–12 moves from the behavior of objects in the Solar system to more abstract concepts. Students are more able to comprehend vast distances, long time scales, and nuclear reactions. By looking outward, astronomers have demonstrated that we live in a vast and ancient universe. Students are fascinated by the age of the universe and how galaxies, stars and planets have evolved.

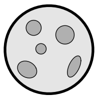
One of the greatest challenges of teaching astronomy in grades 9–12 is that direct experimentation relating to the concepts is difficult or impossible. Students who are not yet capable of understanding content based on abstract concepts such as the space-time continuum will need concrete examples, and guidance through the multiple, logical steps needed to develop this understanding.

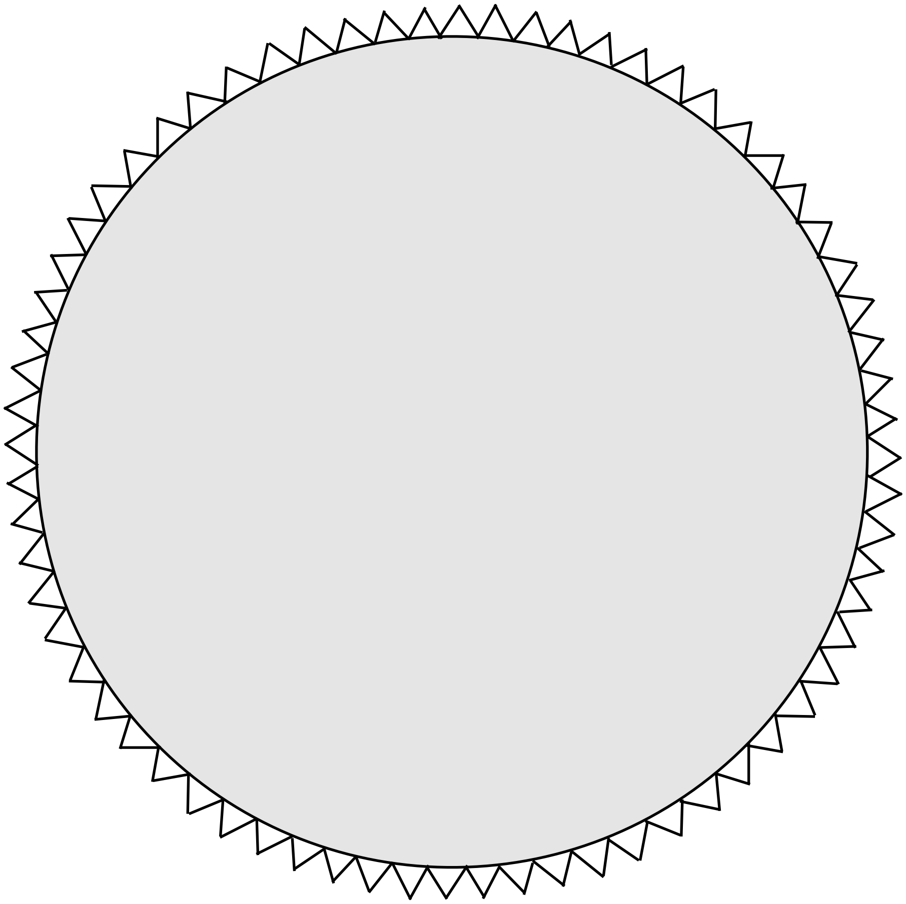
The fundamental astronomical concepts underlying the content standards are as follows:

- One of the greatest questions in science is the origin of the universe. According to the big bang theory, the universe began in a hot, dense state about 14 billion years ago, and the universe has been expanding ever since.
- Matter – primarily light atoms such as hydrogen and helium – clumped together by gravitational attraction early in the history of the universe. These clumps formed countless trillions of stars. The visible mass of the universe is formed by billions of galaxies, each of which is a gravitationally bound cluster of billions of stars.
- Nuclear reactions – primarily the fusion of hydrogen atoms to form helium – are the means by which energy is produced in stars. The formation of all the other elements has occurred as a result of these and other processes in stars.

Although this book makes no attempt to cover the topics discussed in grades 9–12, it does provide solid background material needed for teaching the basic astronomy discussed in grades K–4 and 5–8. In Chapter 2, we will begin our studies by examining three of our most familiar celestial objects.

Chapter 2: Earth, Moon, and Sun





Astronomy involves objects in the sky. Let us begin our study with a discussion of the *brightest* objects seen in the sky – the Sun and the Moon – and the planet on which we live – the Earth. This should be a good place to start because every student should have seen the Sun, Moon and Earth; if not, this can usually be quickly remedied.

There are many things we would like to find out about the Sun, Moon, and Earth. How should we go about learning about these three objects? We could, of course, simply look up the desired information, in books found in the library or on one of the numerous web pages devoted to these subjects. Or, we could determine the answers to our questions by making our own observations and measurements. Most of us would probably choose the first alternative as it is probably going to prove to be faster and more accurate to rely on the previous work of others. But what if there were no books available? What if no one had yet determined the properties of the Sun, Moon, and Earth? Then we would have no choice but to make the measurements ourselves. How well would that work?

Caveman Astronomy

To illustrate this approach, let us go back in time to the days (and nights) of the caveman, when astronomy texts were comparatively rare. Caveman astronomers had to rely on their own observations and intelligence to figure things out. As an example, let us consider the caveman's perception of our three principal objects:

> The scene opens with a group of cavemen and cavewomen sitting around in a cave (where else?) having a lively discussion about natural science. When the topic of the Earth comes up, they realize they have no data; accordingly, they send one of their number outside to observe the Earth.
>
> The questions are simple, because the cave people are simple:
>
> 1. What is the size of the Earth?

What would you say? Go outside and look at the Earth (or send your students outside to look at it) and come up with a simple description of the Earth's size.

> After some contemplation, our cave person decides that the Earth is rather large – much bigger than a caveman anyway – and therefore the answer to this first question is 'BIG'.
>
> Upon hearing this, the cave people immediately come up with another question:
>
> 2. What is the shape of the Earth?
>
> Back outside goes the intrepid cave person to deduce the Earth's shape. Of course this answer will depend to some degree on the local terrain around the cave, but very likely the cave person arrives at an answer quite similar to the one you obtain today – 'FLAT'. (Not perfectly flat of course, but close enough for this exercise.)
>
> The indoor cave group receives this result with enthusiasm and responds with a final question:
>
> 3. Does the Earth move?
>
> A silly question, thinks the cave person trudging back outside, because anyone can see – or rather feel – that the Earth does not move. Just stand and look down at it, and you can see that it is not going anywhere. The obvious answer is a simple 'NO'.

Thus by simple observations the cave people learned that the Earth is big and flat and does not move. They continued their scientific observations by inquiring next about the Moon.

1. What is the size of the Moon?

It appears rather SMALL as it hangs in the sky – certainly much smaller than the Earth.

2. What is the shape of the Moon?

This one is rather tricky because the Moon's shape is not always the same – it VARIES from day to day.

3. Does the Moon move?

Not very rapidly, but YES, it does move across the sky, given enough time.

Finally they examined the Sun, using the same questions and obtaining the following answers:

1. The Sun appears to be very similar in size to the Moon – SMALL.
2. The Sun is generally rather ROUND.
3. YES, the Sun moves gradually across the sky during the day.

Let us now summarize the scientific findings of the cave people in the following table:

OBJECT	SIZE	SHAPE	MOTION?
Earth	Big	Flat	No
Moon	Small	Varies	Yes
Sun	Small	Round	Yes

Of course we live in an enlightened age in which we know more about the Earth, Moon, and Sun than the cave people could deduce. In fact, we can tell from examining the table that some of their observations were not quite accurate. What are the Earth, Moon, and Sun *really* like?

Motions

Let us begin with the third question of motion. Is the Earth really at rest while the others are moving, or do we have this mixed up? The actual answer is that *everything* moves, and the motions are too complex to explain in a sentence or two. We will save this topic for later chapters.

Shapes

What about shapes? Do the Earth, Moon, and Sun actually have different shapes? As we now know, all three are 'round'. However, round is not a very precise word. A better way to describe the shapes of these objects is to say that each is a *sphere* (or a *ball*, for very young children). (They are not necessarily *perfectly* spherical but are certainly close enough for us.) We can easily see that the Sun is a sphere, and in Chapter 5 we will learn how the Moon is a sphere that appears to vary its shape, but how do we know that the Earth is a sphere at all? What observations tell us that?

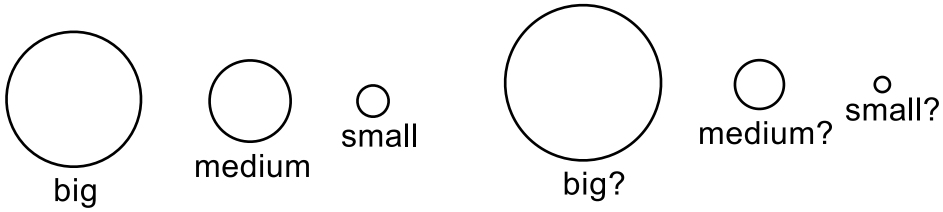
One obvious observation is the pictures taken from space by the astronauts, showing the spherical Earth floating in space. Of course the Earth's spherical shape was known long before that. The ancient Greek astronomers deduced the Earth's shape by noting the curved shadow cast on the Moon by the Earth during a lunar eclipse (see Chapter 6). Only a sphere would always cast such a shadow. Persons living on the shores of large bodies of water noticed that when ships sailed away, the bottoms of the ships disappeared from view before the tops of the masts did, implying a curved surface to the water.

But how is it that the Earth can be a sphere and still appear flat to us? This can only be the case if the sphere is very large, and indeed, the cave person said that the Earth was big. Therefore, we must now consider the question of sizes of the Earth, Moon, and Sun.

Sizes

So far we have big, small, and small. Is it true? Or is it big, medium, and small? Or medium, small, and big? But even if we get the order right, what does it mean? Anyone who buys soft drinks or fries at a fast food restaurant knows that these adjectives do not always translate into the same sized serving (see Figure 2.1).

Figure 2.1: Relative sizes



In order to make proper comparisons we need to use *numbers*, which means we need something to measure. What dimension of a sphere should we measure? There are several possibilities:

> We could measure the distance from the center of a sphere to the outside. That distance would be the **radius**.
>
> We could measure the longest distance all the way through the sphere, passing through the center. That distance would be the **diameter**.
>
> We could measure the distance all the way around the sphere. That would be the **circumference**.
>
> We could measure the **surface area** of the sphere.
>
> Or we could measure the **volume** of the sphere.

Measurement of each of these dimensions will give us a number. Of course we will need to attach some units to these numbers, in order to make some sense out of them. Appropriate units are typically either miles or kilometers (square miles, cubic kilometers, etc.) The following table gives the values of these five dimensions for the Earth:

Dimension	**Miles**	**Kilometers**
Radius	**3964**	**6378**
Diameter	**7928**	**12756**
Circumference	**24900**	**40074**
Surface Area	**197,500,000 sq**	**5.06×10^{8} sq**
Volume	**260,900,000,000 cu**	**1.07×10^{12} cu**

1 Mile ≈ 1.6 Kilometers

> Notice that the numbers are large: even the smallest one in this table is much too large for a young child to comprehend. (Clearly we will need better ways to communicate sizes of astronomical objects to children.) Note also that the numbers for surface area and volume are extremely large. Such numbers are best written in **scientific notation**, which has been used for the values in the kilometer's column for these two quantities. [$4321 = 4.321 \times 10^{3}$, 1 million = 10^{6}, etc.] Although astronomy naturally involves large numbers, we will try to minimize their usage and instead find other ways to get the picture across.

One way to visualize distances is in terms of traveling time. Most youngsters have spent time riding in a car to visit a relative or go on a vacation. How long would it take to travel these astronomical distances by car? The easiest to these to imagine is driving around the circumference of the Earth, non-stop, at 55 miles per hour. Ignoring the oceans, mountains, and other hazards one might encounter, how long would the trip take? The answer is about 19 days, with no stops for sleeping, meals, or bathrooms. Nineteen days should seem like a long time to spend in a car, just as the Earth's circumference is much greater than any automobile trip taken by most children these days.

What about the other dimensions? In order to compare sizes, do we need to look at all the different ways to measure a sphere? We certainly could, but as it turns out, that is unnecessary. The different properties of a sphere (radius R, diameter D, circumference C, surface area A, and volume V) are related to each other, as follows:

$$D = 2\,R$$

$$C = 2\,\pi\,R$$

$$A = 4\,\pi\,R^2$$

$$V = {}^4/_3\,\pi\,R^3$$

$$\text{(where } \pi \approx 3.141592654\text{)}$$

For this reason, we need not compare all five values, but instead only one for each sphere, usually R or D. Comparing radii of the Earth, Moon, and Sun and using kilometers for units gives the following:

Radius:	**EARTH**	**MOON**	**SUN**
Kilometers	**≈ 6400**	**≈ 1700**	**≈ 700,000**

If we are able to understand numbers of this size, we see clearly that the Sun is the largest of these three bodies – much larger than either the Earth or the Moon. Similarly, the Moon is a bit smaller than the Earth. But suppose we cannot comprehend such large numbers. What then?

The numbers are large because the objects being measured are large and the units being used are relatively small. If we used bigger units, the numbers would be smaller. (This is similar to measuring the length of your classroom in millimeters, and then again in yards.) We have need for a unit that is substantially bigger than a mile. Few such units are employed in everyday life because miles and kilometers are normally adequate for human activities on the Earth's surface. However, astronomers have had to devise big units, and we will make use of one of them here.

The unit we need is called the Earth radius, and it is equal in size to the Earth's radius. If we use it to measure the radius of each object, we get the following results:

Radius:	**EARTH**	**MOON**	**SUN**
Kilometers	**≈ 6400**	**≈ 1700**	**≈ 700,000**
Earth Radii	**1**	**0.27**	**109**

Now these numbers are indeed smaller, and therefore more easily understood. The Sun has a radius over 100 times greater than the Earth's, while the Moon's radius is about a quarter of the Earth's. Of course, because decimals and fractions are usually not introduced in the lower grades, we still need a better way to convey sizes.

The best method involves a picture. We could draw three circles to represent the true relative sizes of the three objects: the radii (or diameters) of the three circles would have the ratios given in the table above. An even better plan would be to find a set of three spheres with the correct relative sizes. One such set is as follows:

Let the Earth be a marble, about one half inch in diameter. The Moon is then a BB, and the Sun will be an earth ball, about five feet across. (These three can also be sketched on a blackboard if the actual spheres are not available.)

This model of our three objects gives a pretty good picture of their true relative sizes, a picture that differs significantly from the caveman's observations. The difference is caused by the caveman's inability to judge the distance of each object, which of course affects the object's apparent size. To complete our model, we will include the distances of the Moon and Sun from Earth, using several different sets of units:

Distance from Earth:	**MOON**	**SUN**
Kilometers	**≈ 384,000**	**≈ 150,000,000**
Earth Radii	**60**	**23,400**
Time at 55 mph	**6 Months**	**194 Years**

In our model in which the Earth is a marble, the Moon would be a BB at a distance of 16 inches from the marble, and the Sun would be an earth ball at a distance of 175 yards from the marble.

We could construct a different model using larger spheres. Let the Earth be a 12-inch diameter globe. Then the Moon is a baseball at a distance of 30 feet from the globe, while the Sun will be the size of a baseball infield at a distance of two and a quarter miles from the globe! How big is your classroom? Your school? Your playground? Your town?

As a side note, we should mention that the Earth is not a perfect sphere but is slightly flattened at the poles and bulging at the equator (we say the Earth is **oblate**).

Equatorial Diameter = 7928 miles
Polar Diameter = 7902 miles
Difference = 26 miles

The Earth's **oblateness**, which is this difference divided by the equatorial diameter, is about 1/300, or about one millimeter on a 12-inch globe. This amount is certainly not very noticeable, and we are justified in approximating the Earth as a sphere.

Temperature

Now that we understand the relative sizes of the Earth, Moon, and Sun, we should try to find out some of the physical characteristics of each body. Differences in the physical properties of these three are largely a result of the differences in **temperature** among them. Before we can proceed further, we must learn more about temperature.

Temperature is a measure of the amount of energy contained in a body. A hot body contains more energy than a cool body. We can use terms such as 'hot' and 'cold' to describe objects, much as we described sizes using 'big' or 'small', but the amount of information contained in such words is quite limited. In order to convey more than the relative energy content of a body we will employ a temperature scale of some type.

There are several temperature scales in use today. Most Americans are familiar with the **Fahrenheit** scale, while much of the rest of the world uses the **Celsius** scale. Both of these scales are based on the freezing and boiling points of water, which freezes at 32°F (0°C) and boils at 212°F (100°C). Large positive numbers indicate very high temperatures, while at very low temperatures, one finds negative values in each scale. Although there is no upper limit on temperature, there is a lower limit, known as **absolute zero**, at about –459°F (–273°C). Astronomers sometimes use Fahrenheit and sometimes use Celsius, but more often use a different scale called **Kelvin**. Kelvin has its zero point at absolute zero and degrees equal in size to

Celsius degrees, producing a temperature scale with no negative values and freezing and boiling points as shown:

	Fahrenheit	**Celsius**	**Kelvin**
Water Boils	**212**	**100**	**373**
Water Freezes	**32**	**0**	**273**
Absolute Zero	**–460**	**–273**	**0**

In your readings about various astronomical objects, you are very apt to encounter different temperature scales. As can be seen, they produce quite different numbers to indicate the same temperature. Care should be taken to note just which scale is being used.

Earth, Moon, and Sun

Let us now return to the Earth, Moon, and Sun and describe their temperatures. What is the temperature of the Earth? Although this is a relatively simple question, a problem arises immediately. Where should we measure the temperature of the Earth? On the inside or the outside? On the surface or up in the air? On a mountain or by the sea? At the poles or at the equator? During the night or during the day? A quick glance at a current weather report should demonstrate that the temperature varies with time, date, and location on the Earth. Thus it is foolish to ask for a single temperature to characterize the whole planet when there is really a rather large range of values to be reported. Similarly, other bodies in space will not necessarily have just one temperature but many. Our simple questions may not always have simple answers.

Now that we are aware of the pitfalls involved, we can proceed with some temperature values for each body as shown in the accompanying chart. For the Earth, we will give a typical range of values for the air temperature at the Earth's surface, both in the day and at night. (Of course values outside these ranges are recorded. These are only meant to be 'typical'.) The daytime side of the Earth is warmer because it is receiving heat from the Sun. The Earth is constantly radiating energy away into space, which causes the nighttime side to cool down.

The Moon is similar to the Earth in that it warms during the lunar day and cools during the lunar night. The principal difference is that the Moon has no atmosphere as the Earth does, and this lack of an insulating layer of air around the Moon causes it to have greater extremes of temperature. It also means that we cannot measure an air temperature on the Moon. Instead we will have to settle for the temperature of the lunar soil, for which maximum daytime and minimum nighttime values are given.

Temperatures:	**Day**	**Night**
Earth (Surface Air)	**277-310 K (39-99 F)**	**260-283 K (9-50 F)**
Moon (Soil Surface)	**Max. 380 K (225 F)**	**Min. 100 K (-279 F)**

The Earth and the Moon are both relatively cool bodies, with surfaces that are mostly solid. The Earth is surrounded by a transparent blanket of air (its **atmosphere**), and a thin layer of liquid water covers a large portion of its solid surface, but otherwise the two bodies are composed primarily of solid or molten rock and iron.

The Sun is another story entirely. It is considerably larger than the Earth, and because of this great size and mass it is by necessity much hotter than the Earth or Moon. Of course there would be no night on the Sun, and there should be no great variation over its surface as there is on the Earth. The temperature of the surface of the Sun is approximately 5800 K (9980 F). This temperature is so high that most materials such as we find on the Earth would be vaporized. The interior of the Sun is even hotter, reaching about 15 million K (27 million F) at the center. The Sun is completely different from the Earth and the Moon: it is a **star** – a huge ball of very hot gas that radiates energy, primarily as visible light. The Earth intercepts some of this light, the ultimate source of most of the energy used by humans (and plants and animals) on this planet.

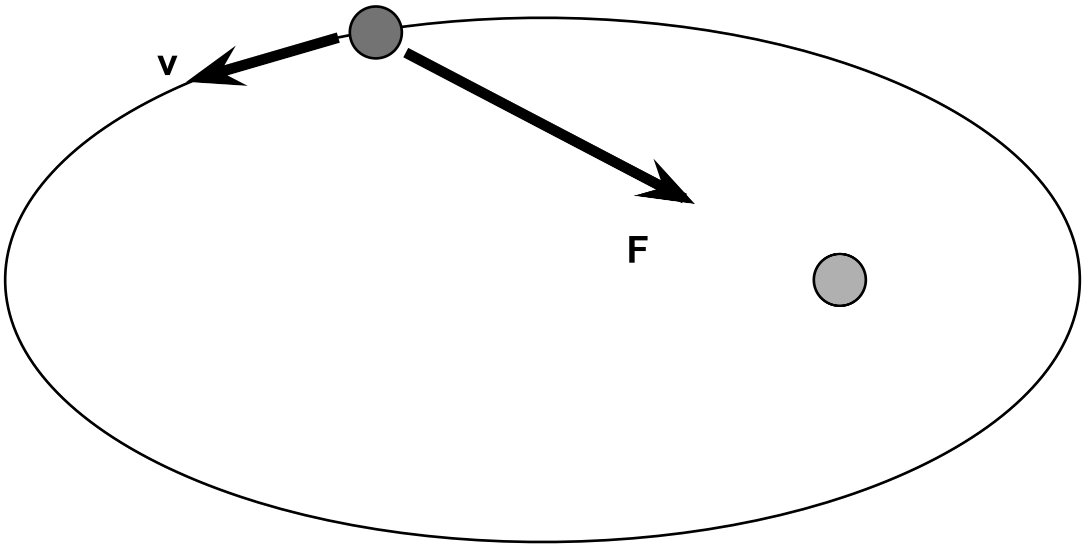
> It may be a good idea at this point to discuss the differences among the various states of matter – solids, liquids, and gases.
>
> A **solid** is matter in which the atoms or molecules that compose it are bound very tightly together, such that their motion is quite restricted. A single piece of solid matter does not flow (although a collection of solid particles – such as sand in an hourglass – can flow), nor does it expand or contract on its own. A solid thus needs no container to hold it as it has a fixed volume and a fixed shape.
>
> A **liquid** is matter in which the atoms or molecules that compose it are bound weakly together, allowing them to move past each other while still maintaining contact. A liquid can flow and thus requires a container, but it generally does not expand to fill all available space in the container. A liquid has a fixed volume and a free shape.
>
> A **gas** is matter in which the atoms or molecules that compose it are fairly independent of each other and move about without maintaining contact other than random collisions. Because the gas particles are not bound to each other, the gas can flow and also expand to fill any container. A gas has a free volume and a free shape.

The Earth and Moon are solid bodies, molded into spherical shapes by their own gravitational forces. The Earth's surface is mostly covered with liquid oceans, bounded by the continents – the walls of the oceans' containers. The Sun, on the other hand, is a gas, also molded into a spherical shape by its own gravitational forces. The Sun's gravity supplies the 'lid' that keeps its gases inside their 'container', and the Earth's gravity provides a similar service to keep our gaseous atmosphere in place on our planet. If gravity could be suddenly turned off, the gases of the entire Sun and the atmosphere of the Earth would both drift away into space, while the solid parts of the Earth and the Moon would remain. (Of course, turning off gravity would have a variety of other effects too.)

The physical properties of each of these bodies are a result of their respective masses. The Moon's mass is so low that its gravity is too weak to hold any atmosphere at all. Visitors to the Moon must bring their own supply of oxygen and wear space suits to give their bodies a normal environment. The Earth has a larger mass and enough gravity to hold a reasonable atmosphere, which makes it an ideal planet for life. (We will see in Chapter 8 that more massive planets have very thick atmospheres that are probably unsuitable for life.) The Sun's mass is so great that its gravity has compressed and heated its matter to the point where solids and liquids cannot exist. The high temperatures that result cause the Sun to radiate light. Thus, the fundamental difference between a planet and a star is mass: bodies of sufficient mass become stars, while those with lower mass will be planets. The Earth, Moon, and Sun are probably typical objects, with many similar bodies found throughout the Universe.

In the next chapter we will be discovering how the mass of a body can have an effect on other nearby bodies, resulting in orbital motion.

Chapter 3: Gravity and Orbits



In this chapter we will explore the motions of objects in space. We will find out what sort of paths planets and moons follow, and we will learn why they move in this manner. To begin, we will establish some basic terminology having to do with movement, which will help us describe more precisely the motions we observe in space.

Position

Our first term is **position**. The position of an object simply tells where it is located with respect to some reference point. Your friend might be sitting two feet to your left. Your home might be three miles east and four miles south of the intersection of two highways. In each case, the position of an object tells both the direction and the distance from the reference point. In short, the position is what we call a **vector**, which has both a length and a direction associated with it.

Velocity

Objects can move, which means that they can change position. The motion of an object will be in some direction, and it will proceed at some rate. The rate of change of position of an object is called **velocity**. Velocity is another vector: motion involves both a direction and a rate. We might say that our car has a velocity of 35 miles per hour to the north. Another related term is **speed**, which refers to the rate at which a body is traveling (with no mention of the direction). Thus in the example just given, our car would have a speed of 35 miles per hour. Although speed and velocity are often used interchangeably, the small distinction between them can occasionally be very important.

Acceleration

Now we have our object at some position, and it may or may not be moving in some direction at some speed. Can this speed or direction ever change? Of course it can. We know that an automobile need not travel at a constant speed in a straight line: it is allowed to speed up, slow down, and turn as necessary. Such changes in the speed or direction of motion are changes in the velocity of the object. The rate of change of velocity of an object is called **acceleration**. Recall the pedal in your car that gets the car moving – the accelerator pedal? It is aptly named because it increases the car's speed. The car's speed is decreased by braking, also called deceleration (negative acceleration). And the car's direction is changed by turning the steering wheel, a process that also falls under the category of acceleration. Thus the accelerator, the brake, and the steering wheel are all used to accelerate, or change the velocity of, your car.

Bodies, whether in space or on the Earth, may have position, velocity, and acceleration. Velocity and acceleration may have values of zero. An object with zero velocity is not moving. An object with zero acceleration is not changing its velocity. Velocity and acceleration are separate, independent quantities. Either one, both, or neither may be zero at a given time.

Force

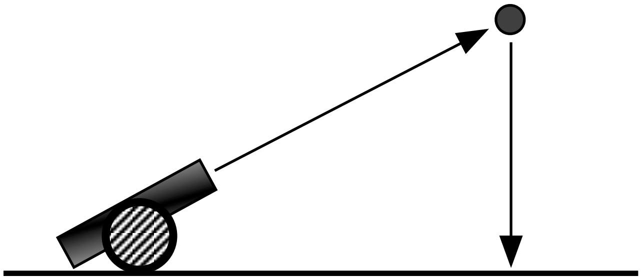
Now that we understand the terminology, we can get on with our study of motion. Why do objects move? Why don't they just sit still? You can answer this yourself by making an object move – your pencil, your book, yourself – and then asking yourself how you did it. The answer is that you had to apply some kind of **force** to the object to make it move. Force has a very simple meaning in science: most physics texts will describe a force as a push or pull, which is certainly not difficult to comprehend. Despite this simple description, we will find that forces may have completely different origins.

If you moved your pencil by pushing it across the table, that motion was obviously the result of a force (the push). What if you simply dropped your pencil, allowing it to move downward? Again a force was involved; this time it was the force of gravity, which we will discuss later in this chapter. Suppose that you use a magnet to pick up a paper clip. That motion is the result of a magnetic force. You may have noticed that in dry weather, your hair sometimes stands out from your head: such motion is caused by electrostatic forces.

Forces of any kind can cause objects to move. But does the motion of an object require a force? Can an object move without a force being applied? Before modern science, people followed the teachings of early Greek philosophers. Motion of objects was believed to be unnatural. If left to themselves, objects would always come to rest.

This is easily demonstrated by pushing a book across the table; it will always stop (unless it runs out of table first). The book will not keep moving unless you continue to push it.

Figure 3.1: Straight line trajectories



Objects on the Earth were believed to move in straight lines, as opposed to curves. The trajectory of a cannonball was thought to resemble two sides of a right triangle as in Figure 3.1. On the other hand, objects in the sky were allowed to have curved paths, being celestial rather than terrestrial objects.

It was not until Isaac Newton produced his famous laws of motion that simple movement of objects was satisfactorily explained. These three laws will be seen to incorporate our ideas about forces and their connection with motion. They apply to terrestrial objects and celestial objects.

Newton's Laws of Motion

#1 A body at rest remains at rest, and a body in motion travels in a straight line at constant speed unless acted upon by a net force.

A book on a table does not move unless it is pushed. A book sliding across a frictionless table would move in a straight line without slowing down. On a real table, the force of friction slows the book to a stop.

#2 A net force acting on a body produces an acceleration that is proportional to the force ($a \approx F$) and inversely proportional to the body's **mass** ($a \approx 1/m$). Together, $a = F/m$ or $F = ma$.

The **mass** of a body is a measure of the amount of matter in the body. More massive objects respond more slowly to a given force and require a greater force to achieve the same acceleration. A fully loaded truck needs more time (and fuel) to get to cruising speed, compared to an empty one.

#3 For every action there is an equal and opposite reaction.

If you kick a rock, the rock kicks you back (or at least it exerts a significant force on your toe). A rocket moves by squirting exhaust gases backwards out through a nozzle; these gases exert an opposing force on the rocket, pushing it forward.

Gravity, Mass, and Weight

In many cases in astronomy, the force involved is **gravity**. As we know, gravity is the force that pulls us downwards and holds us on the Earth. What things are affected by gravity? Obviously, people, dogs, cats, buildings, trucks, and large rocks all respond to the pull of gravity, but what about birds, clouds, balloons, and air? And the Moon? Why don't these things fall down onto the ground? The answer in most cases is that other forces exist that counter the effects of gravity.

> Birds fly because of the difference in the air pressure forces on the tops and bottoms of their wings, caused by the wing shape and the air speed of the bird. Clouds and balloons remain up because the buoyant forces on them are enough to counteract gravity. Air stays up because the constant collisions between air molecules produce random motions that oppose the downward pull of gravity. The Moon is another story, left for later.

On the Earth, the force of gravity accelerates objects downward, toward the center of the Earth. Therefore, we sometimes speak of the **acceleration of gravity**. On the surface of the Earth, this acceleration (called $\boldsymbol{g}$) has a fixed value of 32 ft/sec^2 (9.8 m/sec^2), which means that a falling object increases its speed by 32 feet per second (9.8 meters per second) for every second it falls. Using Newton's second law ($F = ma$), we find that an object of mass m will feel a downward gravitational force of magnitude $F = mg$.

But Earth resists this downward force with an equal and opposite upward force. Its magnitude is called **weight** ($W = mg$). What is the difference between mass and weight?

> We have already mentioned that mass is a measure of the amount of matter contained in a body. The mass of a body depends only on the body itself and should remain unaffected by changes in the location of the body. The mass of a bowling ball would be the same here on the Earth, on the Moon, or out in space.
>
> Weight, on the other hand, is a force – an interaction between the body and the Earth, or more generally, between any two objects. The weight of a bowling ball on the Earth's surface is the force that opposes the Earth's gravitational pull on the ball. However, the weight of the same bowling ball on the *Moon's* surface would be the force that opposes the *Moon's* gravitational pull on the ball, and that would prove to be different. A bowling ball in space would be attracted by the Earth, the Moon, and other bodies, but because it would have no force opposing these gravitational pulls, the ball would then be **weightless**.

What does a bathroom scale measure? When you step on the scale, the Earth's gravitational force pulls you downward onto the scale. Inside the scale is a spring that gets compressed by this force and turns the dial on the scale. Thus the bathroom scale measures the force of Earth's attraction for you: it measures your weight, usually in pounds. Of course, because your weight and mass are related ($W = mg$), you can figure out your mass by simply dividing your weight in pounds by g (= 32 ft/sec^2). If your weight is 128 pounds, then your mass is $128 \div 32 = 4$ **slugs**. (This unit of mass is not particularly elegant. Perhaps that is why it is not generally used.) In the metric system, this same mass would be 58 **kilograms**, and its weight would be $58 \times 9.8 = 569$ **newtons** (because $g = 9.8$ m/sec^2). Mass and weight are related by the acceleration of gravity, g.

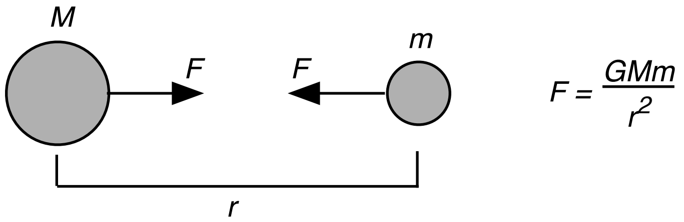
What factors affect the value of g? Does it have the same value everywhere on the Earth? On the Moon? On other planets? The value of g at your location depends on the mass (M) of the body doing the attracting (such as the Earth) and your distance (r) from the center of mass of this body. If you are standing on the surface of the Earth, then this distance is just the radius of the Earth (R). The equation for g contains one other factor, called G – **the gravitational constant** – a number whose value depends on the system of units being used in the equation. The equation [$g = GM/R^2$] shows that the acceleration of gravity is higher for large mass but lower for large radius. The following table gives the relative masses, radii, and surface gravities for the Earth, Moon, and Sun:

	EARTH	MOON	SUN
Mass	1	0.0123	333,000
Radius	1	0.272	109
Gravity	1	0.166	28

We say that the acceleration of gravity on the surface of the Earth is one *g*, while on the surfaces of the Moon and the Sun it would be $^1/_6$ *g* and 28 *g*'s, respectively. A person standing on the Moon would weigh only one sixth of what she normally does on Earth, while anyone bold enough to stand on the Sun would hardly be able to move, with a weight 28 times normal!

Gravity is not confined only to the surfaces of planets and moons: it acts everywhere, including out in space. **Newton's law of gravity** says that for every two masses there is an attractive gravitational force, with each mass pulling on the other. In Figure 3.2 we picture two such masses, M and m, separated by a distance r, and pulling on each other with a force F. The magnitude of the force is given by $F = GMm/r^2$.

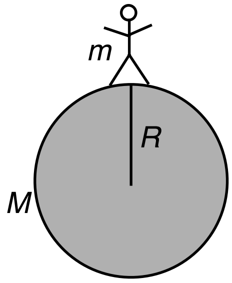
Figure 3.2: Newton's law of gravity



$$F = \frac{GMm}{r^2}$$

This equation applies equally well if the two objects are touching, rather than separated. A simple example of a person standing on the Earth is shown in Figure 3.3. Here m is the mass of the person, M is the mass of the Earth, and their separation is R, the radius of the Earth.

Figure 3.3: Gravity on Earth's surface



$$F = \frac{GMm}{r^2} = m\frac{GM}{R^2} = mg$$

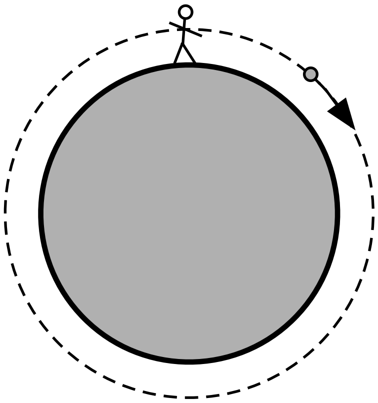
In this example we see that the force (not shown) is given by $F = mg$, which is of course equal to the weight of the person, as we already described above. The two masses involved in the equation may be anything: two persons; the Earth and the Moon; the Earth and the Sun. In each case, the equation will predict the gravitational force existing between the two masses. Let us examine the specific case of the Earth and the Sun.

Orbits

According to Newton's law of gravity, the Sun is pulling on the Earth (and the Earth is pulling on the Sun). Why then doesn't the Earth fall into the Sun? After all, if you let go of a tennis ball, it falls to the ground because the Earth pulls it downward. Shouldn't the Earth react to the Sun in a similar fashion?

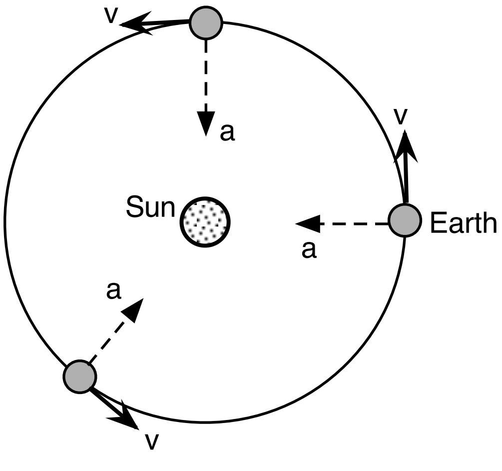
The answer is that it does react that way, but the problem is not that simple. To see why, throw your tennis ball horizontally. You should see the ball move away from you and *curve downward* to land on the ground. Even though the Earth is pulling the ball downward, the ball does not fall *straight* down when it leaves your hand because it already has a horizontal motion (a velocity). The downward curve that you observe is the result of the ball's initial horizontal velocity and the downward acceleration (change in velocity) produced by the Earth's gravity.

Figure 3.4: How gravity results in orbits



If you throw the ball harder, it will travel farther before it hits the ground, but it will still be accelerated downward by gravity. Suppose you could throw the ball so hard that its path curved downward at the same rate that the Earth curved away beneath it, due to its spherical shape (see Figure 3.4). Then the ball would travel all the way around the Earth without striking the ground. The path of the ball would then be called an orbit.

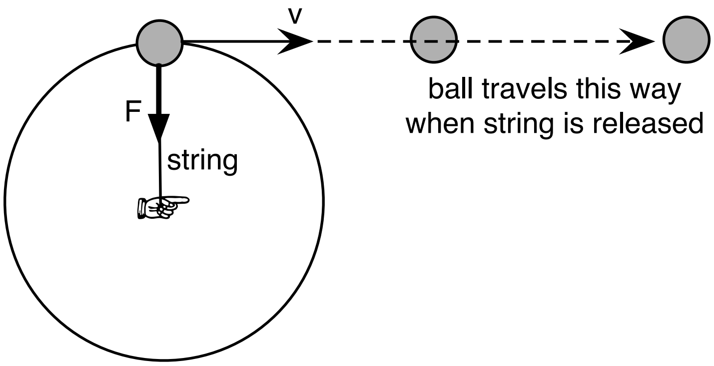
Figure 3.5: Orbital velocity and acceleration



In the same manner, the Earth orbits about the Sun. As the Sun pulls on the Earth, it accelerates the Earth, changing the Earth's velocity. The Earth 'falls' around the Sun, never hitting it, because its speed is sufficient to keep it in orbit (see Figure 3.5). At each point in the orbit, the Earth's velocity (v) and acceleration (a) are essentially perpendicular to each other.

> You can demonstrate the same effect by tying a string to your tennis ball and then twirling the ball around your head by holding onto the string. The string supplies a force that pulls the ball toward the center of the orbit, where your hand is holding the string. But the ball never travels *inward* along the string (even though that is the direction of the force); instead its velocity is constantly modified by the acceleration produced by the force, and the ball travels in a circle about you. If you let go of the string, the force stops acting on the ball, the acceleration of the ball ceases, and the ball flies off in a straight line as shown in Figure 3.6.

Figure 3.6: Effect of centripetal force



The Sun's gravity is a **centripetal force** (meaning directed toward the center), and it produces a **centripetal acceleration** of the Earth. This acceleration, together with the initial velocity of the Earth, creates the Earth's orbital motion.

> In the case of the tennis ball on a string, the string supplies the centripetal force, producing a centripetal acceleration of the ball. This acceleration, together with the initial velocity you gave to the ball, creates the ball's orbital motion.

As you twirl the ball on the string, you will notice that the ball seems to exert an outward force along the string, as if it were trying to get away. This force, called a **centrifugal force**, is just a reaction force (see Newton's third law of motion) to the centripetal force on the ball. There is no real force pulling the ball outward along the string, and in this sense, the centrifugal force is an illusion.

> If there were such a centrifugal force, the ball would be pulled radially outward along the direction of the string when you let go, rather than moving tangentially as shown in Figure 3.6.

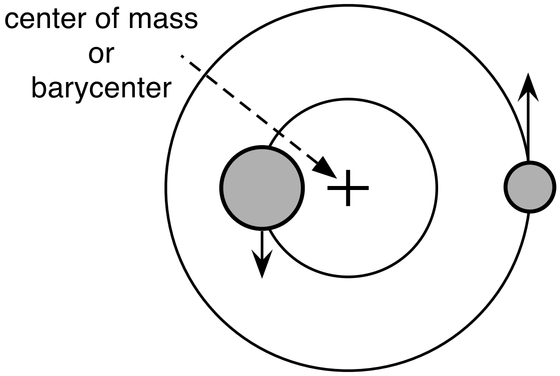
Another example of centrifugal force is found when you turn a sharp corner in your car. When you turn to the left, the passengers seem to lean over to the right, as if a (centrifugal) force were pushing them toward the outside of the curve. But there is no such force. In reality, the car is turning (accelerating) due to the force of the road against the tires, and the passengers are attempting to continue moving straight ahead. When the car pushes on the passengers to make them follow the curve of the road, it appears to them as if they are being pushed against the car by a (non-existent) centrifugal force.

> If all of this sounds unreal, try the following experiment: Get a plastic bucket or pail with a handle and put about an inch of water in it. Then stand holding the pail hanging down at your side and move your arm and the pail rapidly in a vertical circle, such that the pail turns upside-down but the water does not spill out.

(Whether this works or not depends on how fast you move your arm.) With a little practice, you can do this trick both effortlessly and dramatically. To demonstrate how the Earth could fall into the Sun, simply stop the bucket at the top of the arc. (The less dramatically inclined may choose to substitute a tennis ball or several ping-pong balls for the water.)

Now that we understand how gravity can make one object orbit another, we must decide which object is going to be in the center and which will do the orbiting. In the case of the Earth and the Sun, the much larger Sun is obviously the central object, but what if the two objects are equal in size?

Figure 3.7: Center of mass



The truth is that in a system of two bodies, neither one will be absolutely stationary at the center of the orbit. Instead, both objects will orbit about their common center of mass, a point called the **barycenter**, shown in Figure 3.7. The barycenter lies closer to the more massive object. (In the Earth-Sun system, the barycenter is actually inside the Sun, and in the Earth-Moon system, the barycenter is inside the Earth.)

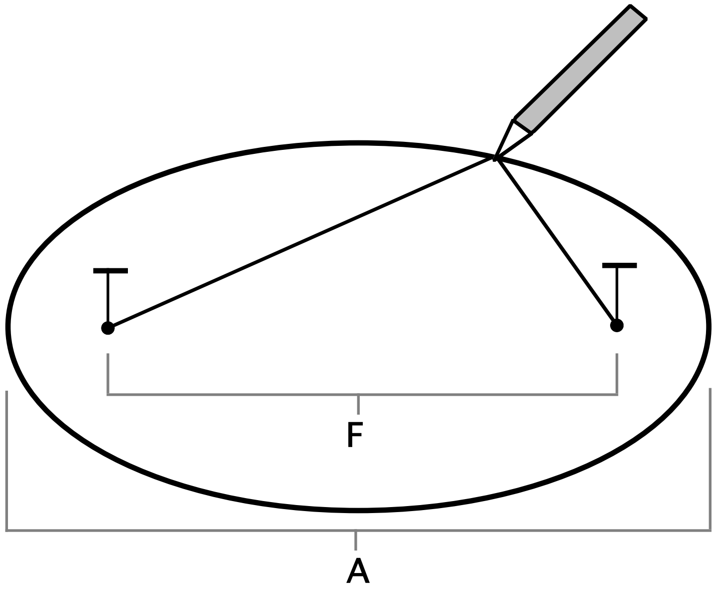
Orbital Shapes

Having determined the cause of orbital motion, we should next investigate the shape of the orbit. In the case of the tennis ball on the string, the shape was a circle because the string had a fixed length. But in real situations where gravity provides the force, the distance is not fixed by anything and may vary around the orbit. The shape for most orbits that we will encounter is not the circle but rather the **ellipse**.

The ellipse is a geometric curve that is easier to draw than to explain. It can be described as a flattened circle; in fact a circle is a special case of an ellipse. The ellipse is drawn by first marking two points called foci (one **focus**, two **foci**). Stick a thumbtack in each focus, connect a length of string between the two tacks, and trace out the ellipse with a pencil as shown in Figure 3.8.

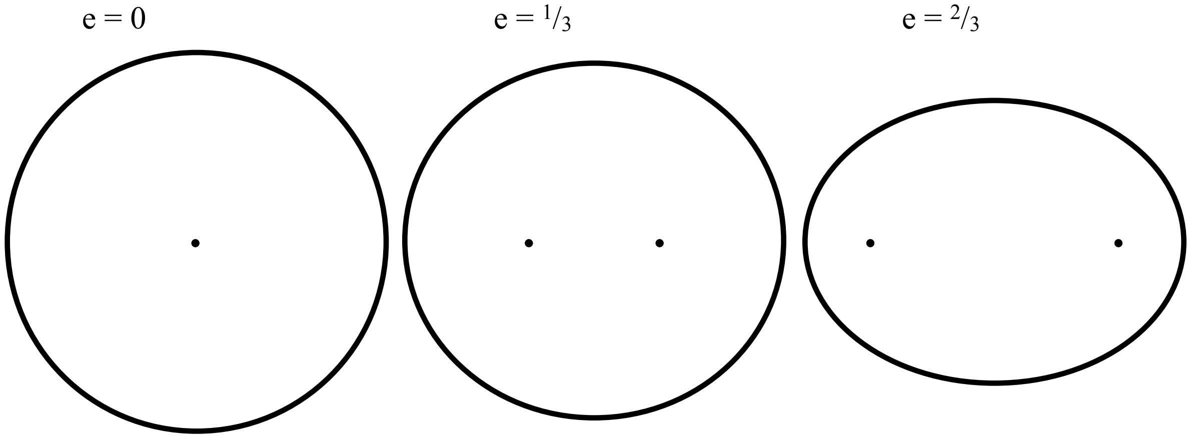
The shape of the ellipse you draw will depend on the length of the string (*L*) and the separation of the two foci (*F*). The length of the ellipse will be approximately equal to the length of the string. The degree of flattening, is measured by the **eccentricity (*e*)**, which is the ratio of *F* to *L* ($e = F/L$). The eccentricity varies from 0 to 1 as the flattening increases.

Figure 3.8: Drawing an ellipse



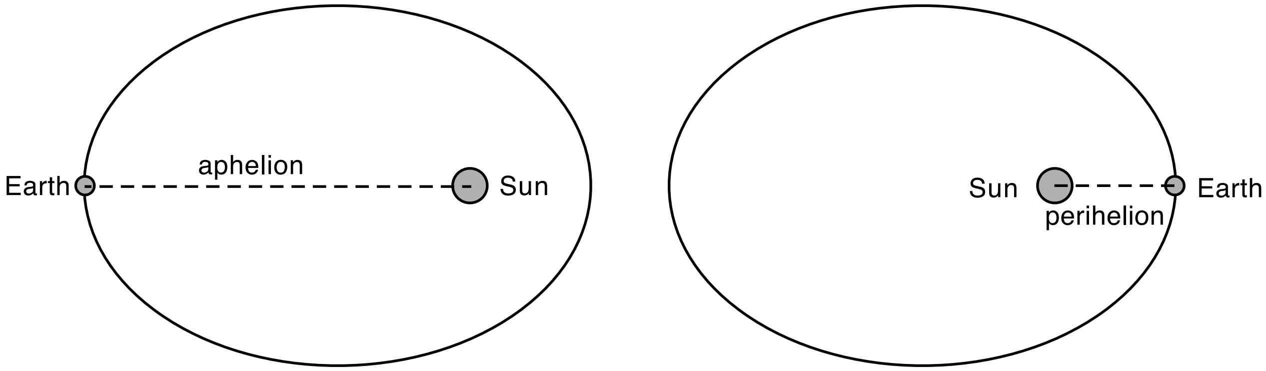
Examples of three ellipses with the same length but different eccentricities are shown in the Figure 3.9. The first one has an eccentricity of 0 and is, in fact, a circle. Note how the separation of the foci increases with the eccentricity.

Figure 3.9: Ellipses of different eccentricities



The orbits we have been discussing are ellipses. In a two-body system, both bodies would describe ellipses about the barycenter, with the barycenter located at one focus of each ellipse. We can get a much simpler picture of the motion by holding one body stationary at one focus while the other body travels around the ellipse. In the case of the Earth-Sun system, the Sun lies at one focus, and the Earth travels around the ellipse. In doing so, the Earth changes its distance from the Sun. Its closest approach is called **perihelion** while its farthest distance is **aphelion**. These distances can be easily calculated for an orbit from the eccentricity (e) and the average distance (a) as follows:

Figure 3.10: Aphelion and perihelion in the Earth's elliptical orbit

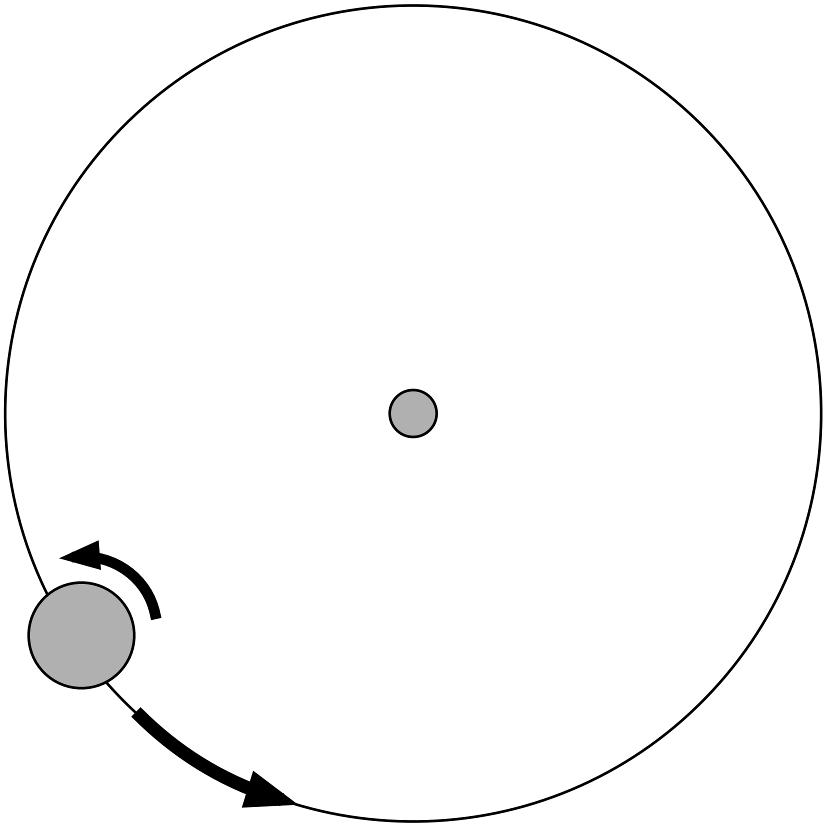


aphelion: $r_{max} = a(1 + e)$ perihelion: $r_{min} = a(1 - e)$

We have already seen (in Chapter 2) that the (average) distance of the Earth from the Sun is 150 million kilometers, a distance we will define to be one **astronomical unit (AU)**. When we combine this value with the Earth's orbital eccentricity of 0.017, we find that the Earth's distance from the Sun varies between 0.983 AUs at perihelion and 1.017 AUs at aphelion – not a huge variation. Of the three ellipses shown in Figure 3.9, the Earth's orbit most closely resembles the first one (the circle). Another quantity that varies around the orbit is the speed of the orbiting body. In general, the orbital speed will be higher when the two bodies are closer together (near perihelion) and slower when they are farther apart (near aphelion).

We are now prepared to study some of the more obvious consequences of orbital motion, such as seasons (Chapter 4), moon phases (Chapter 5), eclipses (Chapter 6), the solar system (Chapter 7), and motions of the night sky (Chapter 9).

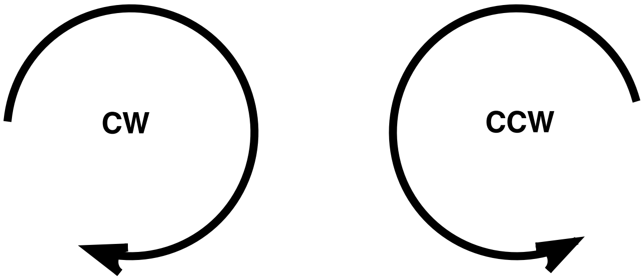
Chapter 4: Earth Motions and Seasons



Revolution

In the previous chapter, we established that Earth travels in a nearly circular orbit about the Sun. We call this motion **revolution** and say that the Earth **revolves** about the Sun. Which direction does it revolve? There are two possibilities, which we will designate as **clockwise** (CW) and **counterclockwise** (CCW), directions that should be familiar to those who have a clock with hands that move (see Figure 4.1).

Figure 4.1: Clockwise vs. counterclockwise



Of course there is the problem of perspective: our specification of clockwise or counterclockwise depends on where we stand to view the orbit. If you look at Figure 4.1 from behind the page (through the paper), you will find the two directions are now reversed. We must either report our viewpoint each time we use clockwise or counterclockwise or adopt a convention to insure that we always view orbits from the same direction. The latter is usually done; the convention is to observe the orbit from the northern side – that is, the side from which we can see most of the Earth's northern hemisphere. (**North** will be explained very shortly.) With this convention we can say that the Earth's revolution is counterclockwise.

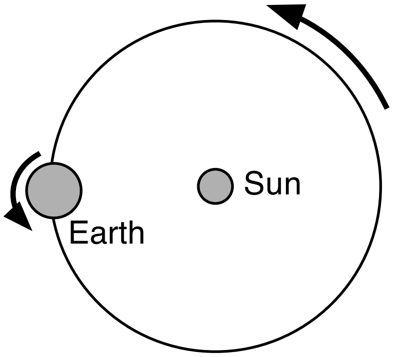
Rotation

In addition to its revolution, the Earth has another motion: it spins on its axis, in the manner of a spinning top, only much more slowly. We call this motion **rotation** and say that the Earth **rotates** on its axis.

> Note that although rotation and revolution refer to two distinct motions of the Earth, they are often confused with each other because the words look and sound somewhat alike. We will be careful to distinguish between them.

Which direction does the Earth rotate? Again there are two possibilities, clockwise and counterclockwise. Using our convention, we will find that the Earth's rotation is counterclockwise, the same as its revolution, as shown in Figure 4.2.

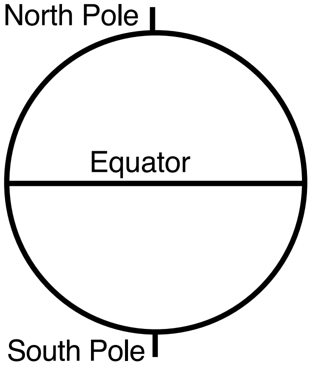
Figure 4.2: Earth's rotation and revolution directions



> You may wonder why the Earth rotates and revolves in the same direction. The answer is that the motions of the Earth (and the other planets) were established during the time of the formation of our **solar system** (see Chapter 7), and they have likely not been modified substantially since then.

The Earth's rotation on its axis defines several special points on the Earth's surface for us, as shown in Figure 4.3. The two points where the axis intersects the surface of the Earth are called the **North** and **South Poles**. If we locate all points on the Earth's surface that are equidistant from both poles, we will identify the **equator**.

Figure 4.3: Rotation-defined features

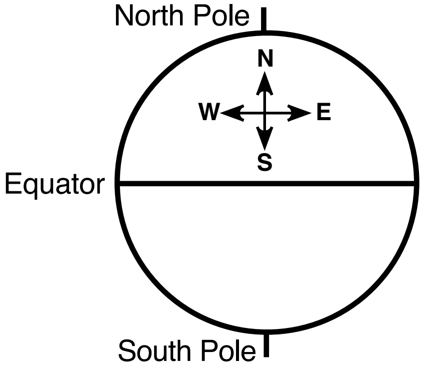


> Note that the equator and the poles are defined by the rotation of the Earth. If the Earth did not rotate, we would not be able to identify these special points – at least, not in the same manner. Therefore, it is best to discuss the rotation first, followed by the poles and equator.

Directions

Having introduced the poles and equator, we can now talk about **directions** on the Earth. We are familiar with the terms **north**, **south**, **east**, and **west**, but what do they mean? Do you know your directions? Can you point to the north? What are you pointing at when you point north? The answer is simple: North is the direction of the North Pole. South is the direction of the South Pole, and east and west are parallel to the equator, as shown in Figure 4.4. All four directions lie in the plane that is tangent to the Earth's surface at the point in question; even though you would actually have to follow the curve of the Earth to get to the North Pole, we define north as the direction you would start walking to get there.

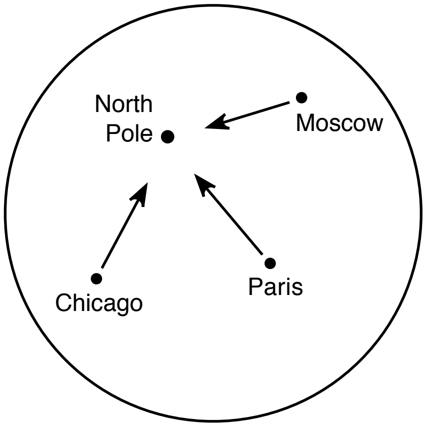
Figure 4.4: Directions on Earth



> If you look at a globe and choose a city on it, it is easy to establish which direction is north at that city. Now choose several other cities and find north for each. You should note that persons pointing north from

each city would not all be pointing in the same direction in space (see Figure 4.5). Some people find this fact confusing, but it is just a consequence of our living on a spherical Earth.

Figure 4.5: Directions on a sphere

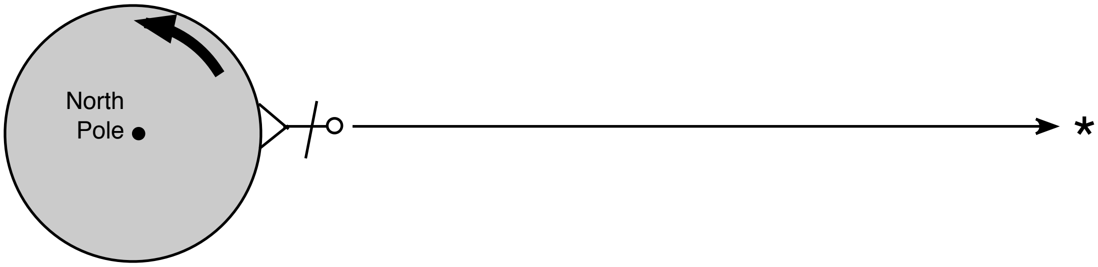


Day and Night

The Sun shines on the Earth, illuminating one half of its surface at a time. We call the time we spend in the illuminated half the **day**; the time spent in the darkened half is the **night**. Rotation of the Earth causes day and night to alternate (for most locations) as we are carried into and out of the darkness by the turning Earth. Rotation causes the Sun to appear to move across the sky, much as your surroundings seem to move if you twirl yourself about. We use this apparent motion of the Sun as a basis for keeping time. Conversely, knowing the time tells us where the Sun is in the sky. Our abbreviations for morning and afternoon, **a.m.** and **p.m.,** stand for **ante-meridiem** and **post-meridiem**. These tell us whether the Sun is before (ante-) or after (post-) the **meridian**, the imaginary line that passes overhead in a north-south direction and divides the sky into an eastern half and a western half.

How long is one day? (We must be careful to define what we mean here because the word day could refer to a complete rotation (daytime and nighttime) or only to the daytime.) Suppose we picture the Earth as shown in Figure 4.6, with a particular star directly above the observer. As the Earth rotates, the star will move slowly across the observer's sky. How long will it be before the star is again overhead for the observer? The answer is an interval of time we call one **sidereal day**, which is equal to **23^{h} 56^{m} 04^{s}**.

Figure 4.6: The sidereal day



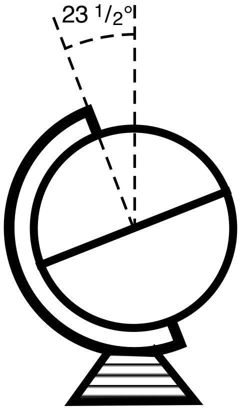
There is another way to measure the day. Suppose that in place of the star in Figure 4.6, we put the Sun. As the Earth turns, the Sun appears to move across the sky. How long will it be before the observer sees the Sun directly overhead again? This will be an interval of time we call the **solar day**, which is equal to **24^{h}**. (The reason for the small difference between the sidereal day and the solar day involves Earth's revolution; this topic will be discussed in more detail in Chapter 9.) Because we humans prefer to coordinate our activities with the position of the Sun in the sky, we use the solar day as the basis of our time keeping system, and our clocks measure **solar time**. Thus, the Earth's **rotation period** is about one day.

> If we were more interested in observing certain stars, we might want to use **sidereal time** (based on the sidereal day) to mark the Earth's rotation. Sidereal time is used primarily by astronomers.

Obliquity

We have mentioned that the Earth rotates about an imaginary axis through the North and South Poles. We can also consider the Earth to be revolving about another imaginary axis through the center of the orbit and perpendicular to the plane of the orbit. Thus we have two axes – a rotational axis and an orbital axis. How do these two axes compare? Are they parallel or do they make some arbitrary angle with each other?

Figure 4.7: Earth's obliquity



As the Earth's two motions are distinct and independent of each other, there is no reason for the axes to be related in any special way. In fact, the two axes are *not* parallel but are inclined to each other by about 23 $^1/_2$ degrees, an angle referred to as the **obliquity**, or sometimes the tilt. Figure 4.7 shows a typical globe, with its rotational axis tilted by 23 $^1/_2$ degrees to the perpendicular, which in turn represents the orbital axis. The table top is parallel to the plane of the Earth globe's orbit.

Equinoxes and Solstices

We have already said that the Earth revolves about the Sun. The time required for each revolution is one year (the **revolution period**). In Figure 4.8 we see the Earth in its orbit about the Sun, with the rotational axis oriented vertically on the page and the orbital axis angled by 23 $^1/_2$ degrees with respect to it. Note that as the Earth orbits the Sun, the rotational axis does not change its orientation but instead remains pointed in the same direction in space.

Something else is noticeable in the diagram: The orientation of the Sun with respect to the Earth's equator seems to change. For the Earth on the left, the Sun appears to be south of the equator and would be seen directly overhead at a point in the southern hemisphere. For the Earth on the right, the Sun appears to be *north* of the equator and would be seen directly overhead at a point in the *northern* hemisphere. Over the whole orbit the Sun appears to move alternately northward and southward in the sky. Due to the Earth's tilt, the Sun appears to move as far south as 23 $^1/_2$ degrees south latitude, a circle on the Earth called the **tropic of Capricorn**, and it appears to move as far north as the **tropic of Cancer**, at 23 $^1/_2$ degrees north latitude. These locations are indicated in Figure 4.8.

Figure 4.8: Tropics of Cancer and Capricorn

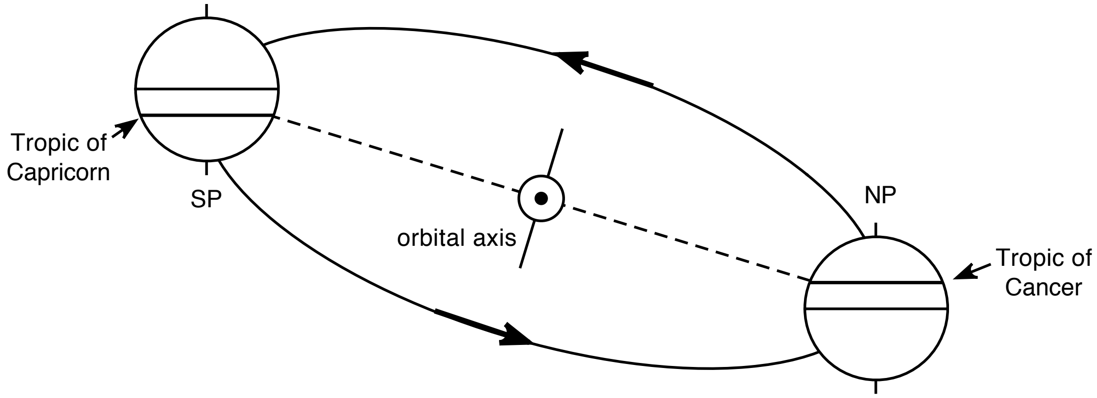
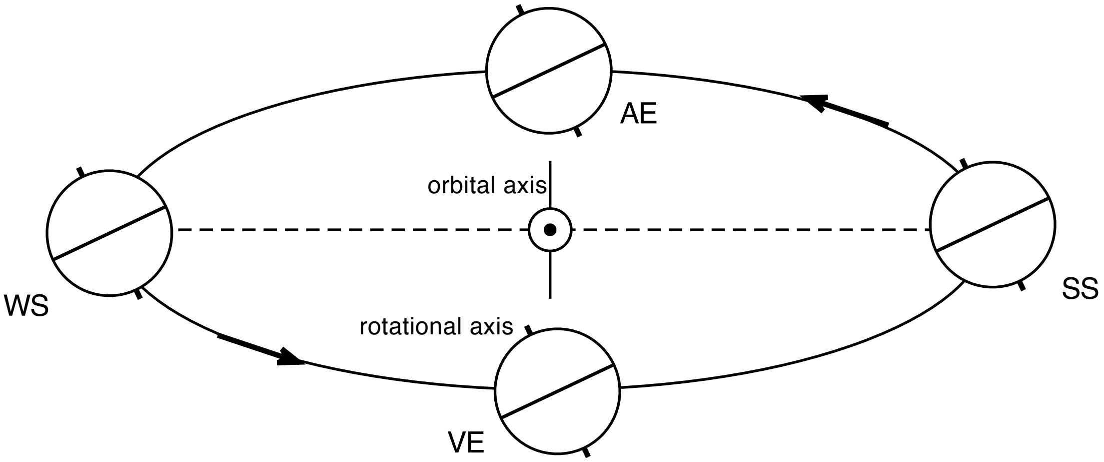


Figure 4.9 shows another view of the Earth-Sun system, one in which the orbital axis is oriented vertically and the rotational axis is tilted. Again notice that as the Earth orbits the Sun, the rotational axis remains pointed in the same direction in space. Now we see that the Earth's North Pole (by convention the one towards the top of each Earth) tips towards or away from the Sun as the Earth moves around its orbit. On the left Earth, the North Pole has its greatest tilt away from the Sun. We call this position the **winter solstice** (WS). On the right Earth, the North Pole has its greatest tilt towards from the Sun. We call this position the **summer solstice** (SS). At the intermediate positions shown, the North Pole is tilted neither towards nor away from the Sun; these positions are called the **vernal equinox** (VE) and the **autumnal equinox** (AE).

Figure 4.9: Solstices and equinoxes



Because the Earth's revolution period is one year, the equinoxes and solstices occur on an annual basis at about the same time each year. The following table shows the dates of each of these events:

Vernal Equinox	**March 20-21**
Summer Solstice	**June 20-21**
Autumnal Equinox	**September 22-23**
Winter Solstice	**December 21-22**

The main reason for the two-day spread is that the length of the year is not an integral number of days, but instead contains a fractional day, as discussed below. Every four years this fractional portion adds up to an extra day, which is inserted during leap year. Thus, while the vernal equinox appears to be moving around over a two-day interval from year to year, it is really our calendar that is shifting to keep pace with the astronomical event we call the vernal equinox. Additionally, the time and date where you are depend on your longitude (east/west position on the Earth); the dates shown above are chosen to match the variation in solstice and equinox dates experienced by North American observers during the current era.

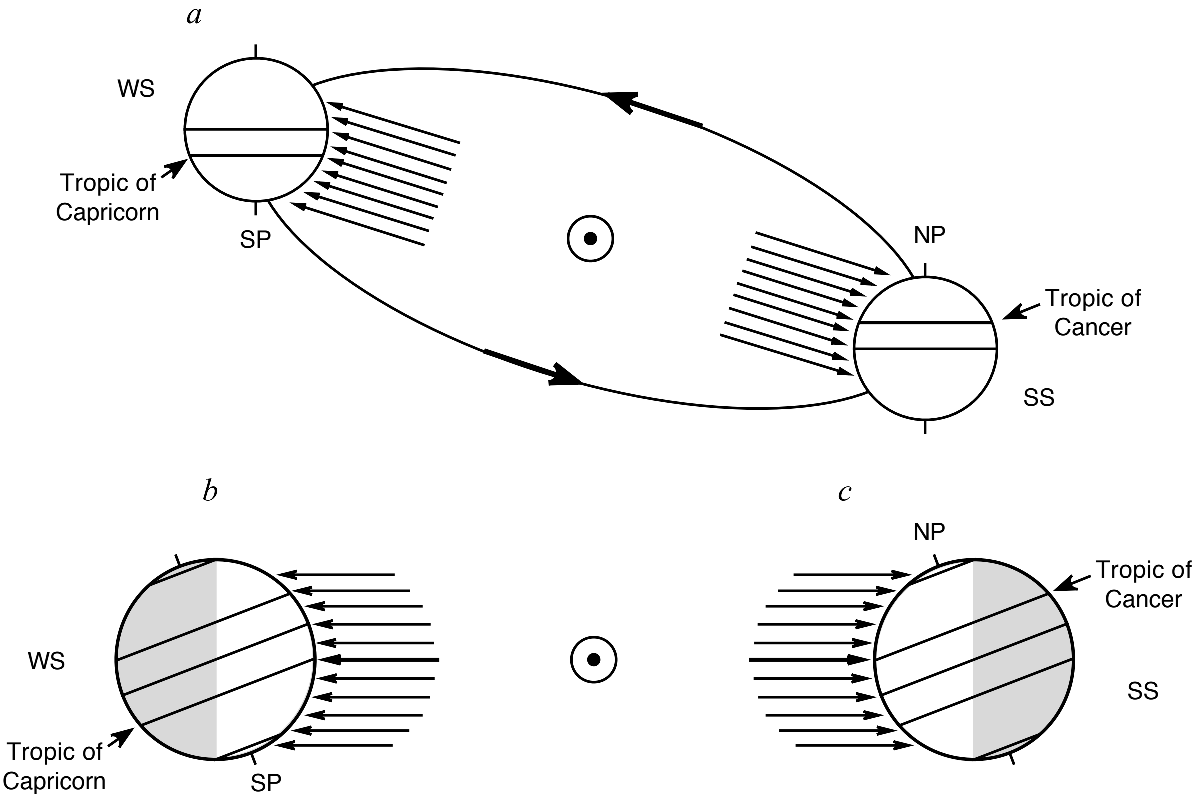
The Year

Just how long is one year? We saw that the length of a day depends on how we define it. The same is true for the year. We can define the revolution period (the year) in terms of the stars: Line up the Earth, the Sun, and a star, start the revolution, and measure how long it takes to get the Earth, Sun, and star in line once again. This interval is called the **sidereal year**, and its length is **365.256366 days** or **$365^{d}\ 6^{h}\ 9^{m}\ 10^{s}$**. Or we could use a different reference – the vernal equinox. Measure the time from one vernal equinox to the next. This interval is called the **tropical year**, and its length is **365.242199 days** or **$365^{d}\ 5^{h}\ 48^{m}\ 46^{s}$**, only slightly shorter than the sidereal year. (The reason for the difference will be explained later, in Chapter 10.) Although we could use either definition of the year, it makes more sense for us to use the tropical year for our calendar because it keeps better track of our **seasons**.

Seasons

You have probably noticed some seasonal-sounding names for the solstices and the equinoxes. This is because there is a definite link between the motions of the Earth and our seasons. To see what causes the seasons, let us examine the orientation of the Earth and Sun at specific points in the orbit: the winter and summer solstices.

Figure 4.10: Variation of direct rays with seasons



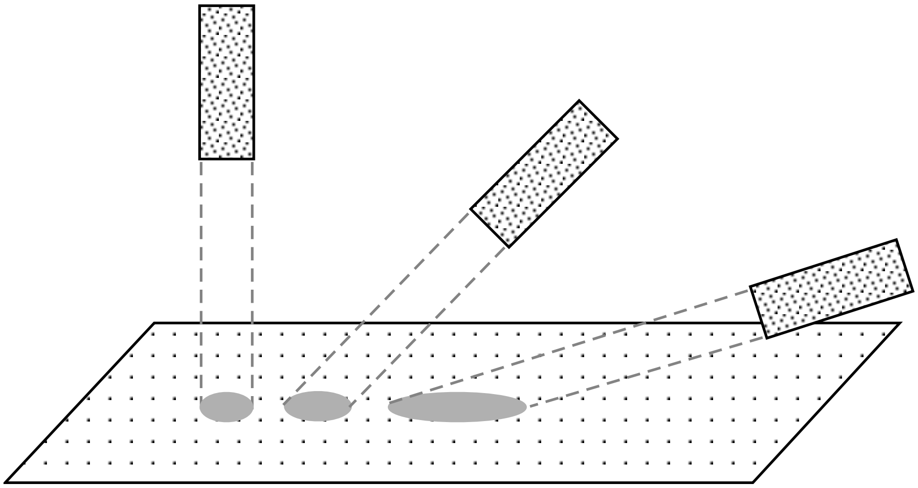
Because the Earth is a sphere, the Sun's rays strike the surface at angles that vary with location on the Earth. The Sun's rays will always fall most directly (from most nearly overhead) on the part of the Earth's surface that lies on a line between the centers of the Earth and Sun. The portion of the surface where this occurs will vary as the Earth moves around in its orbit, as shown in Figure 4.10a.

We see in Figure 4.10b that during the time of the winter solstice, the location receiving the most direct rays lies on the tropic of Capricorn, at 23 $^1/_2$ degrees south latitude. The heating effect of the Sun will be greatest in the southern hemisphere, producing summer conditions there while winter occurs in the north.

In Figure 4.10c (the summer solstice), it can be seen that the reverse is true: rays are most direct in the northern hemisphere, falling vertically on the tropic of Cancer. Greatest heating now occurs in the northern hemisphere, giving summer there while the southern hemisphere is having winter.

> Moving either north or south from these latitudes we would find that the heating effect is diminished because the Sun's rays are spread out over a greater portion of the surface, providing less energy per unit area. This can be seen be shining a flashlight at a flat surface from different angles. (See Figure 4.11) When the flashlight beam shines straight down on the surface, the rays cover the smallest area and are most concentrated. As the beam intersects the surface at a shallower angle, the beam spreads out to cover a larger area. This effect can also be demonstrated by shining a flashlight on different parts of a globe and noting the area covered by the beam.

Figure 4.11: Variation of heating effect with seasons



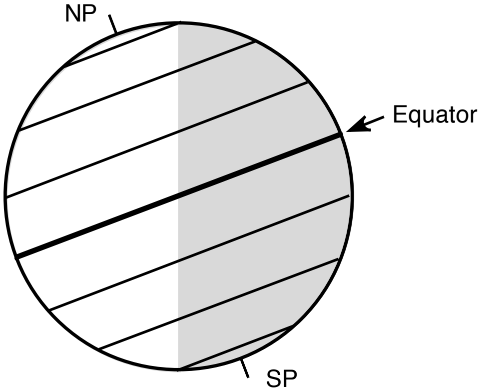
Day/Night Length

An additional effect the tilt has on the seasons can be seen in Figure 4.12, which shows the variation in day and night for various latitudes. In this figure, the North Pole is tilted toward the Sun, and more than half of the northern hemisphere is illuminated. Consequently, persons living at northern latitudes would spend more time in the daylight than the night, and they would receive more energy from the Sun. At the equator, day and night are equal in length, while in the southern hemisphere, the nights are longer than the days. The variation increases as one moves farther from the equator.

The lengths of day and night also vary with the season. At the vernal equinox, the North Pole is tilted neither toward nor away from the Sun. As a result, all latitudes spend equal time in the daylight and the darkness. As the Earth moves past the vernal equinox, the North Pole begins to tilt more and more toward the Sun and daylight becomes longer in the northern hemisphere (and shorter in the south). The extreme is reached at the summer solstice, when the daylight is longest and the night is shortest for northern latitudes. Following the solstice, the days get shorter until they equal the nights at the autumnal equinox; the days continue to get shorter until the winter solstice, after which the trend again reverses. The southern hemisphere experiences the same changes but at opposite times: their days are longest at our winter solstice and shortest at our summer solstice, with the equinoxes still having equal day and night.

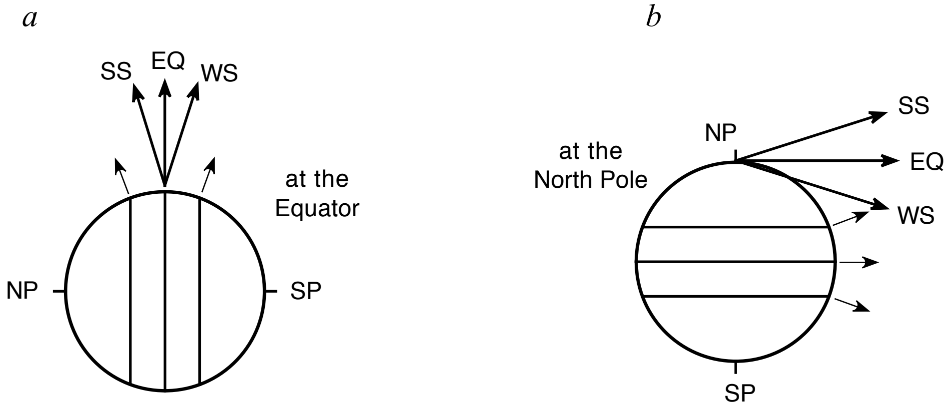
> There could be some confusion with the names of the solstices and equinoxes. The summer solstice occurs during winter in the southern hemisphere. Do residents there call it by the same name? One possible solution is to refer to the June solstice and the December solstice, the March equinox and the September equinox. In this book, we will use the usual northern hemisphere labels.

Figure 4.12: Variation of day and night length with latitude



How long are the days and nights? As mentioned above, the length depends on your latitude and the time of year. If you live at the equator, you will have 12 hours of daylight and 12 hours of darkness each day of the year, because the Sun always illuminates one half of the equator at a time. At noon on the equinoxes the Sun would be straight overhead, at a point we call the **zenith**. At the summer solstice, the noon Sun would be north of the zenith (overhead at the tropic of Cancer), while at the winter solstice, it would be south of the zenith (overhead at the tropic of Capricorn). Thus the noon Sun at the equator seems to oscillate back and forth, north and south of the zenith over the course of the year (see Figure 4.13a).

Figure 4.13: Seasonal motion of the Sun, at the Equator and the North Pole

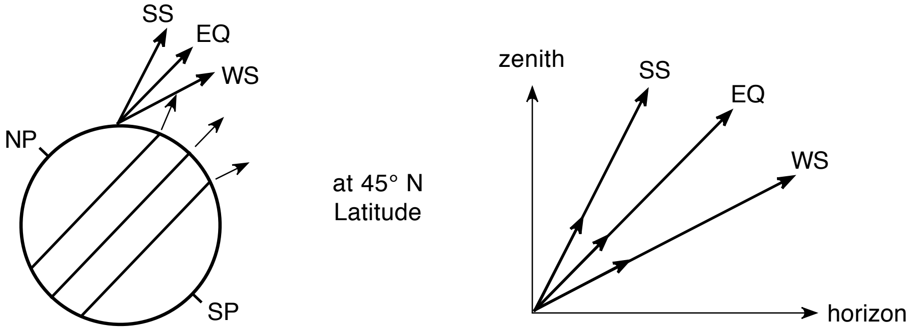


At the North Pole the story is different. At the equinox, the Sun is overhead at the equator; but for an observer at the North Pole, it will be on the **horizon** – the boundary between the sky and the ground. At the summer solstice, when the Sun is north of the zenith for equatorial observers, it will appear above (north of) the horizon at the North Pole, as shown in Figure 4.13b. As the Earth rotates, the Sun will remain above the North Pole's horizon, giving a day length of 24 hours – a phenomenon known as the **midnight sun**. At the winter solstice, the Sun will remain below the horizon of a North Pole observer as the Earth rotates, giving a night that lasts 24 hours. But if the day or night is 24 hours long, when will the Sun rise and set? The Sun rises or sets when it crosses the horizon, and for observers at the North Pole the Sun is on the horizon only at the equinoxes. Thus, sunrise will occur at the vernal equinox and sunset happens at the autumnal equinox. This means that at the North Pole, there will be six months of daylight following the vernal equinox and six months of darkness following the autumnal equinox.

Clearly, the North Pole has a very strange day/night schedule, at least by our standards. Can we experience the midnight sun without going to the North Pole? A look back at Figure 4.12 should provide the answer. If the Sun is to the left, the North Pole is in sunlight. As the Earth spins, the pole remains in the sunlight, giving the midnight sun effect. However, a person located a few degrees of latitude away from the pole would also observe the midnight sun. In fact, you could move as far away from the pole as 23 1/2 degrees and still see the Sun at midnight – but only on the summer solstice. This position at 66 1/2 degrees north latitude is called the **Arctic Circle**; the corresponding location at 66 1/2 degrees south latitude is the **Antarctic Circle**. Persons located north of the Arctic Circle or south of the Antarctic Circle will experience at least some 24-hour days and an equal number of 24-hour nights during the year, with the number being greater for locations closer to the poles.

Between these two circles, the days and nights will vary between 0 and 24 hours. At a middle latitude of 45 degrees (the Twin Cities), the variation is from about 8 1/2 hours to 15 1/2 hours. The summer solstice has 15 1/2 hours of day and 8 1/2 hours of night, while the winter solstice has 8 1/2 hours of day and 15 1/2 hours of night. The equinoxes, of course, have 12 hours of day and 12 hours of night. Closer to the equator, the variation is less extreme.

Figure 4.14: Seasonal motion of the Sun at 45° north latitude



At locations between the tropic of Cancer and the Arctic Circle – e.g. the Twin Cities at 45° north latitude – the noon Sun will be found somewhere between the zenith and the observer's southern horizon, as shown in Figure 4.14. It will be highest in the sky (closest to the zenith) on the summer solstice, and lowest in the sky (closest to the horizon) on the winter solstice. But, contrary to public opinion, it will never be directly overhead; this experience is reserved for people living in the tropics.

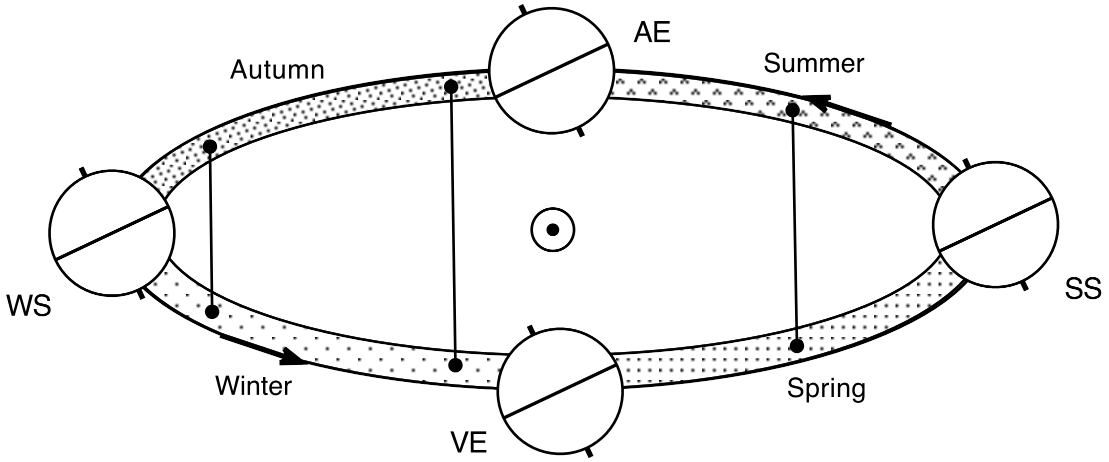
Seasons Revisited

We now understand that the seasons – spring, summer, autumn, and winter –are caused by changes in the directness of the Sun's rays and the length of daylight at a given location: direct rays and long days produce summer conditions. But when is summer? When does it start and end? Any good calendar will tell you that the start of summer is the summer solstice, and its end is the autumnal equinox. But does that make sense? If the greatest heating effect, caused by the most direct rays and the longest daylight hours, occurs on the summer solstice, shouldn't that be the *middle* of summer, rather than the beginning? Of course, our hottest weather does not usually come on the summer solstice but rather several weeks later, in late July or early August, which is the middle of summer. Why is this true?

The answer is called **thermal lag**, or the cold pizza effect. When you pull last night's pizza out of the refrigerator to heat it up for lunch, you turn on the oven to 300° and throw in the pizza. If you reach in and pull out the pizza one minute later, you will find it is still cold; in fact, the oven is not warmed up yet. If you give the oven time to warm up and then toss in the pizza for one minute, it will still be cold when you pull it out because it takes time to transfer enough heat to the pizza to raise its temperature to the desired level.

In a similar fashion, the Sun transfers heat to the Earth. The northern hemisphere gets rather cold in the winter (due to indirect rays and short days), and it spends the spring warming up. By the summer solstice, after six months of lengthening days and increasingly more direct rays, the north is still warming. In fact it does not reach its peak temperatures until midsummer, when the days have been getting shorter for several weeks. As a result of thermal lag, our seasons begin and end on the solstices and equinoxes, as shown in Figure 4.15.

Figure 4.15: Seasonal boundaries; connected dots show 'equivalent' days



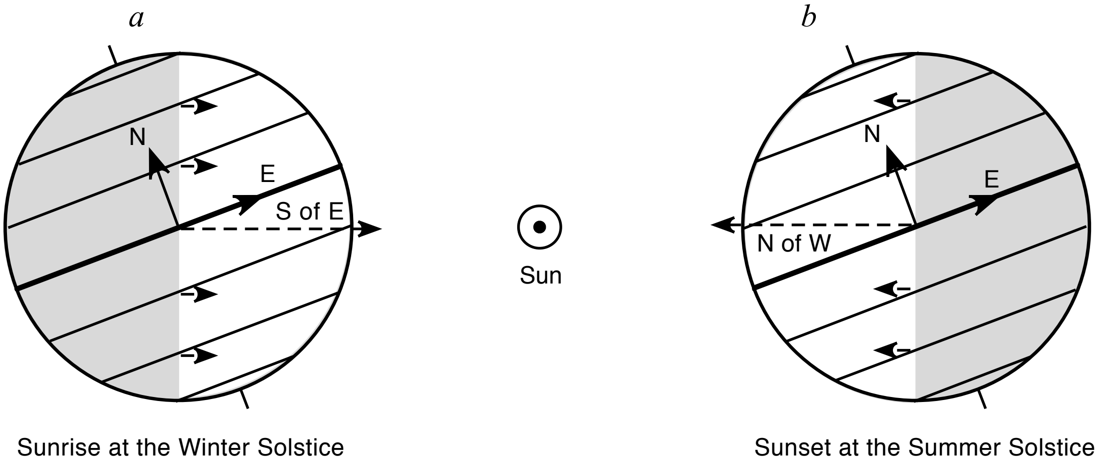
Note that our seasons are not quite as you may have pictured them. Most school children know that summer is when it is hot, and winter is when it is cold; spring and autumn are the 'in-between' seasons that join summer and winter. The perception is then that spring and autumn are similar to each other; however, a look at Figure 4.15 shows that although they are similar in temperature, they are quite different in other aspects. Astronomically speaking, spring is actually more like summer, while autumn is like winter. In both spring and summer the days are longer than the nights. For every hot summer day in late July there is a spring day in May when the Sun gets just as high in the sky, the rays are just as direct, and the day is just as long. The difference is due to the north or south motion of the Sun and thermal lag. The year is divided by the equinoxes: spring and summer are equivalent; autumn and winter are equivalent.

According to the above discussion, the Sun appears to move slowly northward and southward in the sky over the course of a year. How can we observe this motion if it occurs so slowly? And how can we safely measure the Sun's position?

Sunrise and Sunset

The Sun is relatively safe to observe as it *rises* or *sets* because its rays must pass through more of the Earth's atmosphere at that time, causing them to be less intense. We can see evidence of the Sun's gradual movement then because the directions of sunrise and sunset *change* with the seasons.

Figure 4.16: Sunrise and sunset directions (1)



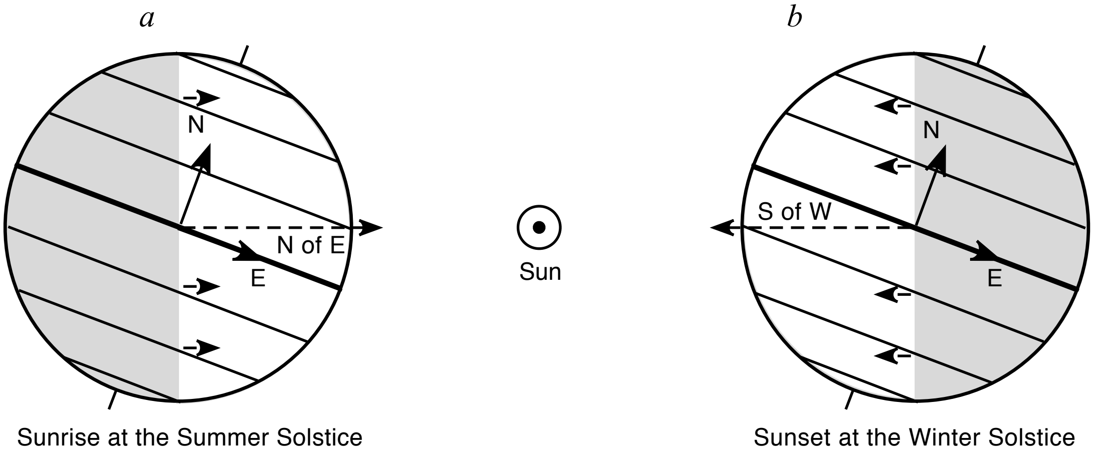
In Figure 4.16a we see the Earth at the winter solstice position; the Sun illuminates half of the Earth as shown. Because the Earth rotates eastward, the boundary between night and day marks the location where people are experiencing *sunrise*. If people along this boundary point toward the Sun, they will point in the direction of the arrow labeled south of east. Figure 4.16b shows the Earth at the summer solstice position, and the day/night boundary shown is where the Sun is setting. For observers along this line, the Sun will set north of west, as indicated by the arrows.

Figure 4.17 shows the view from the opposite direction in space. From this vantage point we observe the *sunrise* boundary at the summer solstice (where the sun rises north of east, as in Figure 4.17a) and the *sunset* boundary at the winter solstice (where the sun sets south of west, as in Figure 4.17b).

The solstices mark the extreme directions of sunrise and sunset. During the rest of the year the sunrise and sunset will vary as follows: On the equinoxes, the Sun rises directly east and sets directly west; during (the northern hemisphere's) autumn and winter, it rises *south* of east and sets *south* of west; and during (the northern hemisphere's) spring and summer, it rises *north* of east and sets *north* of west.

> Some people carry false information about the Sun's motions. They believe that it always rises directly east and sets directly west (and is straight overhead at noon). Or they may believe that the Sun will always set in the *opposite* direction from which it rises. Considering how easy it is to discover that these ideas are wrong, it is odd that they persist among the general public. Perhaps they were given incorrect information in grade school ...

Figure 4.17: Sunrise and sunset directions (2)



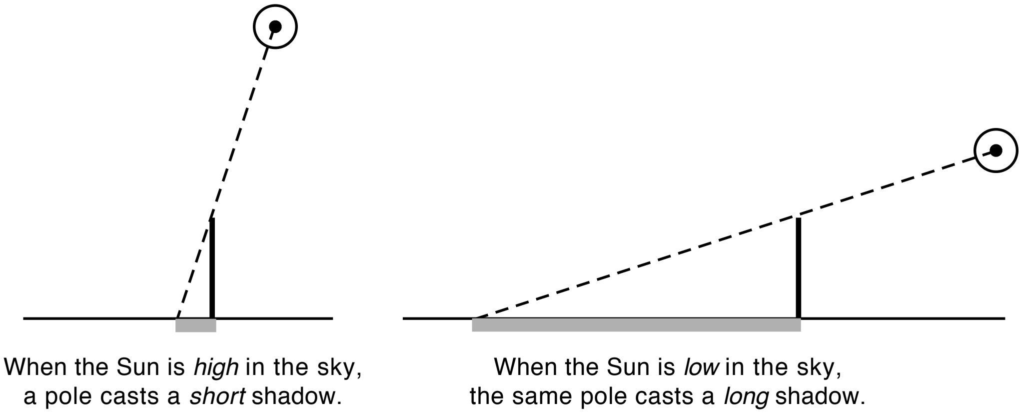
Shadows

Another way to follow the motion of the Sun is to observe shadows, noting both their direction and length; because shadows are safer to look at than the Sun is, they can be much better indicators of the Sun's motion than the Sun itself.

Most people know that a shadow always points away from the Sun. If the Sun is in the eastern sky, shadows will point toward the west; if the Sun is in the western sky, shadows will point to the east. During the middle of the day when the Sun is in the southern sky, shadows will point to the north. (The *exact* directions will vary as the Sun moves across the sky; this is why sundials work.)

The *length* of a shadow depends on how high in the sky the Sun is: the higher the Sun, the shorter the shadow, as shown in Figure 4.18.

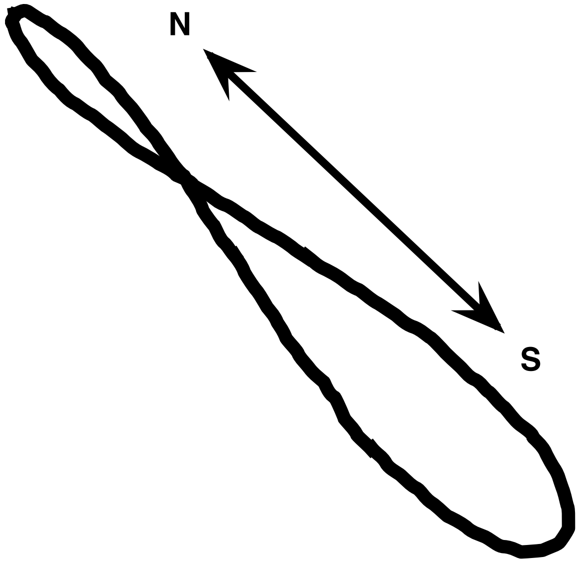
Figure 4.18: Shadow length variations



Go outside on a clear day and find a vertical pole, such as a flagpole or a fence post, that is casting a shadow (or bring a meter stick or a dowel and stand it upright). Find the tip of the shadow cast by the top of the pole and place a rock or other small marker at the tip. After a very short wait, you should notice the shadow tip moving away from the marker. If you continue placing markers at each new position of the shadow tip, you will trace out its motion, and hence, the reverse of the Sun's motion. Over the course of the day a generally (but not exclusively) eastward motion of the shadow tip will result from the Sun's westward drift. You should also see the shadow get shorter as the Sun moves higher in the morning, and get longer as it moves lower in the afternoon.

The north-south motion of the Sun with the seasons can also be traced out, but this motion takes longer to notice. This exercise again requires the shadow of some particular point on an object: the top of a pole, a dot drawn on a window pane, etc. To follow this motion you must mark the location of the shadow at the same time each day, say 10:00 each morning. You should notice the shadow markers moving farther to the north during the summer and autumn (as the Sun moves toward the south), and then back to the south in the winter and spring following the winter solstice. Over the course of a whole year, your markers for this exercise will trace out a figure-8 shape called an **analemma**, a design found on many globes (usually in the Pacific Ocean), and whose full explanation is beyond the scope of this discussion. Figure 4.19 shows an analemma traced out by the Sun in the eastern sky. Shadow markers would trace out the north/south reverse of this pattern.*

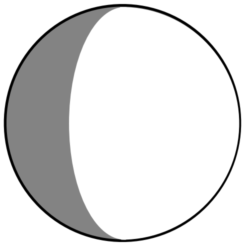
Figure 4.19: An analemma

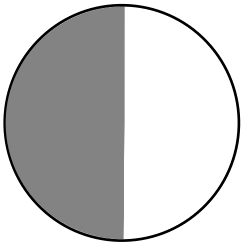


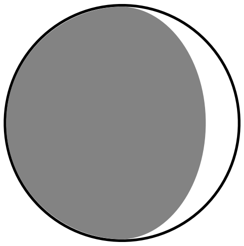
---

* See **SHADOW EXPERIMENTS** in the Appendix.

Chapter 5: Moon Motions and Phases





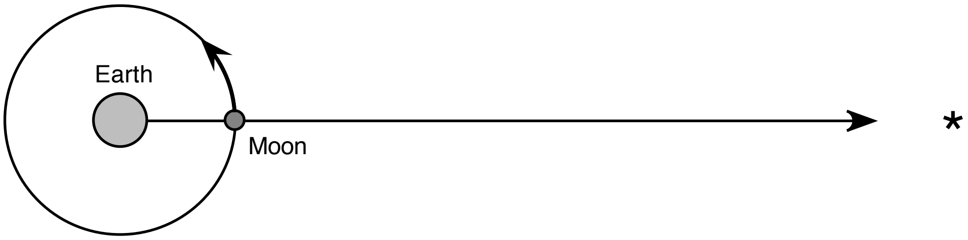


In this chapter we will discuss our nearest celestial neighbor, the Moon, introduced in Chapter 2. We will concentrate on the Moon's motions and appearance as seen from Earth; descriptions of the Moon's surface features can be found in Chapter 8.

Revolution

The Moon has motions similar to those of the Earth. The Moon revolves about the Earth in a counterclockwise direction, much as the Earth revolves about the Sun in a counterclockwise direction. In comparing the relative distances of the Sun and Moon given in Chapter 2, we see that the Sun-Earth distance is about 400 times the Earth-Moon distance. The Moon's orbit about the Earth is considerably smaller than the Earth's orbit about the Sun, and the Moon takes less time to make one orbit than does the Earth. In Chapter 4, we saw that we could measure the sidereal year by observing the revolution of the Earth with respect to a star. If we use the same basis to measure the Moon's revolution, we get the **sidereal month**, as shown in Figure 5.1.

Figure 5.1: The sidereal month



The length of a sidereal month is about 27 $^1/_3$ days. (Although the word month comes from moon, the sidereal month is not equivalent to *any* of our calendar months.) This means that every 27 $^1/_3$ days the Moon passes close to the same star, as seen from Earth. Its counterclockwise revolution carries it eastward among the stars (from right to left for a northern hemisphere observer facing south).

> The astute reader might point out here that a south-facing observer would see the Moon moving from left to right across the sky as it rises on the eastern horizon and sets on the western horizon. This is of course correct, but the rising and setting of the Moon is caused by a different motion – the rotation of the Earth – which causes the Sun, Moon, and stars all to follow an east-to-west, left-to-right motion. Our current discussion involves only the *revolution* of the Moon, which produces a west-to-east, right-to-left motion with respect to the stars.

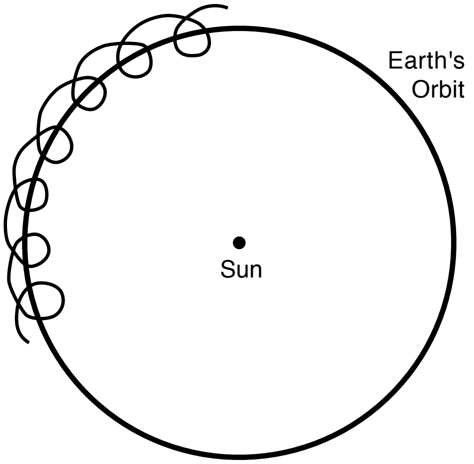
The above description of the Moon's revolution is the *simple* picture; it would be fairly accurate if the Moon and Earth were the *only* bodies in this particular corner of space. We could explain the Moon's orbital motion in terms of the Earth's gravitational attraction and the resulting centripetal acceleration, as we did for the Earth's orbit in Chapter 3. However, in Chapter 3 we explained the *Earth's* orbital motion in terms of the *Sun's* gravitational attraction. Does the Sun *also* act gravitationally on the Moon? Does the Moon try to orbit *both* the Earth and the Sun?

> If you are beginning to feel a bit queasy at this point and would rather just stick with the simple picture already presented, you may want to skip ahead to the section on rotation.

Using Newton's gravitational force equation, we can calculate the force of the Earth on the Moon, and also the force of the *Sun* on the Moon. The Earth is a lot closer to the Moon than the Sun is, but the Sun is much more massive than the Earth. The somewhat surprising result of the calculation is that the Sun exerts a gravitational force on the Moon that is approximately *twice as strong* as the Earth's gravitational force on the Moon. What does this say about the Moon's motion? It implies that the Moon should be orbiting the *Sun* instead of the *Earth*! How can that be if we see the Moon orbiting us?

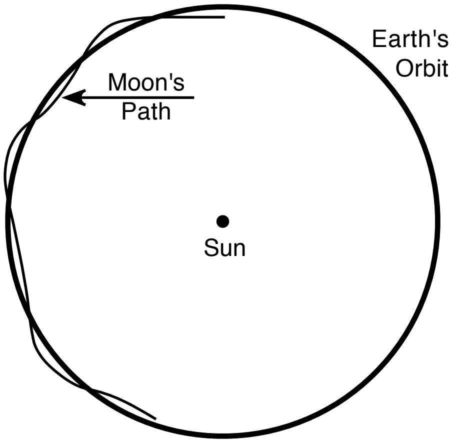
Suppose that for a moment we go back to our first description of the Moon's revolution about the Earth. What path does the Moon follow as it orbits the Earth, which in turn is orbiting the Sun? Our intuitive response might be the looping path shown in Figure 5.2. But each loop should represent a month, and there should be 12 or 13 of these each year. Clearly, this diagram would have too many loops around the orbit to match reality.

Figure 5.2: The looping lunar orbit



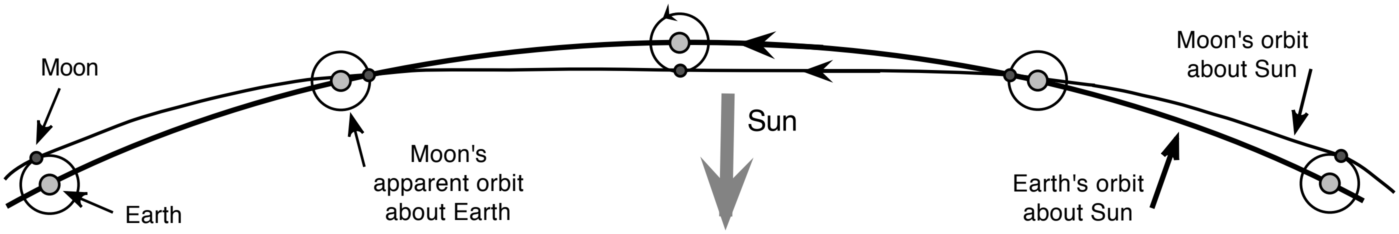
A more accurate path is shown in Figure 5.3, in which the Moon weaves in and out of the Earth's orbit. In this picture, the Moon does *not* loop around the Earth at all; it continuously moves *forward* along the Earth's orbit, *without backing up*. Why is it then that it appears to *circle* us each month?

Figure 5.3: The weaving lunar orbit



The circling is, of course, an illusion, but one that can be explained quite easily. Imagine yourself driving a car along the freeway. When you approach a slower car in your lane, you pull out to pass in the left lane. As you pass the car, it appears to move backwards on your right – an illusion created by your higher speed. Once you get ahead of the car, you pull back into the right lane; immediately, the other car pulls into the left lane and speeds up to pass you. You soon see the other car moving forward on your left and pulling in front of you. From your point of view, the other car has just completed an *orbit* about you. If you pull out to pass again and repeat the sequence of events just described, you are performing the same leapfrogging motion that the Earth and Moon do as they move around the Sun together. Their sequence of steps is shown in Figure 5.4.

Figure 5.4: The weaving lunar orbit – closeup



Thus, both the Moon and the Earth orbit the Sun, remaining reasonably close together as they do so. The fact that the net gravitational forces acting on the Moon and the Earth are directed toward the Sun tells us this must be true. It also tells us that the Moon's path (if properly drawn) should always be concave toward the Sun. This is difficult to achieve on the drawings shown here because, as noted above, the Earth-Sun distance is really 400 times the Earth-Moon distance. In real life, the Moon has no problem with this constraint.

Rotation

The Moon revolves as the Earth does. But does it rotate as the Earth does? An observer in space would see the Earth turning slowly on its axis. When we look at the Moon, we can clearly see features on its surface that will easily show any similar motion. However, when we observe the Moon over a long period of time, we find that it always presents the same features to us and gives no hint of rotation. Does this mean that the Moon does not rotate?

Figure 5.5: Lunar rotation

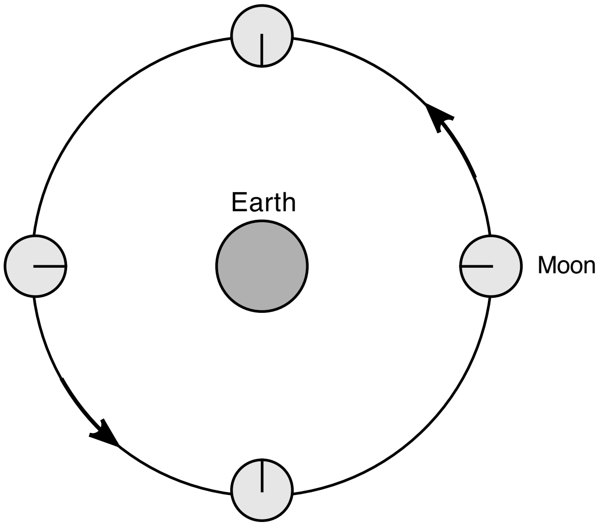


Figure 5.5 shows the Moon at four different positions in its orbit about the Earth. On each figure of the Moon a line has been drawn pointing toward the Earth. Earth-bound observers looking at the Moon would always see the side with the line, no matter where the Moon is in its orbit. But from your vantage

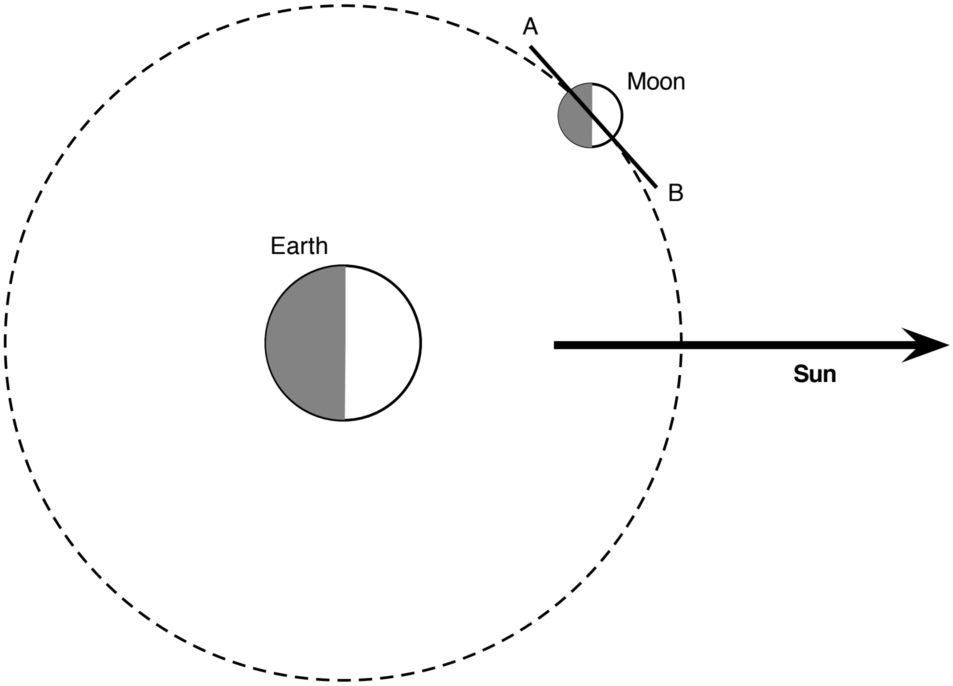
point above the page, the line is not always pointing in the same direction: on the top Moon, it points down; on the left-hand Moon, it points right; and so on. In order for the line to point in different directions (but always toward the Earth), the Moon *must* be rotating. Furthermore, it must be rotating in the same direction it revolves (counterclockwise) and at the same rate. That is, the Moon's **sidereal rotation period** is one sidereal month.

> This is a common problem in astronomy: the apparent motion of an object often depends on the location and motion of the observer. In this particular case, observers on the Earth might say that the Moon does not rotate, while those located on the distant stars would contend that it does. Because the Earth itself is moving, and its motion affects our perception of other bodies' motions, astronomers generally choose the distant (and essentially motionless) stars as the standard reference. Rotation and revolution periods given are usually sidereal periods, unless otherwise stated.*

Phases

Anyone who has observed the Moon has noticed that its shape changes gradually from day to day; these shapes are called the **phases** of the Moon. Of course, the Moon itself is not changing shape – instead it is our vantage point that is changing. Figure 5.6 shows the basic geometry that produces phases:

Figure 5.6: Cause of moon phases

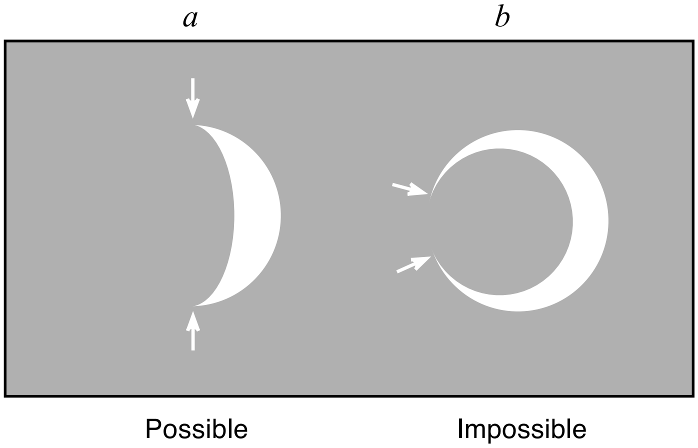


The Earth and the Moon do not generate their own light; they both shine by reflected light from the Sun. Because the Moon and Earth are spheres, the Sun illuminates only one half of each one at a time, as illustrated in Figure 5.6. Because the Moon is a sphere, we can only view one half of it at a time – the half that is turned toward the Earth (the half on the lower left side of line AB). But because the dark portion of the Moon is difficult to observe, we generally will see only the portion of the Earth-facing half that is illuminated. This portion changes as the Moon moves around its orbit, giving us the different lunar phases.

---

* See **MOON ROTATION DEMONSTRATION** in the Appendix.

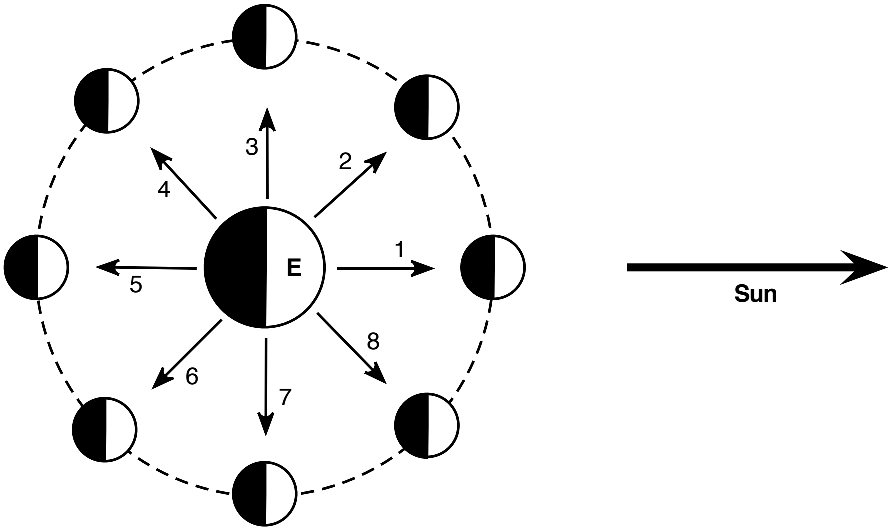
Figure 5.7: Valid/invalid moon phases



> What shapes are possible for phases? Many different representations of the Moon can be found in books, in cartoons, on flags, etc., but they are not always accurate portrayals of the Moon's appearance. To see the range of allowable phases, simply get a ping-pong ball and paint half of it black. Then view the painted ball from all possible angles; the portion of white that you see will correspond to the Moon's phases. You should notice that no matter what the phase, the line between the white and black regions of the ball always begins and ends on opposite ends of a diameter, as shown by the arrows in Figure 5.7a. Any drawing of the Moon that fails to meet this condition – such as Figure 5.7b – is inaccurate.[*]

The Moon's phases appear in sequential order as the Moon moves in its orbit about the Earth. Each day, the Moon-Earth-Sun angle changes slightly, and a different portion of the Moon will be illuminated. In Figure 5.8, we see the Moon at eight different positions in its orbit around the Earth. An observer on the Earth would see the Moon in the direction of the numbered arrow pointing toward it. We will now investigate how each phase would appear as viewed from Earth.

Figure 5.8: The cycle of lunar phases

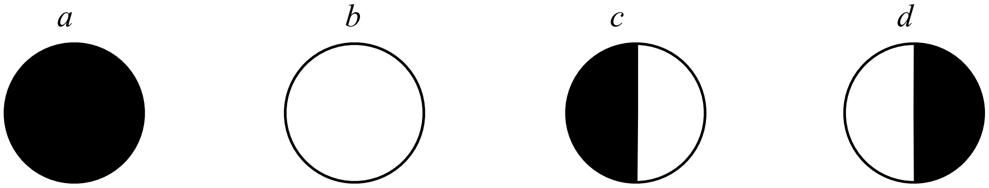


---

[*] See **PHALSE PHASES** in the Appendix; the solution is LUNAR.

Some of the phases are fairly easy to understand. For example, an observer on Earth looking at moon #1 would see only the dark side of the Moon, as shown in Figure 5.9a; on the other hand, moon #5 would appear completely illuminated, as in Figure 5.9b. (To see this, hold this page such that you are looking along the appropriate arrow from the Earth toward each moon in Figure 5.8.) Moon #3 will be half illuminated, with the bright side on the right (Figure 5.9c) while moon #7 should also be half illuminated, but with the bright side on the left (Figure 5.9d).

Figure 5.9: The principal lunar phases

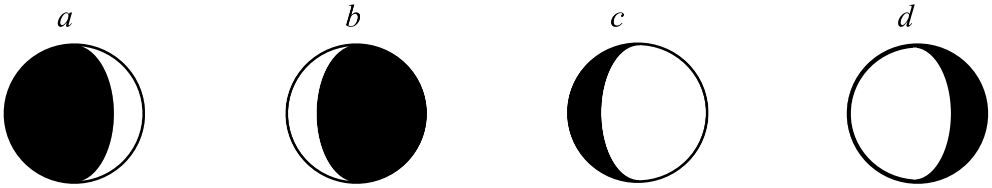


> Many people find moon #7 a bit confusing, because in Figure 5.8 the bright side is on the right, while in Figure 5.9d the bright side is on the left. Of course, *all* of the moons in Figure 5.8 have the bright side on the right because the *Sun* is on the right in that sketch; only one of the eight corresponding phases actually matches this orientation.

These four phases are the principal phases of the Moon – those noted on calendars and in almanacs. (We will name them shortly.) They occur when the Moon is in line with the Earth and Sun or at right angles to the Earth-Sun line. As such, these phases occur at precise times, on certain days of the month. The remaining four phases are not as well known, nor are they as precisely defined. In fact, their shapes vary with time, with the amount of illumination increasing or decreasing, depending on the phase.

For example, moon #2, shown midway between moons #1 and #3, could actually occur anywhere between those two phases. As seen from the Earth, moon #2 would appear to be mostly dark, with the bright side on the observer's right side. It should look something like Figure 5.10a. Moon #7 is similar, but with the bright side on the left, as in Figure 5.10b. Moon #4 will be mostly light, with the dark side on the left (Figure 5.10c), and moon #6 will be the same, but with the dark side on the right (Figure 5.10d). The amount of illumination changes from day to day.

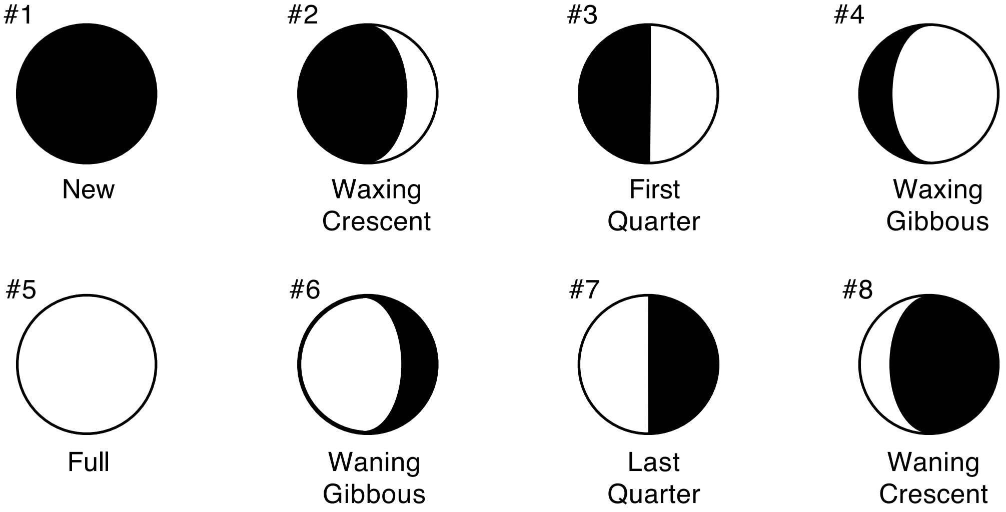
Figure 5.10: Additional phases



> It should be noted here that the Moon does not always appear as shown in books (including this one) 'standing' straight up and down, with light and dark portions on either the right or the left. The curvature of the Earth and the observer's location combine to make the Moon appear to be on its side or even upside down, compared to its depiction here. In fact, readers in the southern hemisphere would do well to rotate the page 180° when looking at these moon phase pictures.

As the Moon moves counterclockwise around its orbit (as in Figure 5.8), it proceeds through all eight phases in numerical order, as shown in Figure 5.11. Also shown in this figure are the official names of the eight phases.

Figure 5.11: Names of lunar phases



Some explanation of the terms should help in understanding them. **New** and **full** phases are the easiest to learn, being all dark or all light, respectively. The **first quarter** and **last quarter** moons are half illuminated and are therefore often called 'half' moons, although this term is not used as the official name. The last quarter moon is also called a **third quarter** moon; either term is acceptable. A **crescent** moon shows us a surface that is less than half illuminated; a **gibbous** moon presents a surface that is more than half illuminated. When the Moon is **waxing** (from new to first quarter to full), the illuminated fraction of the face towards us *increases*; when the Moon is **waning** (from full to last quarter to new), this illuminated fraction *decreases*. The gibbous and crescent phases are most commonly observed: they fill in the time between the special alignments that cause the new, full, and quarter phases.

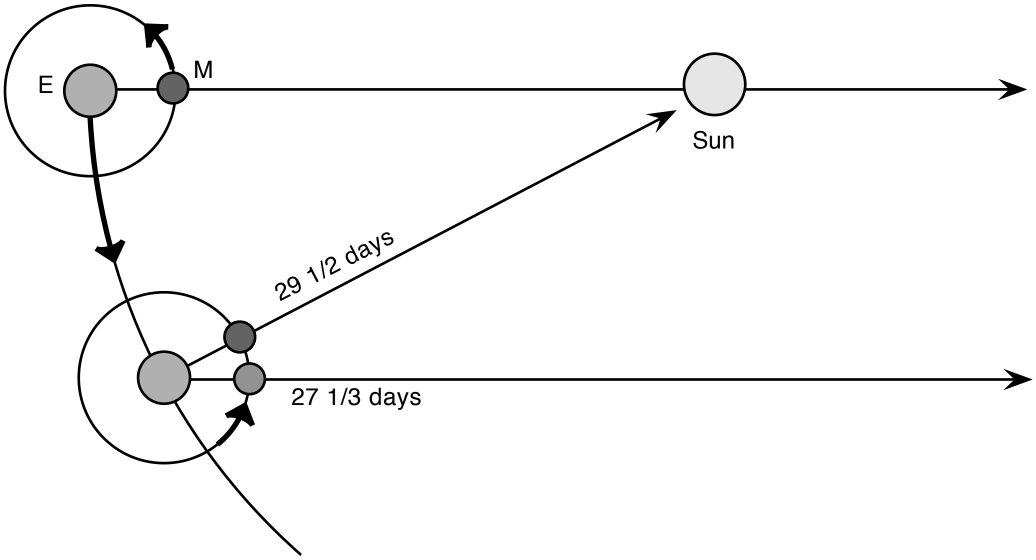
The Synodic Month

The Moon cycles through its phases every month in a time of about $29\ ^{1}/_{2}$ days from new moon to new moon, an interval called a **synodic month**. You should note that this period is slightly different from the previously defined *sidereal month*, which is about $27\ ^{1}/_{3}$ days. The reason for the difference lies in their definitions: while the sidereal month is the period of revolution of the Moon (about the Earth) with respect to the *stars*, the synodic month is the period of revolution of the Moon (about the Earth) with respect to the body that illuminates the Moon and causes its phases – the *Sun*.

While the sidereal month measured the time required for the Moon to orbit once and line up again with the Earth and a distant star, the synodic month measures the time required for the Moon to orbit once and line up again with the Earth and the Sun. If the Earth did not move during this time, the sidereal and synodic months would be the same. Because the Earth *does* move in its orbit around the Sun, the Moon needs about two extra days to catch up to the Sun after it has realigned itself with the distant star, as shown in Figure 5.12.

It takes the Moon about $29\ ^{1}/_{2}$ days to go from new moon to new moon or from full moon to full moon, etc. The interval between new and full moons is about two weeks, while from new moon to first quarter requires about one week. Thus, the principal phases occur at intervals of about one week, with the intervening crescent and gibbous phases each lasting about one week. Although the Moon may appear to be full for *several* days, it is really only full for an instant on one day. Before that time it is a waxing gibbous moon, and afterwards it is a waning gibbous moon.

Figure 5.12: The synodic month

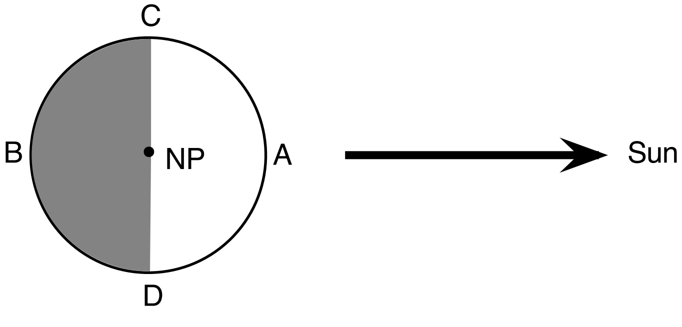


Moonrise and Moonset

We have seen how the rotation of the Earth causes the Sun to rise and set (at least at most latitudes). The Earth's rotation also causes the *Moon* to rise and set. However, the constant orbital motion of the Moon makes it rise and set at times that vary from day to day as the Moon shifts its phases. In order to know when to watch for the Moon to rise, we must know its current phase.

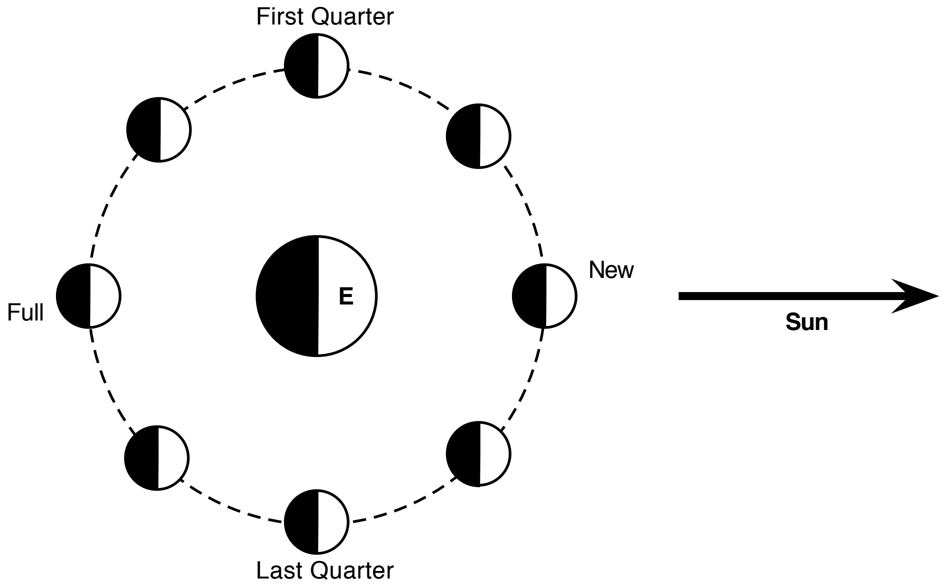
The times of moonrise and moonset are really quite easy to learn if we simplify both the Moon and the clock. Let us consider only the four principal phases, which rise and set at just four different times of the day and night: sunrise, noon, sunset, and midnight.

Figure 5.13: Moonrise/moonset times



The time of day or night depends on your location on the Earth with respect to the Sun. For a person standing in the middle of the illuminated side of the Earth (point A in Figure 5.13), the time should be noon, while midnight occurs for people in the middle of the dark side of the Earth (point B). Observers at points C and D, on the boundary between light and dark, must be experiencing either sunrise or sunset, but which is which? If we note that we are looking down on the North Pole and recall that the Earth rotates counterclockwise, we can immediately deduce that it is sunset at point C and sunrise at point D.

Figure 5.14: Geometry of principal lunar phases



Now we return to the task of determining when the Moon rises and sets. Using Figure 5.14, we see that any observer on the Earth who is looking in the direction of the new moon must also be looking in the direction of the Sun. Because the Sun and the new moon lie in the same direction in space, they must rise and set together. Thus, the new moon rises at sunrise, sets at sunset, and is highest in the sky at noon.

The full moon lies in the opposite direction from the new moon and the Sun, as seen from Earth. This means that when the Sun is rising on the eastern horizon, the full moon would appear in the opposite direction (on the western horizon) where it would be setting. As the full moon is opposite the Sun, it must rise at sunset and set at sunrise.

The first quarter moon comes after the new moon but before the full moon. Accordingly, it rises after sunrise (when the new moon rises) but before sunset (when the full moon rises): the first quarter moon rises around noon. Using similar reasoning, we see that the first quarter moon should set around midnight, the last quarter moon should rise at midnight, etc. The following table shows the rising and setting times for the four principal phases. Note the progression of times, both across and down the table.

Phase	**Rises**	**Highest in the sky**	**Sets**
New	**Sunrise**	**Noon**	**Sunset**
First Quarter	**Noon**	**Sunset**	**Midnight**
Full	**Sunset**	**Midnight**	**Sunrise**
Last Quarter	**Midnight**	**Sunrise**	**Noon**

Rising and setting times for the crescent and gibbous phases can also be deduced from this table: for example, the waxing crescent moon should rise between sunrise and noon and set between sunset and midnight. The closer to first quarter the waxing crescent is, the closer to noon it will rise.

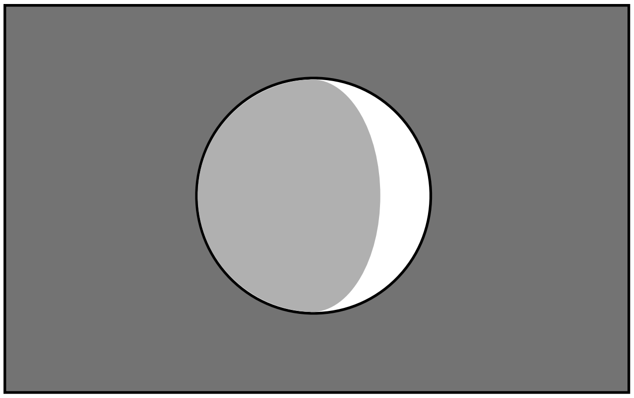
The table points out some interesting facts about the Moon's behavior. Although many people would contend that the Moon is only up at night, it is clear that this is not the case. The full moon is up all night, but the new moon is up all day, and the quarter moons are up half of the day and half of the night. Therefore we conclude that the Moon is above the horizon half of the time, with the daytime and nighttime getting equal shares of the Moon's time. However, they do not get equal shares of the Moon's light. The full moon is very bright and easy to see at night, while the dark new moon is nearly impossible to see in the bright daytime sky. Thus, the Moon is much more obvious when it is above the horizon at night, but it can be seen in the daytime sky if the phase is right.

What moon phase might be visible to observers around 9 a.m. and where in the sky would the Moon appear? The full moon would not be seen then as it sets at sunrise. Nor would the first quarter moon be available before noon. The best possibilities include the waning gibbous moon (if it is not so close to full as to have already set), the last quarter moon, and the waning crescent moon (unless it is too close to new to be visible). The waning gibbous moon would necessarily be in the western sky, away from the Sun, while the waning crescent would be closer to the Sun but still west of it. Similarly, viewers at 3 p.m. would be looking for a waxing gibbous moon in the eastern sky or a waxing crescent closer to the Sun. The Moon's constant motion and changing appearance make it an easy nighttime target and a sometimes challenging daytime object.

Earthshine

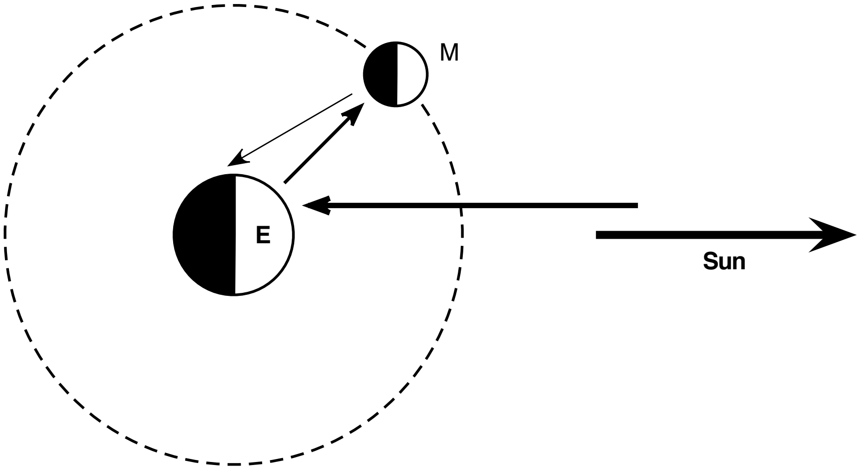
Brief mention should be made of an interesting lunar observational effect. At certain phases, the dark portion of the Moon gives off a soft glow, allowing the full circle of the Moon to be seen (Figure 5.15). There may even be enough light to allow surface features to be distinguished in that region. From what source does this light come?

Figure 5.15: Earthshine



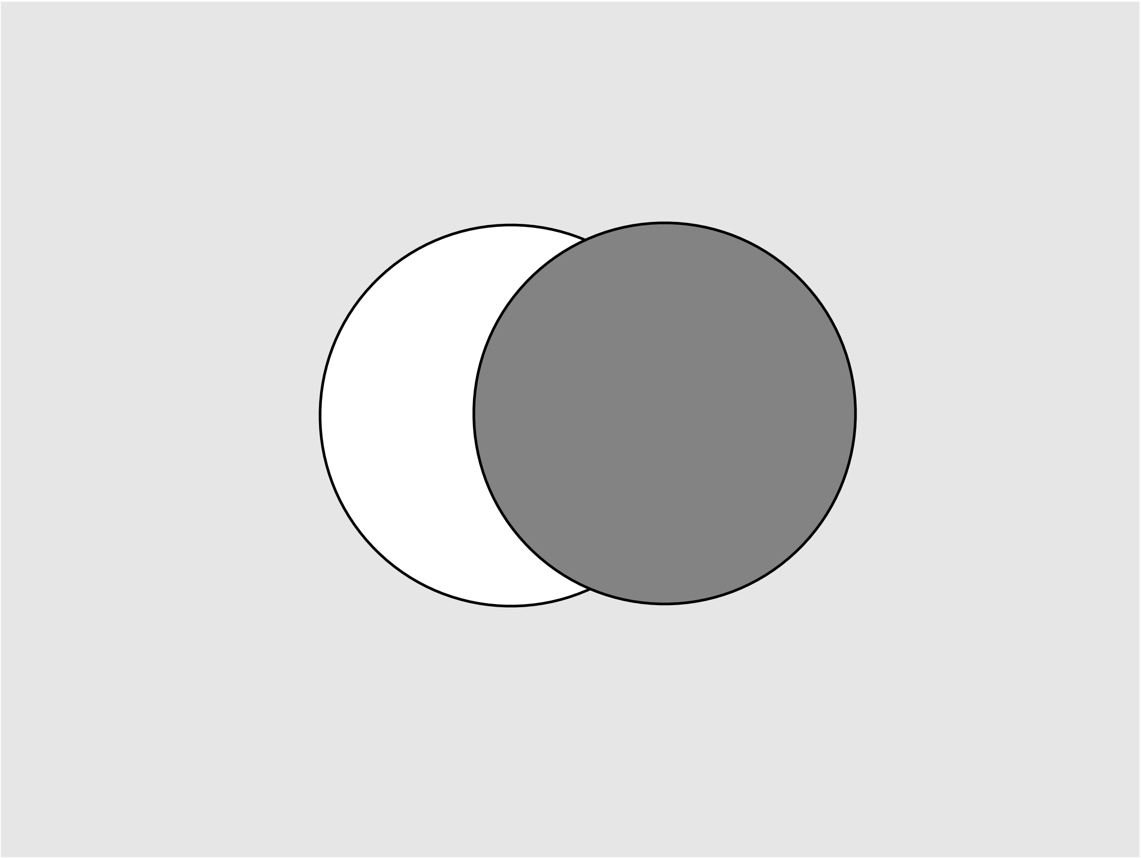
The observed light is seen only in the crescent phases, in which a substantial portion of the darkened Moon is turned toward the Earth. Sunlight shines on the Moon and the Earth both, illuminating half of each. For its part, the Earth absorbs most of the light but reflects about a third of the incident rays back into space. Some of these reflected rays travel to the Moon and land on the dark side, where the Moon's extremely dark surface absorbs over 90% of them. Of the small fraction that is reflected from the Moon, some rays find their way back to Earth, as shown in Figure 5.16. If they fall on the daytime side of the Earth, they will not be noticed, due to the bright daytime sky. However, if these twice-reflected rays strike the *dark* side of the Earth, they may be seen against the darkened evening (or morning) sky. The phenomenon is known as **earthshine**; it can be observed on crescent moons in the morning or evening twilight.

Figure 5.16: Earthshine geometry



Earthshine and moon phases both involve the changing appearance of the Moon as we see it from Earth. In the next chapter we will learn of another way in which the Moon's appearance can vary.

Chapter 6: Eclipses



Eclipses are interesting phenomena for several reasons: they involve familiar bodies (the Earth, Moon, and Sun); they can be viewed easily by the public, without special equipment; they occur in a number of variations; and they are regular enough to be predictable but rare enough to be special events.

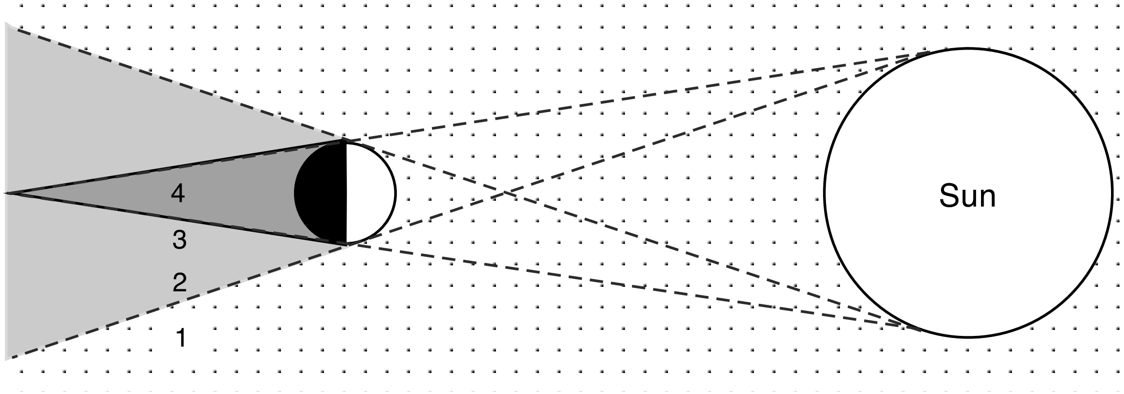
An eclipse occurs when one celestial body blocks light from reaching another body. Or we could say that an eclipse occurs when one body goes into the shadow of another body. Let us investigate shadows in space.

Shadows

Normally your shadow is visible only when it falls on the ground, a wall, or another object. Shadows in space are similar in that respect – we do not see them until they land on something. To make a shadow, we need two things: a source of light, and a body that is *not* a source of light. To see the shadow, we will also need a third body – to intercept the shadow.

The obvious source of light in our solar system is the Sun. (The Earth, Moon, and planets shine too, but only by reflected sunlight.) We saw in Chapter 5 that the Sun illuminates half of the Earth and half of the Moon at one time. Certainly the night side of each body lies in the shadow produced by that body. But there is more to the shadow than just the night side, as Figure 6.1 shows.

Figure 6.1: Shadows in space



To form Figure 6.1, we draw rays from the top and bottom of the Sun through the top and bottom of a non-luminous body (to be named later). Beyond this body these rays form the boundaries of the shadow in space. An astronaut in a rocket traveling in space at point 1 would be able to see the entire disk of the Sun because rays drawn from point 1 to any part of the Sun do not intersect the non-luminous body. At point 2, however, the body does block out rays from the top of the Sun, and the Sun would appear to have a small bite out of its upper edge. As the rocket moves from point 2 to point 3, the body blocks out even more of the Sun. This lightly shaded area that contains points 2 and 3 is the part of the shadow we call the **penumbra**.

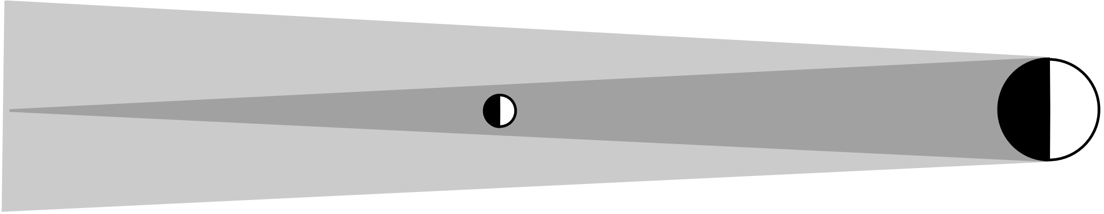
As the rocket moves on to point 4, the astronauts find that the body blocks out *all* of the Sun's disk from their view. This more darkly shaded area is called the **umbra**, and it is the darker of the two shadow regions. Eclipses occur when a third body (in this case, the rocket) moves into the penumbra or the umbra. Different types of eclipses occur depending on what body casts the shadow, what body intercepts the shadow, and what part of the shadow is intercepted.

Living on the Earth as we do, we tend to classify eclipses into two basic types: lunar and solar. In a **solar eclipse**, parts of the Sun are hidden from view (by the Moon), while in a **lunar eclipse**, parts of the Moon are darkened by the Earth's shadow. We will investigate lunar eclipses first.

Lunar Eclipses

In a lunar eclipse, the Moon passes through the Earth's shadow. This means that the Moon must be on the same side of the Earth as the shadow, which is opposite the Sun. For this reason, a lunar eclipse requires a full moon. Because the Moon is much smaller than the Earth, it is able to fit entirely within the Earth's umbra, as shown in Figure 6.2 (where the Sun has been omitted for simplicity). When this occurs, the Moon is completely immersed in the Earth's umbra, where practically no light can reach it. In this case, the Moon appears very dark compared to its normal full phase; such an eclipse is called a **total lunar eclipse**.

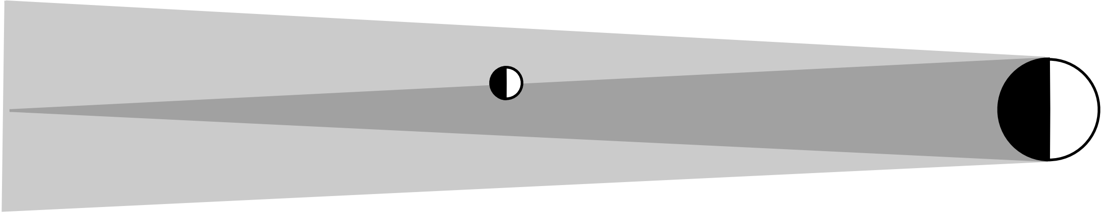
Figure 6.2: Total lunar eclipse



The totally eclipsed Moon does not become black and invisible, despite being completely inside the Earth's umbra. It still receives light from the Sun that has been **refracted**, or bent, into the umbra by its passage through the Earth's atmosphere. Sunlight contains all the colors of the rainbow – red, orange, yellow, green, blue, indigo, violet – which normally all mix together to produce white light. The atmosphere tends to scatter or deflect the blue colors more efficiently than the red ones. The blue colors are easily removed from the Sun's rays to make blue sky here on the Earth; those rays that manage to pass through the atmosphere to be refracted into the umbra are predominantly red. For this reason, the totally eclipsed Moon is usually reddish in color and quite visible, though still much darker than a full moon.

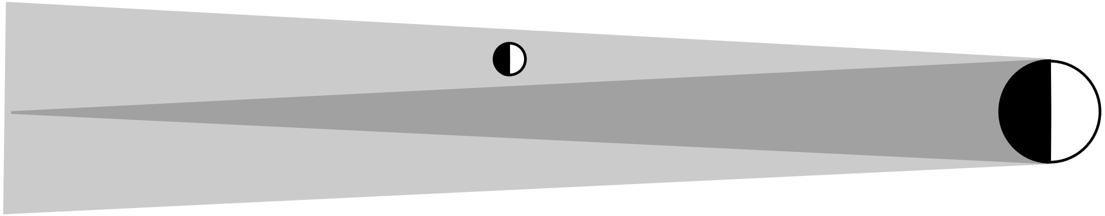
Figure 6.2 is a 'side view' of the Earth and Moon. The North Pole would be toward the top of the Earth, and the Moon orbits the Earth in a plane that is perpendicular to the page. At the time of the eclipse the Moon is coming out of the paper toward you; it will then move to the right between the Earth and you and pass back through the paper to the right of the Earth. As the Moon circles around in its orbit in this manner, it does not always pass directly through the umbra as shown. Sometimes it only skims through the umbra, never becoming completely immersed; in this case, only part of the Moon will be darkened by the umbra. Because the spherical Earth casts a circular shadow, the Moon will appear as a bright cookie with a bite out of it. Such an eclipse, shown in Figure 6.3, is called a **partial lunar eclipse**.

Figure 6.3: Partial lunar eclipse



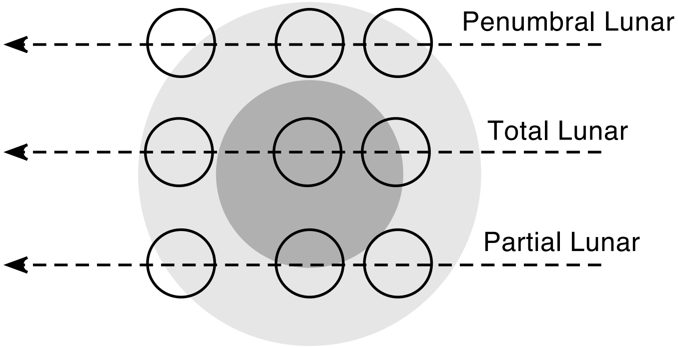
Sometimes the orbiting Moon fails to make contact with the Earth's umbra but does pass through the penumbra. The geometry is shown in Figure 6.4 and the event is called a **penumbral lunar eclipse**.

Figure 6.4: Penumbral lunar eclipse



In this case, the Moon is not darkened appreciably, but because it is in the penumbra, it appears to be shaded across its disk, giving it a distinctive, although subtle, appearance. Figure 6.5 shows our Earth-based view of the changing appearance of the Moon as it moves through the Earth's shadow during each of the three types of lunar eclipses. Note that a total lunar eclipse has both partial and penumbral phases too, and a partial eclipse also contains penumbral phases. (The umbra and penumbra are shown here as they would appear if we could insert a huge projection screen at the distance of the Moon. As no such screen is available, the umbra and penumbra are usually not so apparent.)

Figure 6.5: Lunar eclipses, as seen from Earth



Lunar eclipses are fairly easy to see from the Earth – as easy as the full moon. Any observer located on the night side of the Earth (without too many clouds) will be able to view a lunar eclipse, which may last up to about three hours, depending on the path the Moon takes through the shadow.

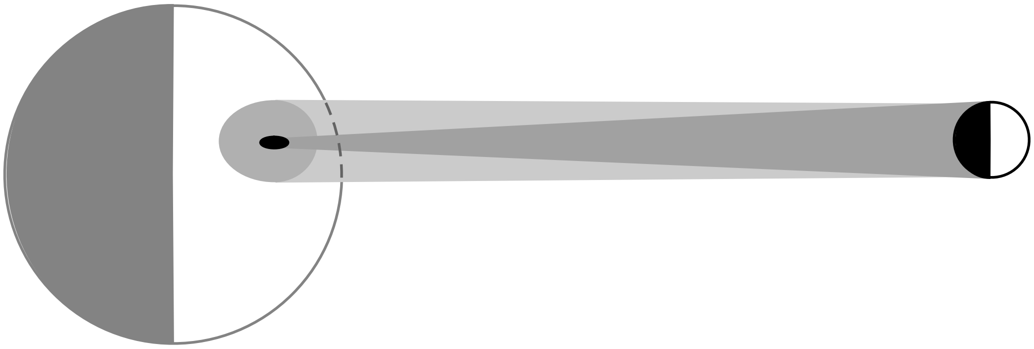
Solar Eclipses

As mentioned above, in a solar eclipse the Moon blocks part of the Sun from our view. This implies that the Moon must be between the Earth and the Sun, a condition that requires a new moon phase. Because the Moon is smaller than the Earth, its umbra is not big enough to contain the whole Earth. Instead, the Moon's umbra and penumbra will form darkened regions on the Earth's surface as shown in Figure 6.6. The type of solar eclipse seen will depend on where the observer is located with respect to the shadow.

A person standing where the Moon's umbra touches the Earth (the black ellipse in Figure 6.6) would have the entire disk of the Sun obscured by the Moon. This spectacular event is called a **total solar eclipse**. During totality the Moon covers the Sun's bright disk, leaving only its thin atmosphere (the **solar corona**) protruding from behind to form a 'crown' around the new moon, as shown in Figure 6.9a.

> One might say that the total solar eclipse provides an opportunity to 'see' a new moon. Of course, as the Moon's face is still completely dark at this time, it is not clear whether we have 'seen' it at all. In any event, we can certainly tell where it is.

Figure 6.6: Total solar eclipse geometry

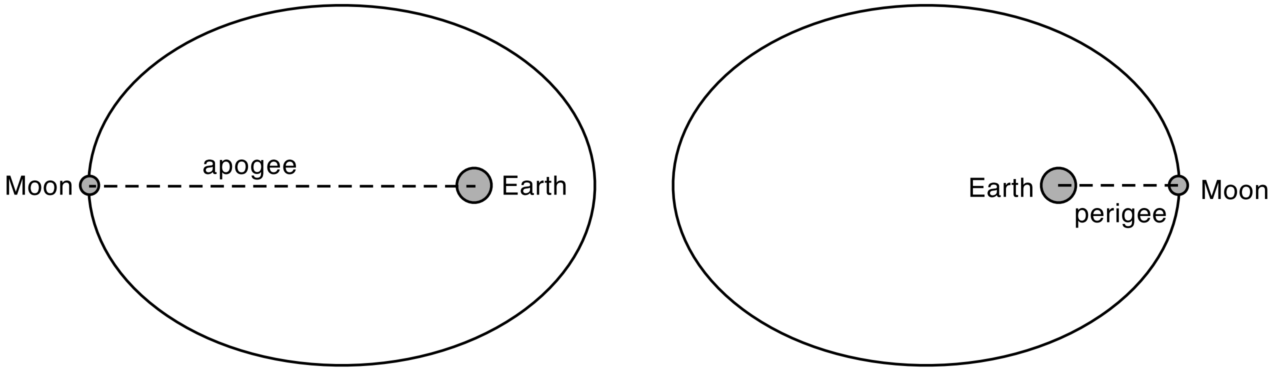


Persons standing in the adjacent shaded region where the Moon's penumbra touches the Earth would observe only *part* of the Sun's disk being covered by the Moon; they would see a **partial solar eclipse** – another bright cookie with a bite out of it, as shown in Figure 6.9b. Of course, the size of the bite depends on the observer's location within the penumbra; those persons on the Earth's surface in the region *outside* the Moon's penumbra would see no eclipse at all.

> Viewing a solar eclipse is somewhat hazardous because the Sun's rays are capable of burning the unprotected eye. Telescopes or binoculars are particularly dangerous because they concentrate the Sun's rays as a magnifying glass does. The best technique is very simple: punch a pinhole in a piece of cardboard and project the Sun's image onto a white screen or paper. Never look at the Sun directly.[*]

There is a third type of solar eclipse, and it requires slightly different circumstances. The cause of the difference is the fact that the Moon's orbit is not circular, but elliptical, as the Earth's is. This means that the Earth-Moon distance varies, from a minimum at **perigee** to a maximum at **apogee**, as shown in Figure 6.7. (The actual variation is not nearly as extreme as depicted, being only about ± $5^1/_2$%.)

Figure 6.7: Apogee and perigee in the Moon's elliptical orbit



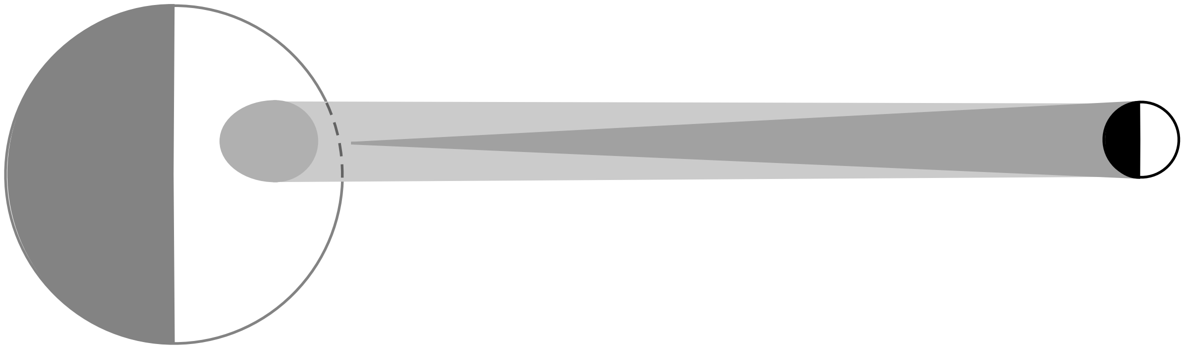
apogee: $r_{max} = a(1 + e)$ perigee: $r_{min} = a(1 - e)$

Figure 6.6 showed the conditions around perigee, which produce a total solar eclipse. Figure 6.8 shows the conditions at apogee, when the Moon is farther away from the Earth than normal. In fact, it is so far away that the Moon's umbra does not reach to the Earth's surface, thus making a total solar eclipse impossible.

---

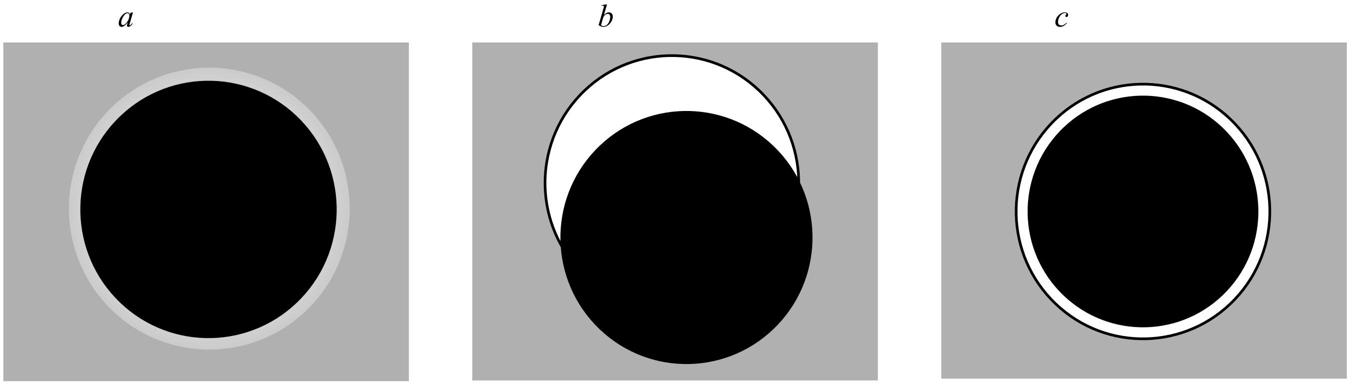
[*] See **SOLAR VIEWING TUBE** in the Appendix.

Figure 6.8: Annular solar eclipse geometry



A person standing in the shaded region where the Earth intercepts the Moon's penumbra would see a partial solar eclipse, as before. However, if the person were directly below the tip of the Moon's umbra (to the left of it, in this diagram), exactly in line with the centers of the Moon and Sun, where the umbra would touch the Earth if it were long enough, then a different view would be obtained. From this point, the Moon and Sun would be aligned, but the Moon would be too small (due to its increased distance) to cover the Sun's disk. The Sun would still be visible as a bright ring of light around the dark new moon, as shown in Figure 6.9c. Because a ring shape is called an **annulus**, this event is named an **annular solar eclipse**.

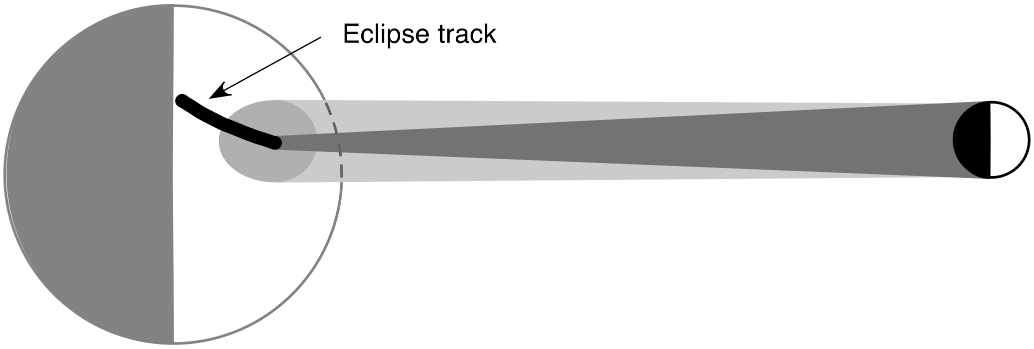
Figure 6.9: Solar eclipses – (a) total, (b) partial, and (c) annular



> It is an interesting fact that the Moon and the Sun appear to be about the same size in our sky, despite being considerably different in diameter and distance. That the Sun should be about 400 times larger in diameter and also about 400 times farther away than the Moon is quite a coincidence. It is also coincidental that the eccentricity of the Moon's orbit (about 0.055) is just enough to make the Moon appear alternately larger and smaller than the Sun, giving us *both* total and annular solar eclipses.

Just as the Moon moves through the Earth's shadow during a lunar eclipse, the Moon also moves in its orbit during a solar eclipse, dragging its own shadow across the surface of the Earth and producing an **eclipse track**. Persons living along the eclipse track will be treated to a solar eclipse when the shadow passes over them. Those who live outside the eclipse track will have to travel to it in order to view the eclipse in person. Because the Moon's umbra is not very wide where it touches the Earth's surface, total solar eclipses are very brief compared with total lunar eclipses. The maximum duration of totality is only a few minutes, but the partial eclipse phases may last for two or three hours.

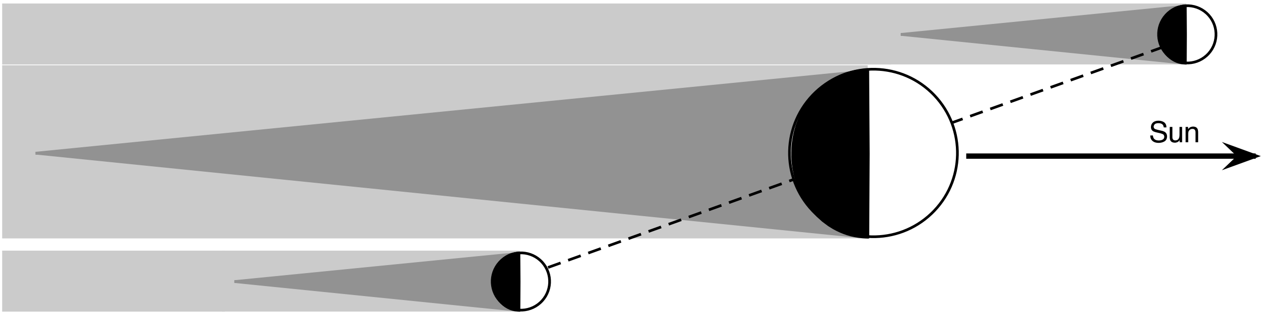
Figure 6.10: An eclipse track for a total solar eclipse



Eclipse Frequency

Having learned that lunar eclipses occur at full moon and solar eclipses occur at new moon, one might be tempted to think that eclipses will occur about twice per month, whenever these phases are encountered in the lunar cycle. However, there is an additional constraint on the conditions necessary for an eclipse: the Earth, Moon, and Sun must be almost perfectly in line. This would be easy if not for the fact that the Moon's orbit about the Earth is not in the same plane as the Earth's orbit about the Sun but instead is inclined to it by about 5°. This means that at full moon, the Moon may pass up to 5° north or south of the Earth's shadow, missing it entirely. Similarly, at new moon, the Moon may pass up to 5° north or south of the Sun, such that its shadow does not fall on the Earth. In either case, no eclipse would occur because the necessary alignment conditions are not met.

Figure 6.11: Eclipse requirements



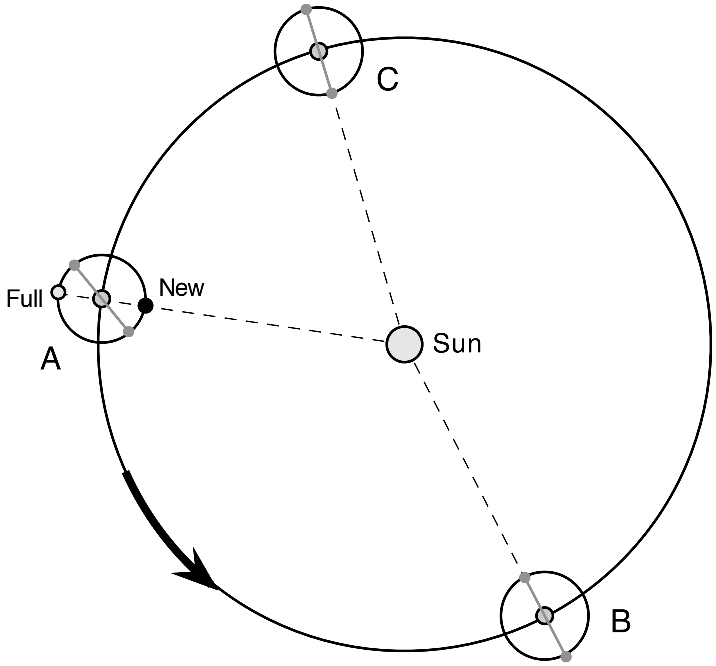
These conditions are illustrated in Figure 6.11, which shows a side view of the Earth-Moon system. Although the moon on the left is full, it is not quite in line with the Earth and Sun, and it misses the Earth's shadow. The moon on the right is new, but due to the inclination of the Moon's orbit (represented by the dashed line joining the two moons) with respect to the Earth's orbital plane, the Moon's shadow fails to fall on the Earth and no eclipse occurs.

Allowing for all of the geometrical factors, we find that eclipses occur at only two intervals during the year; these are known as the **eclipse seasons**. At these times, the new moon and full moon will be sufficiently close to the plane of the Earth's orbit such that the Moon's shadow will fall on the Earth at new moon and the Earth's shadow will fall on the Moon at full moon, causing solar and lunar eclipses, respectively. These eclipse seasons are not fixed in time; instead, they migrate gradually around the calendar. Eclipses can occur in *any* month, but within a given year they will be confined to two month-long periods about six months apart.

Figure 6.12 shows the Earth's orbit about the Sun and the Moon's orbit about the Earth at three positions (A, B, and C). Because the Moon's orbit is inclined by 5° to the Earth's orbit, the two orbits are really not in the same plane. Half of the Moon's orbit is south of the Earth's orbital plane (behind the paper) and half is north of it (in front of the paper). The Moon passes through the Earth's orbital plane at the points marked by the small gray dots. These points are called the **nodes** in the Moon's orbit. In order for an eclipse to occur, the Moon must be either new or full and must also be at (or very near) a node.

When the Earth is at position A, neither the new moon nor the full moon would occur at a node; when the Moon does reach a node, it would be either a waxing gibbous or a waning crescent phase. Thus, no eclipses can occur at position A.

Figure 6.12: Eclipse seasons

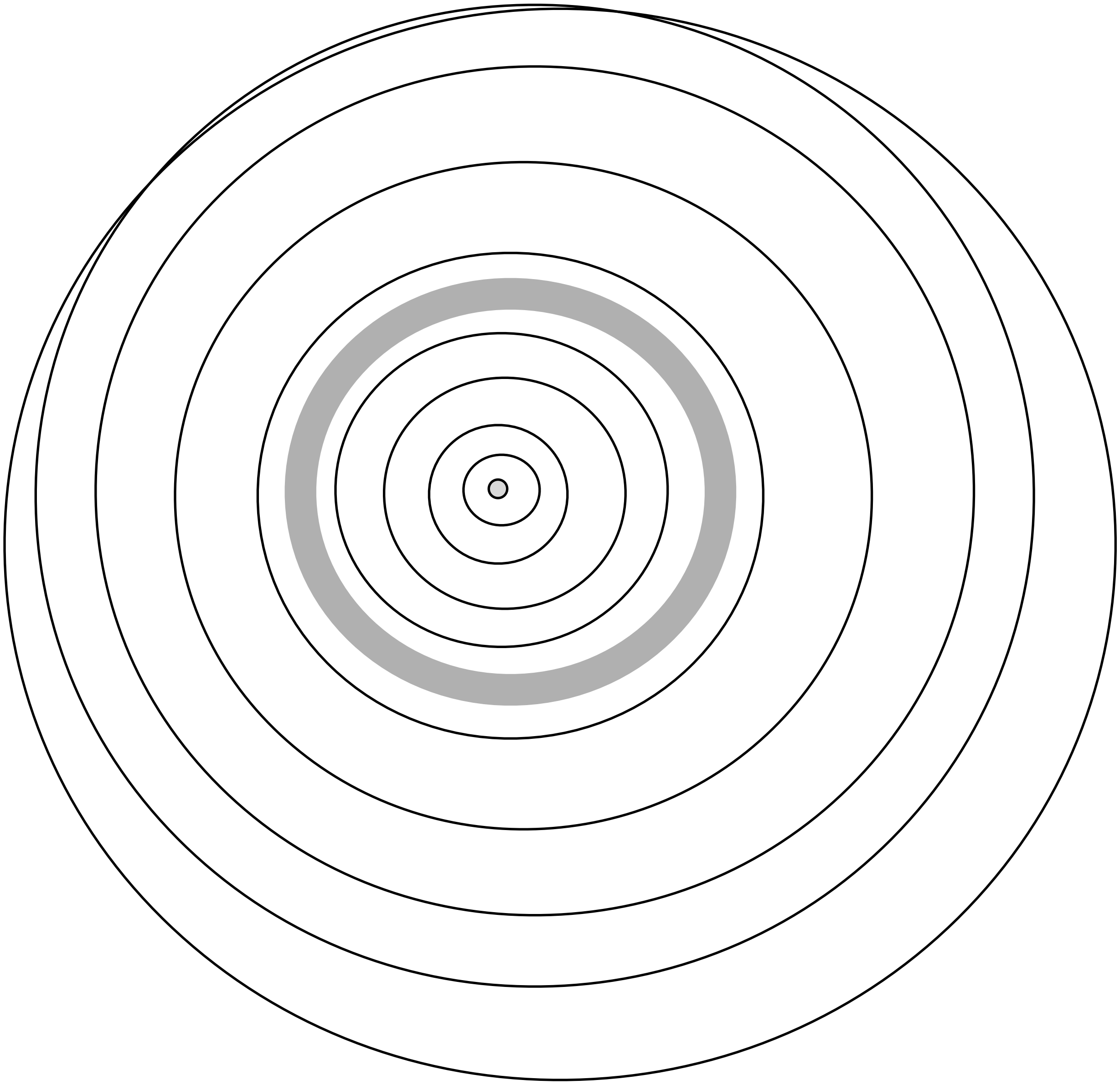


At position B, the Earth has moved in its orbit such that the line from the Sun to the Earth passes through the nodes. A new or full moon will occur at or near a node, resulting in eclipses. Position B marks the center of one of the eclipse seasons.

The next eclipse season will occur on the other side of the orbit, at position C, which is not exactly 180° away from position B. This is because the line joining the nodes is not fixed in direction; it rotates slowly clockwise, causing the interval between eclipse seasons to be somewhat less than six months.

Although eclipses in general are fairly commonplace, with several happening each year, an eclipse that is visible at a given location on Earth – such as your home – might be quite rare. Lunar eclipses are easiest to see because they can be viewed from half of the Earth at once. Solar eclipses are somewhat more frequent than lunar eclipses, but the viewing area for them is considerably more restricted. Over the last few decades very few solar eclipse tracks have crossed North America. In fact, the next two total solar eclipses to be seen from the continental United States will occur in 2017 and 2024. Those eager to view a total solar eclipse before that must be willing and able to travel out of the country. Details of upcoming eclipses, both lunar and solar, can be found on the web (search '*NASA eclipse*').

Chapter 7: The Solar System



As mentioned in Chapter 1, the solar system is a collection of objects bound together by the gravity of the Sun. Planets, asteroids, and comets all orbit the Sun, and various satellites orbit some of the planets. In this chapter we will concentrate on the general layout of the solar system; in Chapter 8 we will examine the physical characteristics of the principal bodies themselves.

A Model Solar System

The most basic information about the planets includes their names and their order from the Sun. Relative sizes and distances of the planets are also fairly easy to discuss. A simple way to present this information is in the form of a model of the solar system. We will assemble a collection of spheres of different sizes and assign each of them to one of the celestial bodies in our model. To gain the most insight from our model, we should construct it to scale, such that each planet has the proper size relative to all the others. We can choose any scale we want – the first model planet can be any size – but once the scale is chosen, the sizes of all the other model planets will be set.

The following table shows one such model; it includes the Sun, the eight planets, Pluto[*], and the Moon, along with their symbols and relative sizes. The scale has been chosen by selecting a blue marble to be the Earth: this results in model planets that range in size from Jupiter, a 6-inch Styrofoam ball of the type found in hobby and craft stores, to Pluto, a tiny ball even smaller than the BB that represents the Moon. The Sun is quite large in comparison, as we already learned in Chapter 2.

Symbol	Body	Ball	Diameter	Earth Diameters
☉	**Sun**	**Earth ball**	**5 ft**	**109**
☿	**Mercury**	**Steel Ball**	**5 mm**	**0.38**
♀	**Venus**	**White Marble**	**$1/2^-$ in**	**0.95**
⊕	**Earth**	**Blue Marble**	**$1/2^+$ in**	**1.0**
☽	***Moon***	***BB***	***4 mm***	***0.27***
♂	**Mars**	**Red Eraser**	**7 mm**	**0.53**
♃	**Jupiter**	**Styrofoam Ball**	**6 in**	**11.2**
♄	**Saturn**	**Styrofoam Ball**	**5 in**	**9.4**
⛢	**Uranus**	**Styrofoam Ball**	**2^+ in**	**4.0**
♆	**Neptune**	**Styrofoam Ball**	**2^- in**	**3.9**
♇	**Pluto**	**Shiny Ball**	**3 mm**	**0.18**

This model nicely establishes the relative sizes of the principal solar system bodies. Next, we will demonstrate the relative distances of the planets from the Sun, using the same scale. If the Earth is a marble and the Moon is a BB, how far apart should they be placed to show the correct spacing? The following table shows the distance of each body from the model Sun, along with the actual distances of the planets, in both astronomical units (AUs) and light travel time (the time it would take light to travel that distance).

This table also includes the nearest star to the Sun – *Alpha Centauri*. Even in our scale model, this star is a tremendous distance from the Sun – much farther away than Pluto, which appears quite local, in comparison.

---

[*] In 2006, Pluto was redefined as a 'dwarf planet'. But we will still include it in our discussion.

Body	Distance (Model)	Distance (AUs)	Light Travel Time
Mercury	65 yards	0.38	3.2 minutes
Venus	125 yards	0.72	6.0 minutes
Earth	175 yards	1.0	8.3 minutes
Moon	16 inches (from Earth)	1/400	1.3 seconds
Mars	265 yards	1.5	13 minutes
Jupiter	1/2 miles	5.2	43 minutes
Saturn	1 miles	9.5	1.3 hours
Uranus	2 miles	19	2.6 hours
Neptune	3 miles	30	4.1 hours
Pluto	4 miles	39	5.5 hours
Alpha Centauri	27,000 miles	268,000	4.3 years

The next table shows the rate of orbital motion of each of these bodies. It is easily seen that the more distant planets take longer to complete their orbits. This is because they travel farther (having larger orbits) and also more slowly. The orbital period given for each planet is its sidereal revolution period or sidereal year, as described for the Earth in Chapter 4.

Body	Speed (Model)	Speed (Actual)	Orbital Period
Mercury	15 feet/day	48 km/sec	88 days
Venus	11 feet/day	35 km/sec	225 days
Earth	9.6 feet/day	30 km/sec	365 days
Moon	3.8 inches/day	1.0 km/sec	27.3 days
Mars	7.7 feet/day	24 km/sec	687 days
Jupiter	4.1 feet/day	13 km/sec	11.9 years
Saturn	3.1 feet/day	9.7 km/sec	29.4 years
Uranus	2.2 feet/day	6.8 km/sec	83.7 years
Neptune	1.7 feet/day	5.5 km/sec	164 years
Pluto	1.5 feet/day	4.7 km/sec	248 years

The planets all orbit the Sun in approximately – but not precisely – the same plane; as a result, the solar system is often said to be disk-shaped. However, our model solar system, with a few tiny spheres scattered over several miles of emptiness, would hardly convey the image of a disk to the casual observer. The motions of the planets would slowly trace out the disk, but as we have seen, this motion is so gradual as to be almost imperceptible, especially for the outer planets.

The Farthest Planet

The orbits of the planets are all elliptical, as is the Earth's (see Chapter 3). The orbital eccentricities vary from planet to planet, with some orbits being more circular and others more elongated than Earth's. Most of the planet orbits do not overlap or intersect, but Pluto and Neptune provide an interesting case study.

Pluto has a higher eccentricity (0.25) than any of the eight planets; its distance from the Sun varies from 49.2 AUs at aphelion to 29.7 AUs at perihelion. Neptune, on the other hand, has a nearly circular orbit, with one of the lowest eccentricities (0.009) and a small variation, from 30.4 AUs at aphelion to 29.8 AUs at perihelion. Thus, Pluto at perihelion is closer to the Sun than Neptune! For 20 out of every 248 years in Pluto's period (most recently, from 1979 to 1999 – when Pluto was still regarded as a planet), Neptune is farther from the Sun than Pluto. Of course, because Pluto is more distant *on the average*, astronomers did not rewrite the textbooks to list Pluto as the eighth planet and Neptune as ninth during this 20-year interval.

> As Pluto moves inside Neptune's orbit, we might question whether the two bodies might collide someday. There are two reasons why we need not worry about this problem: First, Pluto's orbit is inclined by 17° to the Earth's orbit, while Neptune's inclination is less than 2°. Because the two orbital planes are so different, the orbits they contain do not intersect each other. Second, the periods of the two orbits are such that whenever Pluto reaches its perihelion, Neptune is always far away on the other side of its orbit. The two bodies never get close together.

The Closest Planet

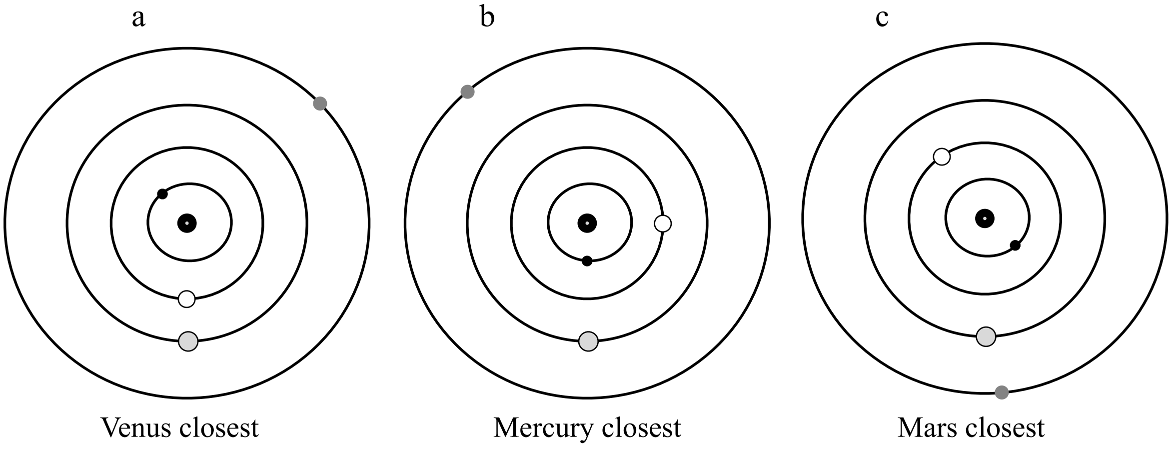
Obviously, if a child asks you which planet or dwarf planet is farthest away, it might be a trick question – to see whether you are aware of the Neptune/Pluto crossover. What if a child asks you which of the planets is the *closest*? This question is even trickier to answer because it can be taken in several different ways.

The first response to this simple question should be to ascertain what the planet is closest to: Closest to the Sun? In this case the answer is *always* Mercury because no planet approaches the Sun more closely. Closest to the Earth? Now the answer will be one of three planets (Mercury, Venus, or Mars), depending on how we measure the distance.

The following table shows the spacing of the orbits of the four inner planets, together with the minimum and maximum distance of each planet from the Earth. (For simplicity, the orbits are considered to be circular.) A quick glance at this data is enough to show that although Venus' orbit lies nearest the Earth's, Venus gets far enough away from Earth that both Mercury and Mars can come closer to the us, at times.

Planet	**Distance from Sun (AUs)**	**Minimum Distance from Earth (AUs)**	**Maximum Distance from Earth (AUs)**
Mercury	**0.38**	**0.62**	**1.38**
Venus	**0.72**	**0.28**	**1.72**
Earth	**1.0**	**0**	**0**
Mars	**1.5**	**0.5**	**2.5**

Figure 7.1: Planet proximity



Venus closest Mercury closest Mars closest

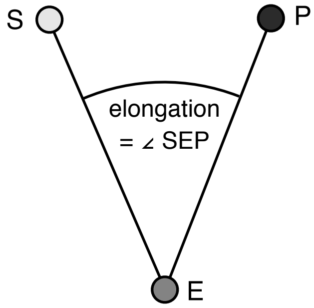
Figure 7.1 shows the orbits of the four inner planets about the Sun. In each diagram, the Earth is in the same position in its orbit, the third one out from the Sun. We can see in Figure 7.1a that Venus can get closer to Earth than any other planet can. However, Venus moves around in its orbit relative to Earth and is not always the closest planet to Earth, as shown in Figures 7.1b and 7.1c. Thus, this simple question does not always have a simple answer.

Planetary Configurations

Because the planets move around constantly, it is useful to have special terminology that describes their positions with respect to the Sun and the Earth. In this section we will discuss the planetary **configurations** that are frequently used in newspapers and almanacs to report the planets' positions.

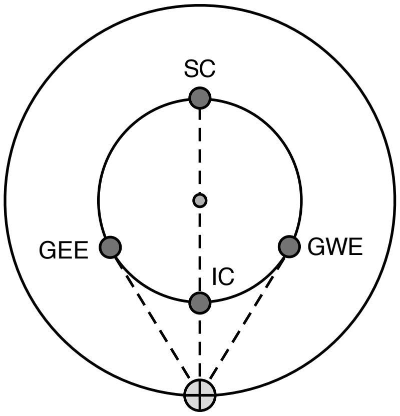
The key concept in describing planet positions is **elongation**, the angle between the Sun and the planet, as seen from the Earth (shown in Figure 7.2). If the planet is west of the Sun, as shown in Figure 7.2, it has a western elongation; if the planet is east of the Sun, it has an eastern elongation. Elongations are generally given in degrees.

Figure 7.2: Elongation



We next split the planets into two groups, depending on the locations of their orbits. Planets that have orbits inside the Earth's are called **inferior planets**. These include Mercury and Venus. The remainder of the planets, with orbits lying outside the Earth's are called **superior planets**. Figure 7.3 shows the configurations of the inferior planets, followed by a table that lists the names of these configurations, the elongations, and the phases associated with them.

Figure 7.3: Inferior planet configurations



Configuration	Elongation	Phase
Superior Conjunction	**0°**	**Full**
Inferior Conjunction	**0°**	**New**
Greatest Eastern Elongation	**depends on planet**	**Quarter**
Greatest Western Elongation	**depends on planet**	**Quarter**

The term conjunction refers to two objects appearing close together in the sky, at or near 0° elongation. At **superior conjunction** (SC) the planet is in line with the Sun (and therefore not visible from Earth), but it is fully illuminated. At **inferior conjunction** (IC) the planet is again in line with the Sun, with its illuminated side turned away from us, which makes this configuration even more difficult to observe. The planet can be best viewed from Earth when it is separated the most from the Sun – that is, when it has the **greatest elongation**, the maximum angle from the Sun. This will occur twice during each orbit, at **greatest eastern elongation** (GEE) and **greatest western elongation** (GWE).

At greatest eastern elongation the planet is as far east of the Sun as it can get; it will rise after the Sun, follow the Sun as it moves westward across our sky and set after the Sun sets. Thus, a planet at this configuration is best viewed just after sunset in the evening sky.

At greatest western elongation the planet is as far west of the Sun as it can get; it will rise before the Sun, precede the Sun westward across our sky and set before the Sun sets. Thus, a planet at this configuration is best viewed just before sunrise in the morning sky. At both greatest elongations the planet will be only half illuminated (quarter phase).

> We sometimes refer to morning stars and evening stars – really morning *planets* and evening *planets* – meaning the time of day when the planet can be seen. Obviously a given planet is not *always* a morning star/planet or an evening star/planet, for it switches back and forth as it orbits the Sun.
>
> A handy way to remember which time is best for viewing the greatest elongations goes as follows: for GEE and GWE, take the middle initial of each (E and W) and turn it upside down to form E and M, respectively. The E means that GEE is best viewed in the evening while the M means that GWE is best viewed in the morning.

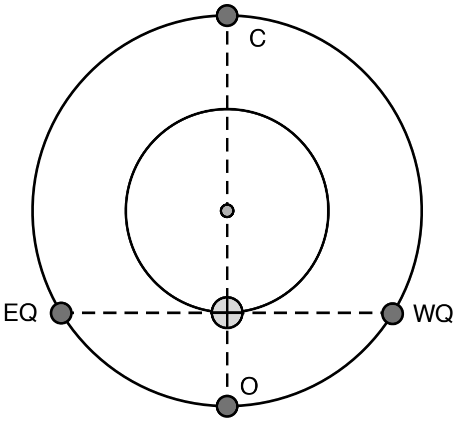
GEE → G<u>E</u>E → <u>E</u> → <u>E</u>vening

GWE → G<u>W</u>E → <u>M</u> → <u>M</u>orning

Figure 7.4 shows the configurations of the superior planets, followed by a table that lists the configurations, elongations, and the phases associated with them.

Again, the term **conjunction** refers to two objects appearing close together in the sky, at or near 0° elongation. With superior planets, this alignment can happen only one way; a superior planet at **conjunction** (C) is on the far side of the Sun from us and cannot be seen. **Opposition** (O) refers to the planet's being on the opposite side of the Earth from the Sun. A planet in this position will behave as a full moon does, being fully illuminated and staying up all night long. Because opposition also marks the planet's closest approach to the Earth, this is the best configuration for viewing a superior planet. A planet at **eastern quadrature** (EQ) will be highest in the sky at sunset and visible in the evening sky, while a planet at **western quadrature** (WQ) will be highest at sunrise and visible in the morning sky. The two quadratures mark the phases of minimum illumination of the superior planet's surface as seen from Earth.

Figure 7.4: Superior planet configurations



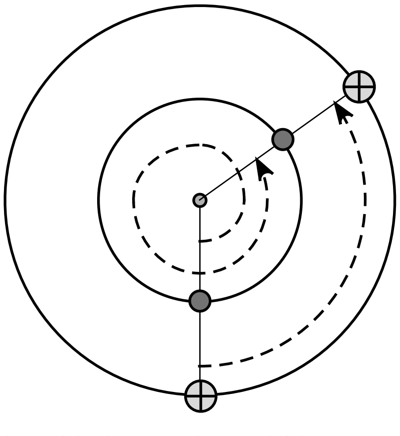
Configuration	Elongation	Phase
Conjunction	0°	Full
Opposition	180°	Full
Eastern Quadrature	90° E	Gibbous
Western Quadrature	90° W	Gibbous

We can apply the same method to quadrature that we learned for greatest elongation: for EQ and WQ, take the first initial of each (E and W) and turn it upside down to form E and M, respectively. The E means that EQ is best viewed in the evening while the M means that WQ is best viewed in the morning.

EQ → EQ → E → Evening
WQ → WQ → M → Morning

Once the configurations are understood, one can follow the progress of planets among the stars as they move from one configuration to the next. How long does it take for a planet to move through its cycle of configurations – from inferior conjunction to greatest western elongation to superior conjunction to greatest eastern elongation and back to inferior conjunction (for an inferior planet), or from conjunction to western quadrature to opposition to eastern quadrature and back to conjunction (for a superior planet)?

Figure 7.5: Synodic period geometry: inferior conjunction to inferior conjunction



At first glance, one might guess that this interval would be equal to the planet's orbital period. But this is not so because the Earth and the planet *both* move, and each configuration requires a particular alignment of the planet, Sun, and Earth. Figure 7.5 shows the paths of the Earth and Mercury during the interval from one inferior conjunction to the next. Note that while the Earth moves about one third of the way around its orbit, Mercury moves one full orbit plus another third. The time that it takes for an inferior planet to lap the Earth (or for the Earth to lap a superior planet) is called the **synodic period** (or **synodic revolution period**), and this is the interval we want. (Note that for residents of Mercury, Figure 7.5 demonstrates the interval between successive *oppositions* of *Earth* – which is the same synodic period.)

The following table gives sidereal and synodic revolution periods of the planets and Pluto (as seen from Earth). Note that for the more distant bodies, the synodic period approaches one year. This simply reflects the fact that these bodies move much more slowly in their orbits, hardly changing their positions from one year to the next.

Planet	Sidereal Period	Synodic Period
Mercury	88 d	116 d
Venus	225 d	584 d
Mars	687 d	780 d
Jupiter	11.86 y	399 d
Saturn	29.5 y	378 d
Uranus	84 y	370 d
Neptune	165 y	367.5 d
Pluto	248 y	366.7 d

> Venus spends half of its synodic period – about nine months – as a 'morning star' and another nine months as an 'evening star'. Due to its brightness and persistence in the evening sky, most children who have wished on the Evening Star have probably been wishing on Venus.

Bode's Law

Why do the planets have the spacing that they do? Is there anything that determines the distances of the planets from the Sun, or could they be *anywhere*? This question was asked in the late 1700s and resulted in a rule known today as **Bode's Law**. Bode's Law provided a mechanism for generating the distances of all the planets known at that time, from Mercury through Saturn. It began with the sequence of numbers 0, 1, 2, 4, 8, 16, 32, etc., created by doubling each number (after the 0) to get the next one. Each of these numbers is then multiplied by 3; next we add 4 to this product and divide the sum by 10. The result gives the approximate distances of the planets, in AUs, as shown in the following table:

	Step 1		Step 2		Step 3	Result	Actual	Planet
0	x 3 =	0	+ 4 =	4	÷ 10 =	0.4	0.4	Mercury
1	x 3 =	3	+ 4 =	7	÷ 10 =	0.7	0.7	Venus
2	x 3 =	6	+ 4 =	10	÷ 10 =	1.0	1.0	Earth
4	x 3 =	12	+ 4 =	16	÷ 10 =	1.6	1.5	Mars
8	x 3 =	24	+ 4 =	28	÷ 10 =	2.8	–	–
16	x 3 =	48	+ 4 =	52	÷ 10 =	5.2	5.2	Jupiter
32	x 3 =	96	+ 4 =	100	÷ 10 =	10.0	9.5	Saturn

When Bode's Law was first published, there were only six planets known, but shortly after, in 1781, the planet Uranus was discovered. Amazingly, Uranus was found to fit Bode's Law very nicely:

	Step 1		Step 2		Step 3	Result	Actual	Planet
64	x 3 =	192	+ 4 =	196	÷ 10 =	19.6	19.2	Uranus

The law also predicted a planet at 2.8 AUs, but none was known to be there. However, when the first asteroid, Ceres, was discovered in 1801, it was found to be at a distance of 2.8 AUs (as were several others, which were discovered later). Was Bode's Law really meaningful?

	Step 1		Step 2		Step 3	Result	Actual	Planet
8	**x 3 =**	**24**	**+ 4 =**	**28**	**÷ 10 =**	**2.8**	**2.8**	**Ceres**

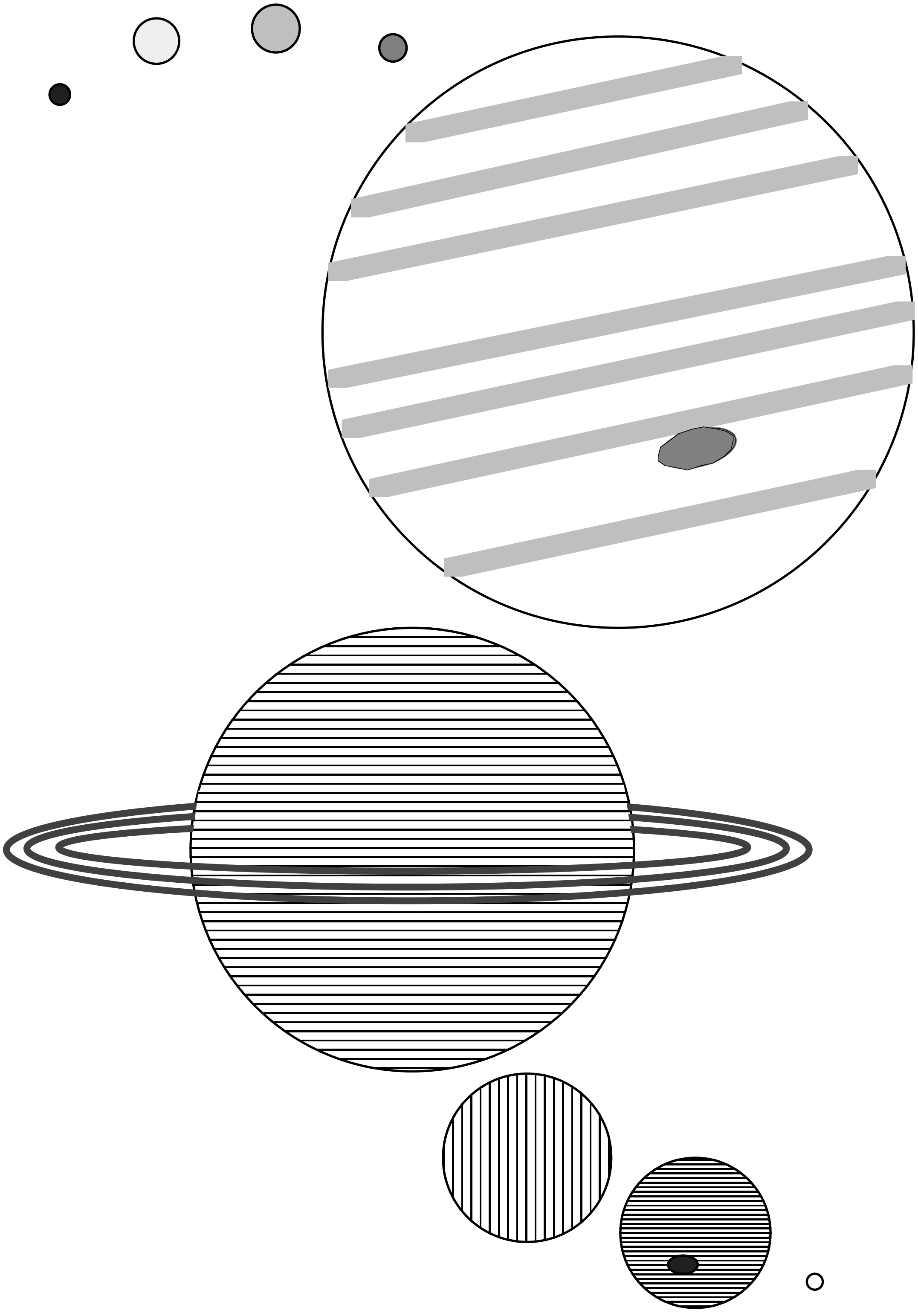
With the success in predicting positions of Uranus and Ceres, people began to wonder whether Bode's Law really had some unknown physical basis. But the discoveries of Neptune in 1846 and Pluto in 1930 showed that Bode's Law was not perfect – and not even very close for these outermost planets:

	Step 1		Step 2		Step 3	Result	Actual	Planet
128	**x 3 =**	**384**	**+ 4 =**	**388**	**÷ 10 =**	**38.8**	**30.1**	**Neptune**
256	**x 3 =**	**768**	**+ 4 =**	**772**	**÷ 10 =**	**77.2**	**39.5**	**Pluto**

Bode's Law appears to be just a curious mathematical relation that works pretty well most of the time. There is no scientific theory that predicts it, and there is no reason to believe that it would hold for another planetary system.

The orbits of asteroids and comets in the solar system will be discussed in the next chapter because they are quite intertwined with the nature of these bodies.

Chapter 8: Planet Properties



The planets in our solar system are relatively convenient objects to study. There are not too many of them, they have fairly easy names, and they are so nearby in space that we have sent unmanned probes to most of them to obtain numerous pictures and considerable amounts of data. There is now an overwhelming amount of information about planets available to us – far more than is needed for our purposes. Our modest goal is simply to try to develop an understanding of the nature of each planet and the way in which it differs from the others. This chapter contains brief descriptions of the planets and a few other related bodies in the solar system.

Planets have a variety of properties; some of these are fairly easy to obtain while others are very difficult. Some properties can be measured from right here on Earth while others require a close-up view. Some properties that we think we know, turn out to have different values later on. This means that in most listings of planet properties there will be some numbers that are quite accurately known and some that are poorly known, with a full spectrum in between. This book is no different – just because you read it here (or anywhere else) does not mean that the number is absolutely correct. In fact, any two books on planets will likely disagree somewhat on the values for each planet, due to differing sources of information, changes in measurement techniques, different methods of rounding numbers, and of course, typographical errors. The values given here are intended to be reasonably correct and in general agreement with those found in most current sources.

We will begin our discussion by listing and defining the properties reported for each planet. This will not be an exhaustive list, but it should be sufficient to describe each planet. It should also help clarify terms encountered in other sources.

Radius

The **radius** is the distance from the center of the planet to the surface. If the planet is spherical, the radius will be the same all around. However, most of the planets are not perfect spheres; they have an equatorial bulge caused by their rotation. This means that the **equatorial radius** will be larger than the **polar radius**, with the **average radius** in between. Generally when only one value for the radius is given, it is the equatorial radius. As we saw in Chapter 2, from the radius, we can also find the diameter, circumference, surface area, and volume. Usually only the radius (or sometimes the diameter) will be listed for each planet.

Oblateness

The **oblateness** measures the degree to which a planet is non-spherical. It is calculated by finding the difference between the equatorial and polar radii and then dividing this difference by the equatorial radius. A perfect sphere has an oblateness of 0, while the most oblate planet in the solar system has an oblateness of about 0.1.

Mass

Mass is a measure of the amount of matter in a planet.

Density

The (average) **density** measures how tightly packed the matter is in a planet. It is the mass per unit volume, usually measured in grams per cubic centimeter. The density of water is one g/cc.

Composition

Knowing the density of a planet gives us a clue to its **composition** – the types of matter and the chemical elements that make up the planet's interior.

Surface Gravity

Gravity holds a planet together and holds us onto the Earth's surface. As we discussed in Chapter 2, the **surface gravity** depends on a planet's mass and radius and determines how much a person would weigh on the planet.

Escape Velocity

The **escape velocity** is the minimum speed needed to launch a rocket (or anything else) from the surface of a planet. Knowing the escape velocity allows us to determine how easily atmospheric particles can escape from the planet and thus, what sort of atmosphere the planet has retained.

Atmosphere

The **atmosphere** is a layer of gasses that may surround a planetary surface. The atmosphere may contain clouds that prevent our viewing the surface, or it may be transparent. The gasses that compose the atmosphere may be beneficial to life on the surface, or they may be poisonous.

Surface Features

If the atmosphere is transparent or non-existent, we may be able to identify a variety of **surface features** on a planet: craters, mountains, valleys, volcanoes, etc. In some cases we can identify these features *despite* a thick cloud cover, by using radar to probe beneath the clouds.

Sidereal Rotation Period

The planets all rotate (spin) on their axes. The **sidereal rotation period** measures the duration of one rotation with respect to the stars – a relatively stationary reference frame. You could determine the Earth's sidereal rotation period by going outside at night, pointing at a star, and measuring how long it takes for the same star to move around the sky and return to your finger. Most planets spin counterclockwise about their north poles. Planets that spin clockwise about their north poles are said to have **retrograde** rotation.

Solar Day

We can also measure the rotation of a planet with respect to the Sun. Go outside during the day, point at the Sun, and wait for one **solar day** until the Sun again lines up with your finger. In general, the solar day and the sidereal rotation period will not be identical, although they may be very close.

Obliquity

A planet's rotation defines one axis, and its revolution defines another. The angle between these two axes is the **obliquity**, sometimes called the tilt. As we saw in Chapter 3, this angle is responsible for many of our seasonal effects.

Sidereal Revolution Period

Planets orbit about the Sun. The time for a planet to complete one orbit with respect to a distant star is the **sidereal revolution period**.

Average Distance from the Sun

Planets move in elliptical orbits, constantly changing their distances from the Sun. The **average distance from the Sun** is a measure of the size of the planet's orbit.

Orbital Eccentricity

The shape of an elliptical orbit is measured by the **orbital eccentricity**, which ranges from 0 for a circular orbit to near 1 for a highly elliptical orbit.

Orbital Inclination

The solar system is nearly planar, but not perfectly so. The orbits of the planets are all inclined to each other by small angles. The **orbital inclination** measures the angle between the planet's orbit and the ecliptic (the Earth's orbital plane).

Number of Moons

Most of the planets have moons (natural satellites). The larger moons of each planet have been known for some time. Smaller ones are still being discovered, primarily by our planetary probes.

Rings

Several of the planets have rings – systems of many tiny particles orbiting the planet to form a planar ring. Some of these rings can be seen easily from the Earth while others have only recently been discovered by spacecraft.

Distinctive Features

We will want to mention whether a planet is particularly noted for any of its properties. What distinguishes each planet from the others?

Planetary Groups

Some of the planets share similar properties. This allows us to group them together and make some general statements about each group. The two main groups are the **terrestrial planets** and the **Jovian planets**. The terrestrial (or Earth-like) planets are Mercury, Venus, Earth, and Mars; the Jovian (or Jupiter-like) planets are Jupiter, Saturn, Uranus, and Neptune. (Pluto has never counted in either group -- even when it was still counted as a planet.) The following table shows the differences in several basic properties for the two groups. In each case the division is absolute: *every* terrestrial planet is more dense than *any* Jovian; *every* Jovian planet has more moons than *any* terrestrial; and so on. Pluto, on the other hand, shares some properties with *each* group, and thus is unlike any of the planets; its reclassification as a 'dwarf planet' was really not all that surprising.

Property	Terrestrial Planets *Mercury, Venus, Earth, Mars*	Jovian Planets *Jupiter, Saturn, Uranus, Neptune*	*Pluto*
Distance from Sun	**Close**	**Far**	**Far**
Size/Mass	**Small**	**Large**	**Small**
Density	**Hi**	**Lo**	**Lo**
Composition	**Rocks, Iron**	**Gases, H, He**	**Ices**
Revolution	**Fast**	**Slow**	**Slow**
Rotation	**Slow**	**Fast**	**Slow**
Moons	**Few (3)**	**Lots (169)**	**(5)**
Rings	**None**	**All**	**None**

To determine specific planet properties, we must find an appropriate source. The trick is to remember that not all sources will agree, and further that some of the properties may be revised by new observations. Following is a summary of properties for each planet based on values found in Arthur N. Cox's *Allen's Astrophysical Quantities* (2000), with moon totals updated from the web (search '*planetary satellites list*'). In many cases, values have been rounded, to provide more convenient numbers. A table of properties and a brief discussion of each body is given.

Earth

The Earth, our home, is listed first because we use it to define or derive several units, including those for time (years, days, hours, seconds, etc.), mass ($M_\oplus = M_{Earth}$), length (AU, $R_\oplus = R_{Earth}$), and gravity (g). (Most of these have been discussed in previous chapters.) Earth is the largest of the terrestrial planets and has the highest density of all. It is the only planet with substantial amounts of liquid water on its surface and the only planet known to have life. This life has had a part in establishing the present atmosphere: the large fraction (nearly 21%) of highly reactive free oxygen in our atmosphere was produced by plant life over the last few billion years. No other planet in our solar system has such a high abundance of O_2.

Earth's Properties

Equatorial Radius	6378 km (= 1 $R_\oplus$)
Oblateness	0.00335
Mass	5.97 x 10^{27} grams (= 1 $M_\oplus$)
Density	5.52 g/cc
Surface Gravity	980 cm/s^2 (= 1 g)
Escape Velocity	11.2 km/s (≈ 25,000 mi/hr)
Sidereal Rotation Period	23.934472 hr
Solar Day	24 hours
Obliquity	23.45°
Sidereal Revolution Period	365.256 days (= 1.000 yr)
Average Distance from the Sun	149.6 million km (= 1 AU)
Orbital Eccentricity	0.017
Orbital Inclination	(0°)
Number of Moons	1

Earth is one of only two terrestrial planets to have a moon. The Moon's properties are listed here for comparison with those of the planets.

Moon

The Moon is included here even though it is not a planet. It is very close to us and thus is easily studied using binoculars or a small telescope. One of its principal features is a lack of any significant atmosphere. This means that there are no clouds to obscure our view of the surface, where craters, mountains, and maria – huge lava-filled basins – are visible. Most of these features were created by the impacts of other celestial bodies on the lunar surface. Impacts of the larger bodies excavated the basins, which subsequently were flooded with molten rock from the interior. Many of the mountain ranges seen today on the Moon are the rims of these huge basins. Numerous smaller impacts have formed the craters we find today covering most of the Moon's surface. (Craters are seen on bodies *throughout* the solar system, indicating that cratering is a widespread phenomenon. Only a few craters are found on Earth, not because Earth has avoided collisions, but rather because the erosion and tectonic motions of Earth's crust have largely erased all but the most recent craters.) Rocks on the Moon are very old, approaching the 4.6 billion year age of the solar system.

The Moon's Properties

Equatorial Radius	1738 km (= 0.272 $R_\oplus$)
Oblateness	0.00045
Mass	7.35×10^{25} grams (= 0.0123 $M_\oplus$)
Density	3.34 g/cc
Surface Gravity	1/6 *g*
Escape Velocity	2.4 km/s
Sidereal Rotation Period	27.32 days
Solar Day	29.53 days
Obliquity	6.68°
Sidereal Revolution Period	27.32 days
Average Distance from Earth	384,400 km (= 1/389 AU)
Orbital Eccentricity	0.055
Orbital Inclination	5.15°
Number of Moons	0

The lack of a lunar atmosphere has other consequences. Of course it means that space suits are necessary for lunar visitors, for there is no air to breathe there. Lack of air also means there will be no wind on the Moon (making kite flying difficult), no scattering of light by air molecules (making skies black rather than blue), and no sound waves (making radio communication necessary). The Moon does have gravity, but it is only one sixth as strong as the Earth's; a rock dropped on the Moon will still fall to the surface, but it will not fall as rapidly. With no air and no water on the Moon, it is a very lifeless body.

Night and day on the Moon are each fairly long – approximately two weeks each – as the rotation period with respect to the Sun is just the synodic revolution period we found for the Moon's phases (see Chapter 5). The Sun moves across the lunar sky but the Earth does not. An astronaut on the near side of the Moon would always find the Earth above the horizon, during both day and night and would occasionally be able to view solar eclipses as the Earth covers up the Sun (during our lunar eclipses). An astronaut on the far side of the Moon would be very lonely, being unable to see the Earth or send radio messages to it.

Mercury

Mercury, the smallest terrestrial planet, is very Moon-like in appearance as shown by the images from the Mariner 10 flybys in 1974-5 and the MESSENGER mission, beginning in 2008. Mercury has no atmosphere and lots of craters but relatively few of the maria found on the Moon. Its proximity to the Sun makes it difficult to study from the Earth, even though it is visible to the unaided eye. Mercury has an interesting relation between its rotation and its revolution: the two motions are linked in a 3:2 resonance, such that Mercury rotates three times in every two revolutions about the Sun. The solar day length depends on both these motions, with the result that the interval from one noon to the next on Mercury is equal to two revolutions, or 176 days. Thus we find that Mercury residents will experience two Mercury years per Mercury day. But with long, hot days and equally long, cold nights, Mercury is not apt to attract many visitors in the near future.

Mercury's Properties

Equatorial Radius	2440 km (= 0.382 $R_\oplus$)
Oblateness	0
Mass	3.30×10^{26} grams (= 0.055 $M_\oplus$)
Density	5.43 g/cc
Surface Gravity	0.378 *g*
Escape Velocity	4.2 km/s
Sidereal Rotation Period	58.65 days
Solar Day	176 days
Obliquity	0.0
Sidereal Revolution Period	0.241 yrs (= 88 days)
Average Distance from the Sun	0.387 AUs
Orbital Eccentricity	0.206
Orbital Inclination	7.00°
Number of Moons	0

Venus

Venus is very similar in size to the Earth and has often been called Earth's twin or sister planet. Early observers knew that Venus was closer to the Sun – and therefore hotter – and covered with a layer of dense clouds. By assuming the clouds were similar to those found on Earth, they envisioned a tropical climate for Venus, with good chances for a variety of life. Discovery of carbon dioxide in the atmosphere made the possibility of plant life on Venus even more likely. However, we now know that the temperatures on Venus are far too high for liquid water to exist, due to the **greenhouse effect**. Light from the Sun filters through the clouds and warms the surface of the planet, which then reradiates the energy as infrared rays. However, the dense carbon dioxide atmosphere absorbs the infrared rays, trapping the energy below the cloud layers and keeping the surface temperature abnormally high – nearly 900° F.

> In a greenhouse, light from the Sun filters through the glass and warms the interior, which then reradiates the energy as infrared rays. However, the glass does not allow infrared rays to pass through, thus trapping the energy inside the greenhouse and keeping the plants warm.

With its high temperatures and dense atmosphere, the surface of Venus is quite unlike that of the Earth, and certainly is unsuitable for life as we know it. Venus appears to be geologically active: radar mapping of the cloud-covered surface by the Magellan spacecraft in 1991 has revealed a variety of terrain, including impact craters and features produced by volcanic activity. The clouds are also unique: unlike our clouds of water droplets, those on Venus are made of sulfuric acid droplets.

Venus' Properties

Equatorial Radius	6052 km (= 0.949 $R_\oplus$)
Oblateness	0
Mass	4.87 x 10^{27} grams (= 0.815 $M_\oplus$)
Density	5.24 g/cc
Surface Gravity	0.905 *g*
Escape Velocity	10.4 km/s
Sidereal Rotation Period	243.0 days (retrograde)
Solar Day	117 days
Obliquity	177.3°
Sidereal Revolution Period	0.615 yrs (= 225 days)
Average Distance from the Sun	0.723 AUs
Orbital Eccentricity	0.007
Orbital Inclination	3.39°
Number of Moons	0

Like Mercury, Venus has a very slow rotation; its 243-day sidereal rotation period is the longest of any planet. In addition, its rotation is **retrograde**, or backwards from the normal counterclockwise motion of the planets. This motion couples with the planet's orbital motion to produce a solar day on Venus of 117 days. Thus, even though Venus has the longest sidereal day, its solar day is second to Mercury's in length. And while Mercury calendars have two *years* per *day*, those on Venus have approximately two *days* per *year*.

Mars

The 'red planet', Mars, has been studied with great interest for many years, due in part to its similarities to the Earth. Mars has a mostly transparent atmosphere, which allowed early astronomers to view seasonal changes in the polar ice caps and the blue-green markings on its otherwise orange surface. Such observations suggested the presence of water and perhaps plant life on Mars. Later, observations of straight-line markings and their interpretation as canals caused some to assume the presence of Martians, who supposedly constructed the canals to bring water from the polar regions to irrigate the equatorial deserts. Numerous books and movies supported this idea, but the Mariner and Viking missions to Mars in the 1960's and 70's did not. They depicted a less hospitable world with a very thin atmosphere of carbon dioxide and temperatures too low for liquid water to exist. The Martian surface is certainly *interesting*, with occasional craters, inactive volcanoes, dust storms, dry riverbeds, and polar ice caps of water ice and frozen carbon dioxide (dry ice), but there is *no* indication of life on Mars. Although it appears that in the distant past the atmosphere was denser and liquid water probably flowed on the Martian surface, the Viking spacecraft that landed there in 1976 found no conclusive evidence of any type of life. More recent Martian rovers have confirmed our suspicions of liquid water in the past and continue to explore the planet for signs of life.

Mars' Properties

Equatorial Radius	3397 km (= 0.533 $R_\oplus$)
Oblateness	0.00648
Mass	6.42×10^{26} grams (= 0.107 $M_\oplus$)
Density	3.94 g/cc
Surface Gravity	0.379 *g*
Escape Velocity	5.0
Sidereal Rotation Period	24.623 hr
Solar Day	24.620 hr
Obliquity	25.2°
Sidereal Revolution Period	1.88 yrs (= 687 days)
Average Distance from the Sun	1.524 AUs
Orbital Eccentricity	0.093
Orbital Inclination	1.85°
Number of Moons	2

Mars owns two of the three satellites that orbit terrestrial planets: Phobos and Deimos are tiny moons with irregular shapes and may be captured asteroids. Because of Phobos' very rapid orbital motion about Mars, Martian observers would see Phobos rise in the *west* and set in the *east* while Deimos follows a more normal east-to-west route.

Jupiter

Jupiter is completely different from the terrestrial planets previously described; in fact, it is the prototype of the Jovian planets. Jupiter is the largest planet in the solar system and also the most massive, containing more mass than all the other planets put together. But Jupiter's density – about one quarter the value of the Earth's density – is not extremely high because Jupiter is a gas giant, composed largely of gases of hydrogen, helium, and other lightweight elements. The planet probably does have a small core of iron and rock at the center that is surrounded by hydrogen and helium compressed to a liquid form by the tremendous pressures of Jupiter's interior. The surface of Jupiter is not solid but fluid, making it quite unlike the terrestrial planets. We cannot see this surface because it is covered by layers of clouds; the patterns we see on Jupiter – colored bands, belts, and oval spots – are all features in the cloud layers. Jupiter's rapid rotation causes considerable motion in these features, with rotating spots, and adjacent bands flowing in opposite directions. The most notable of these features is the Great Red Spot, which has been observed for over three centuries.

Jupiter's Properties

Equatorial Radius	71,492 km (= 11.21 $R_\oplus$)
Oblateness	0.0649
Mass	1.90 x 10^{30} grams (= 318 $M_\oplus$)
Density	1.33 g/cc
Surface Gravity	2.36 *g*
Escape Velocity	59.5 km/s
Sidereal Rotation Period	9.925 hr
Solar Day	9.925 hr
Obliquity	3.1°
Sidereal Revolution Period	11.9 yrs
Average Distance from the Sun	5.203 AUs
Orbital Eccentricity	0.048
Orbital Inclination	1.31°
Number of Moons	67

Jupiter has a number of satellites, with the four largest (Io, Europa, Ganymede, and Callisto) easily visible in binoculars. Their orbital periods range from two days to about two weeks, and they can be seen to change position from night to night. Io and Europa are about the size of our Moon while Ganymede and Callisto are about the size of Mercury. The Voyager flyby missions in 1979 discovered several new moons and a set of thin rings orbiting the planet. The 1995 Galileo mission and other more recent observations have pushed the moon total to several dozen, giving Jupiter the lead in this category.

Saturn

Saturn is the most distant planet to be known to the ancient astronomers; its brightness is sufficient to make it easily visible to the naked eye. In a small telescope, Saturn is a special sight because of its system of bright rings. These rings are made of millions of small particles orbiting the planet in its equatorial plane. Unlike the rings of the other Jovian planets, which are thin and relatively distinct, Saturn's rings appear to be broad and fairly continuous, without significant gaps between them.

In other respects, Saturn is another gas giant planet, smaller than Jupiter. It too is composed chiefly of hydrogen and helium, but due to its smaller mass, it is compressed less than Jupiter. As a result, Saturn has the lowest density of any of the planets – so low that Saturn could float in water if a sufficiently large bathtub could be found. Saturn's clouds are not as colorful as Jupiter's; the bands and spots found here are much more subtle. Saturn's rapid rotation has made it the most oblate planet, with a noticeable difference between its polar and equatorial diameters.

Saturn is second to Jupiter in number of moons. The larger moons appear to be solid, with surfaces heavily covered with craters. The largest moon – Titan – has its own atmosphere, which has prevented direct viewing of its surface and promoted speculation on the possibility of life having developed there. The 2004 Cassini mission to Saturn launched a special probe to Titan, which plunged through the moon's atmosphere and reported its findings.

Saturn's Properties

Equatorial Radius	60,268 km (= 9.45 $R_\oplus$)
Oblateness	0.0980
Mass	5.69×10^{29} grams (= 95.2 $M_\oplus$)
Density	0.70 g/cc
Surface Gravity	0.914 *g*
Escape Velocity	35.5 km/s
Sidereal Rotation Period	10.656 hr
Solar Day	10.656 hr
Obliquity	26.7°
Sidereal Revolution Period	29.4 yrs
Average Distance from the Sun	9.537 AUs
Orbital Eccentricity	0.054
Orbital Inclination	2.48°
Number of Moons	62

Uranus

Uranus was not studied by the early astronomers because it is barely bright enough to be seen by the unaided eye and thus easily mistaken for a faint star. It was discovered in 1781 by William Herschel, who noted that its telescopic image appeared somewhat different from that of the stars in the same field. Further observations showed that it was moving slowly among the stars – orbiting the Sun.

Uranus' Properties

Equatorial Radius	25,559 km (= 4.01 $R_\oplus$)
Oblateness	0.0229
Mass	8.68×10^{28} grams (= 14.4 $M\oplus$)
Density	1.30 g/cc
Surface Gravity	0.887 *g*
Escape Velocity	21.3 km/s
Sidereal Rotation Period	17.240 hr (retrograde)
Solar Day	17.240 hr (retrograde)
Obliquity	97.9°
Sidereal Revolution Period	83.7 yrs
Average Distance from the Sun	19.19 AUs
Orbital Eccentricity	0.047
Orbital Inclination	0.77°
Number of Moons	27

Uranus is one of the smaller Jovian planets, but it still has a diameter four times that of the Earth. Uranus is covered with a thick cloud cover and lacks a solid surface; its clouds have proved to be especially featureless, without significant spots or bands. The most distinctive feature of Uranus has always been its obliquity of 97.9°, which means that the rotational axis lies nearly in the orbital plane. (To see this effect, tip a globe until its axis is almost horizontal. Such an orientation for the Earth would result in rather dramatic seasonal changes.) At the solstices, Uranus' poles *point* almost directly toward the Sun, rather than just *tilting* toward it as the Earth's do. The land of the midnight sun (see Chapter 4) extends from the pole to within 8° of the equator on Uranus, and the Sun reaches the zenith as far north as 8° from the pole! (Of course, the cloud cover should prevent any residents there from actually viewing these phenomena.)

Uranus has a 98° obliquity, meaning its rotation is retrograde (CW); some sources will list an 82° obliquity and/or a negative rotation period to convey the same information.

In 1977 Uranus became the second planet known to have rings, but they are not easily seen from Earth. The passage of Voyager 2 in 1986 increased the number of moons of Uranus from five to fifteen , and many more have been added since then. Both the rings and the moons orbit in Uranus' equatorial plane, which is tilted by 98° from its orbital plane. At some times in its orbit, Uranus presents itself as a huge target, with the planet as the bull's-eye and the rings and moon orbits forming the surrounding rings of the target.

Neptune

After the discovery of Uranus in 1781, astronomers monitored its motion to determine its orbit. After several years, sufficient observations had been made to allow its orbit to be predicted, but in the years that followed it became apparent that Uranus was not following the predictions, moving too rapidly at first and then too slowly. Several mathematicians and astronomers suspected the presence of another planet, whose gravitational tugs would have altered Uranus' orbital speed. Their calculations resulted in the prediction of a new planet beyond Uranus. When the search was finally made in 1846, Neptune was discovered, right where the predictions had placed it.

Neptune's Properties

Equatorial Radius	24,764 km (= 3.88 $R_\oplus$)
Oblateness	0.0171
Mass	1.02 x 10^{29} grams (= 17.1 $M_\oplus$)
Density	1.76 g/cc
Surface Gravity	1.12 *g*
Escape Velocity	23.7 km/s
Sidereal Rotation Period	16.110 hr
Solar Day	16.110 hr
Obliquity	29.6°
Sidereal Revolution Period	164 yrs
Average Distance from the Sun	30.07 AUs
Orbital Eccentricity	0.009
Orbital Inclination	1.77°
Number of Moons	13

Neptune is often confused with Uranus because both planets are similar, in both size and location in the solar system. Another Jovian planet, Neptune is a bit smaller, slightly more massive, and considerably more colorful than Uranus. Voyager images from the 1989 flyby show Neptune to be quite blue, due to absorption of red light by methane in its atmosphere. Several interesting features were seen, including small white spots and one large blue oval called the Great Dark Spot. The Voyager confirmed that Neptune has a set of thin rings and also raised its total of moons from two up to eight; as with the other Jovian planets, this value has continued to increase.

Pluto

Following Neptune's discovery, its position was monitored to determine its orbit. Calculation of the orbit followed by further monitoring showed that it too was not behaving as predicted, causing several astronomers to suspect another planet. Once again searches were planned, and in 1930, young astronomer Clyde Tombaugh did indeed discover a new planet, which was given the name Pluto.

In its day, Pluto was a planet of many extremes: its orbit was the largest, most eccentric, and most highly inclined; its average orbital speed was the slowest, and its sidereal orbital period was the longest. Pluto itself turned out to be the smallest, least massive planet – a body even smaller than our Moon. Despite its small size, Pluto has a significant moon of its own, called Charon, whose discovery in 1978 enabled accurate determinations of Pluto's size and mass; recent observations have now brought Pluto's moon total to five.

Pluto's icy composition and frozen atmosphere made it neither a terrestrial nor a Jovian planet; Pluto may well have more in common with comets or some of the Jovian moons than with the other planets (the New Horizons mission should provide more answers when it arrives in 2015). As it turns out, tiny Pluto was far too small to have been responsible for the perturbations in Neptune's orbit that led astronomers to search for a ninth planet. This has resulted in speculation about a tenth planet, beyond Pluto, but no such planet has yet been found.

Pluto's Properties

Equatorial Radius	1195 km (= 0.180 $R_\oplus$)
Oblateness	0
Mass	1.3 x 10^{25} grams (= 0.0022 $M_\oplus$)
Density	1.1 g/cc
Surface Gravity	0.083 *g*
Escape Velocity	1.3 km/s
Sidereal Rotation Period	6.387 days (retrograde)
Solar Day	6.387 days (retrograde)
Obliquity	119.6°
Sidereal Revolution Period	248 yrs
Average Distance from the Sun	39.48 AUs
Orbital Eccentricity	0.249
Orbital Inclination	17.14°
Number of Moons	5

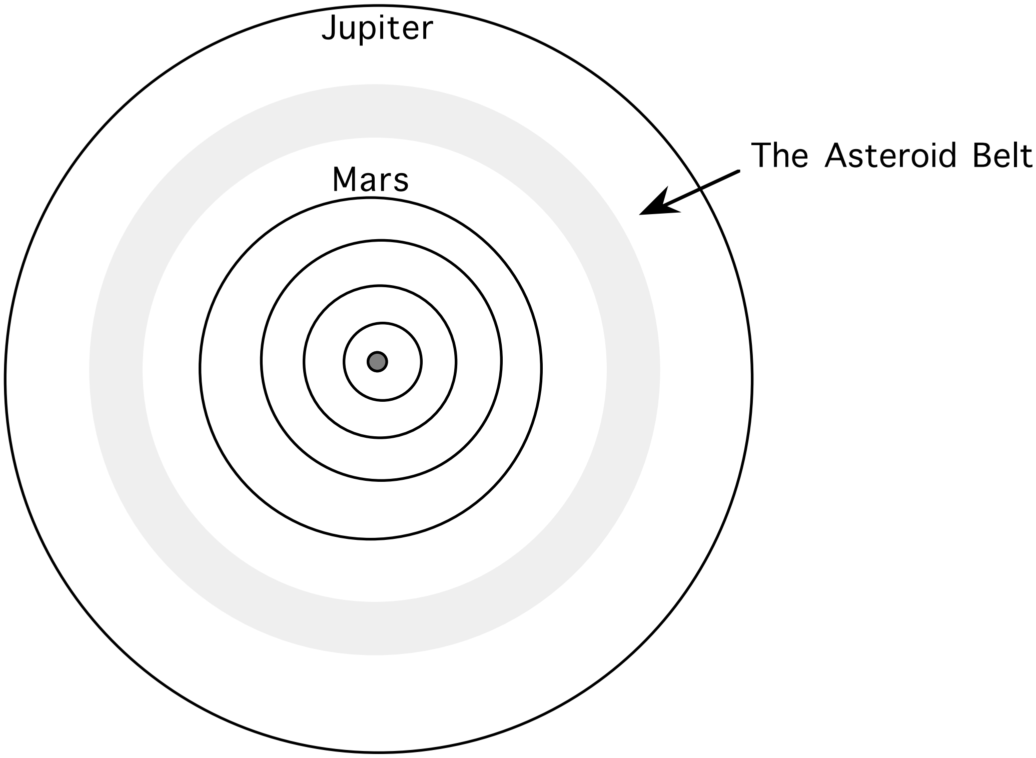
In 2006 Pluto's status changed dramatically when astronomers redefined Pluto as a '**dwarf planet**' – a move that did not exactly meet with unanimous support.

The 2006 definition by the International Astronomical Union (IAU) states that, in the solar system, a **planet** is a celestial body that

- is in orbit around the Sun,
- has sufficient mass so that it assumes a hydrostatic equilibrium (nearly round) shape, and
- has "cleared the neighborhood" around its orbit.

A non-satellite body fulfilling only the first two of these criteria is classified as a **dwarf planet**.
A non-satellite body fulfilling only the first criterion is termed a **small solar system body** (**SSSB**)

Figure 8.1: The asteroid belt



Asteroids

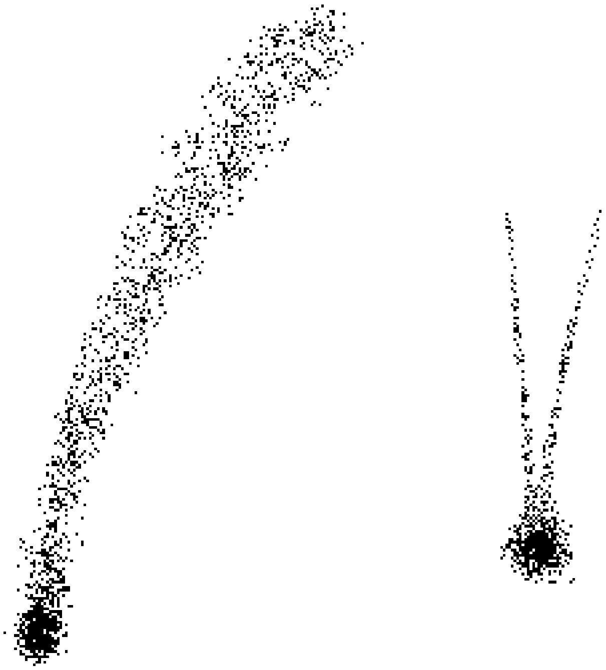
As already mentioned in Chapter 7, there are a number of smaller bodies orbiting the Sun; some of these are called **asteroids**, or **minor planets**. Most of the asteroids seem to have orbits that lie between the orbits of Mars and Jupiter, a region known as the **asteroid belt** (see Figure 8.1). Although there are thousands of asteroids known and probably many more yet undiscovered, the spacing between asteroids is still quite large; our space probes to the outer planets have all passed through the asteroid belt without colliding with anything large enough to damage them.

The typical asteroid is not spherical but irregular in shape, a few kilometers across. The largest asteroids are a few hundred kilometers across, but there are not many of these; the total asteroid mass, if combined, would form a body smaller than the Moon. The largest asteroid, Ceres, is now classed as a **dwarf planet**, as is Pluto; the other asteroids are **SSSBs**.

Most asteroids are composed of rocky material, believed to be left over from the time of the formation of the solar system. Whereas most such **rocky planetesimals** collided with each other and formed into planets, the asteroids were apparently kept stirred up by the tidal forces of Jupiter and never had a chance to form a single body.

Asteroids do occasionally collide and break apart, providing fresh debris in the solar system. Some of these small chunks of rock and iron eventually collide with the Earth and produce **meteors** as they burn up in our atmosphere or **meteorites** when they land on the Earth's surface. A collision between the Earth and a whole asteroid could be disastrous, even if the asteroid is fairly small. Such collisions were common billions of years ago as the Earth was forming, but they are quite rare now. There is some evidence that such a collision might have led to the extinction of the dinosaurs about 65 million years ago. Let us hope that we do not suffer a similar fate, as there is little we could do to avoid such a catastrophe today.

Figure 8.2: Two comets with tails



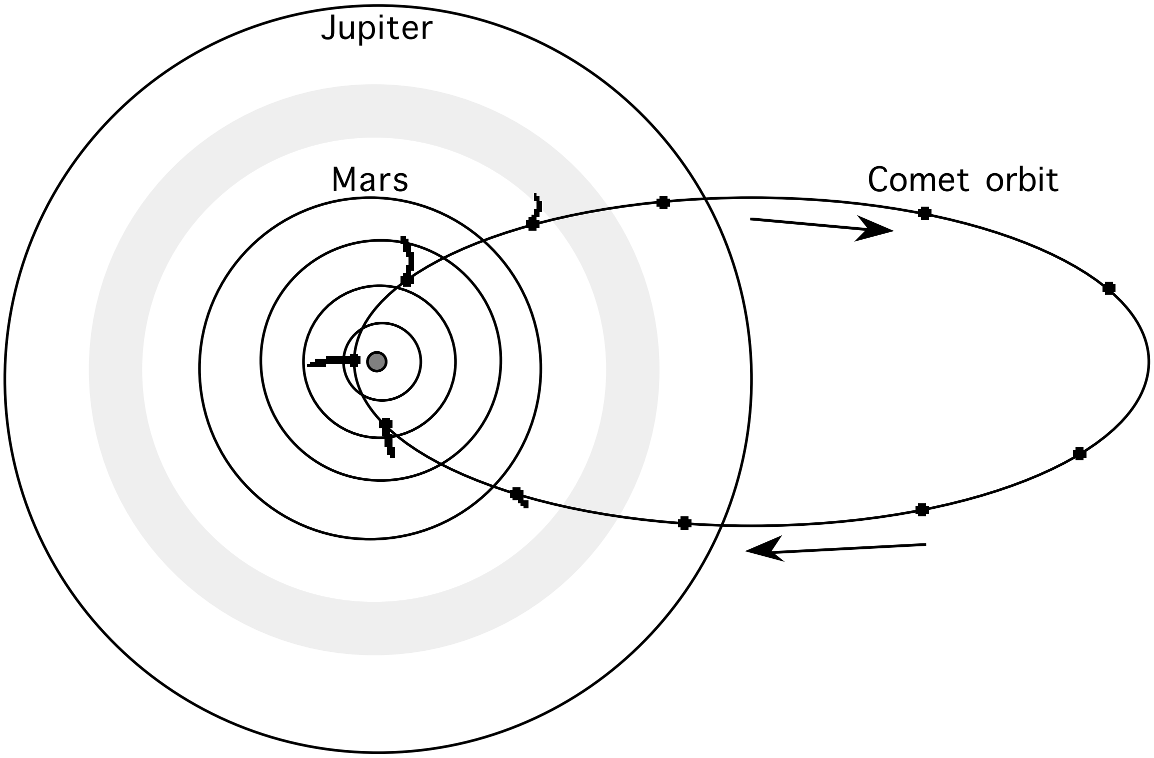
Comets

There are other bodies orbiting the Sun that are neither planets nor asteroids; these are the **comets**, which can provide spectacular shows in the night sky. Comets were observed (and completely misunderstood) by early sky watchers, who thought these strange lights were part of the Earth's atmosphere. They seemed to appear rather suddenly, remain visible for a few weeks, and then disappear. They did not resemble any of the normal celestial objects – Moon, planets, or stars – instead being rather fuzzy and often displaying a long tail, as shown in Figure 8.2. They were generally regarded as bad omens, responsible for all sorts of human misery – of which there was plenty – on Earth.

We now know that the comets' strange appearance results from their composition. Whereas the asteroids tend to be mostly rocky, the comets seem to be composed of frozen gases of lightweight elements. The standard model of a comet **nucleus** is a '**dirty snowball**', a mass of ices a few kilometers across with bits of rock and dust imbedded in it. Comets are now classed as **SSSBs**.

These **icy planetesimals** orbit the Sun in highly elongated orbits. Most of their time is spent far from the Sun, but periodically they head for the inner solar system, swoop around the Sun, and leave after only a few weeks or months of visibility. Their presence is made even more spectacular by the growth of a tail. As the comet nears the Sun, it is warmed by the Sun's radiation. Some of the ices vaporize and stream out behind the comet forming a tail, which always points away from the Sun, as shown in Figure 8.3. Some of the snowball's dirt is released as the ice melts, providing additional material for the tail and eventually more debris for the solar system collection.

Figure 8.3: A comet orbit



While there are usually a few comets passing through the inner solar system at any given time, only rarely do they become bright enough to view without a telescope. Although they can be found in any part of the sky, the brighter ones are often seen best when they are closest to the Sun and have the longest, brightest tails. As such, they will be seen either in the eastern sky, before sunrise, or in the western sky after sunset (similar to the viewing of Mercury and Venus as morning stars or evening stars, as discussed in Chapter 7). Comets do not *streak* across the sky; instead they hang among the stars, gradually changing their position from night to night. Those that pass close to the Earth will seem to change most rapidly. There is another group of objects that do make very brief appearances in the sky; these are the **meteors**.

Meteors

The solar system is strewn with debris, small bits of rock that have been produced by collisions between asteroids or released by the evaporation of comets. Those bits of space debris that have orbits about the Sun that carry them into the Earth's path are called **meteoroids**. When a meteoroid encounters the Earth, it plunges through the atmosphere at a high rate of speed. The meteoroid's passage through the atmosphere creates friction with the air molecules, heating them enough to cause them to radiate light. The luminous trail of heated air produced in this fashion is called a **meteor**. Other common names for this phenomenon include **shooting star** and **falling star**; but clearly, meteors have nothing to do with stars.

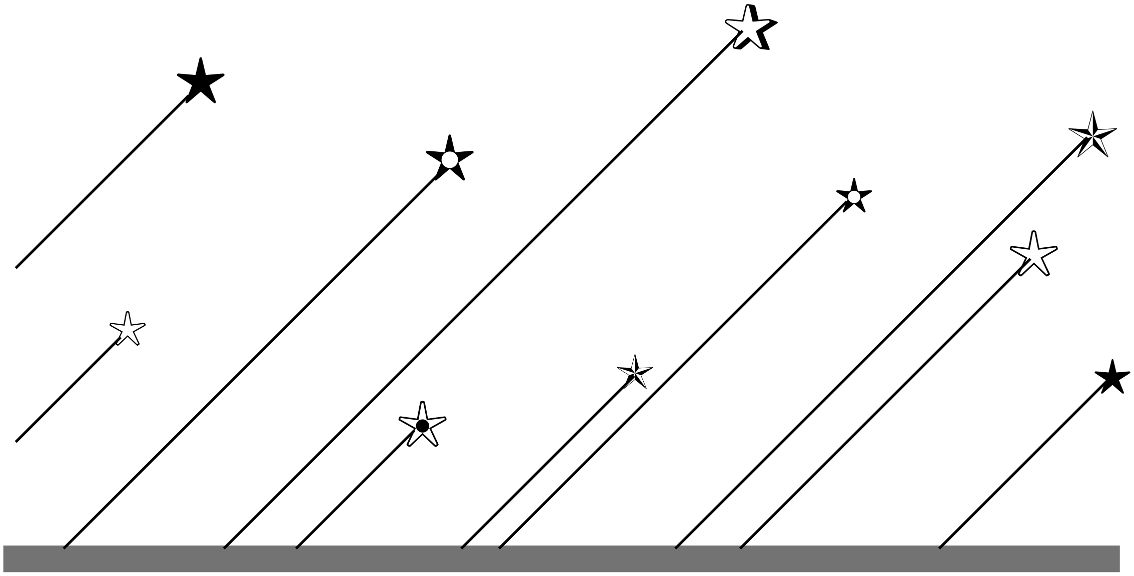
Because most meteoroids are quite small, they tend to burn up or vaporize as they pass through the atmosphere. However, the larger ones are not destroyed in this manner but manage to land on the Earth; these rocks are called **meteorites**. Most meteorites are made of stony materials that may be difficult to distinguish from ordinary terrestrial rocks. Some of the meteorites are made of nickel and iron and thus are easier to identify as visitors from space.

Meteors are not rare; in fact they can be seen on any clear, moonless night at a location where the sky is relatively dark. The meteor's streak will be brief, lasting only a second or so before it fades from view. Meteors can occur in any part of the sky at any time, but they are more abundant *after* midnight when the observer is on the *front* half of the Earth as it orbits the Sun, plowing through the meteoroids.

> In the same manner, a car driving down the road on a warm summer evening will collect more bugs on its windshield than on its rear window.

As comets evaporate, they release debris that becomes strewn along their orbits. If the Earth passes through the orbit of a comet, it will collide with an increased number of meteoroids, causing an increased number of meteors. Such an event, called a **meteor shower**, happens at the same point in the Earth's orbit – and thus on the same date – every year. Furthermore, because these meteoroids are all traveling in about the same direction in space, the meteors they create seem to all radiate from the same point in the sky. Meteor showers are named for the constellation in which this **radiant** is located. One of the most famous showers is the Perseids, which occurs around August 11 each year and has a radiant in the constellation Perseus.

Chapter 9: Motions of the Night Sky



The principal celestial bodies discussed so far in the previous chapters have been a limited number of reasonably bright, close objects – the Sun, the Moon, and the planets. However, a glance at the night sky reveals many, many more faint points of light: the distant stars. Each of these is really a sun, perhaps with planets orbiting about it. Many of them are double or multiple systems with two or more suns orbiting each other. But to us, they appear as small lights spread over the whole sky in a non-uniform distribution.

It is interesting to be able to locate particular stars and groups of stars in the night sky. (It is also a *practical* skill to have if you are ever lost in the woods.) The reason that locating stars is not necessarily easy is that the sky appears to move, in response to the motions of the Earth. In the next two chapters we will learn how the Earth's motions (described in Chapter 4) affect the appearance of the sky.

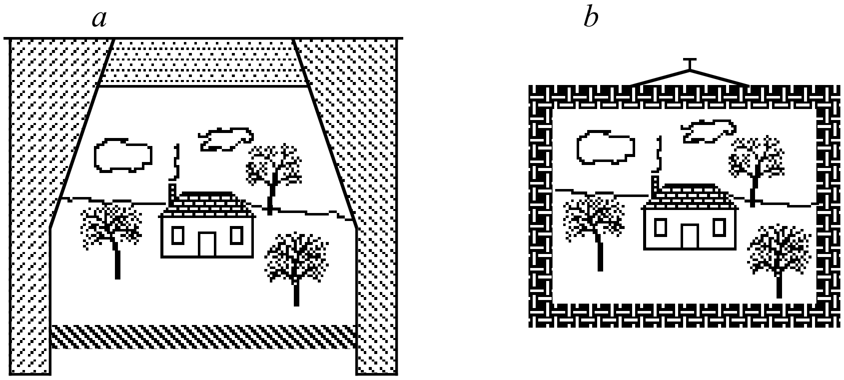
The Celestial Sphere

To help us locate a particular star, we need to have some means for describing positions in the sky. Our first step will be to understand the *shape* of the sky; then we can consider its apparent motion.

It may seem odd to discuss the *shape* of the sky because space extends in all directions without any real boundaries. In this context, we will consider the sky to be our window on the universe – we look out through the sky to view the stars around us, which are spread throughout space.

> As an analogy, consider a window through which we look out to see houses and trees in the distance (Figure 9.1a). Then consider a painting of the same houses and trees, hanging on the wall beside the window (Figure 9.1b).

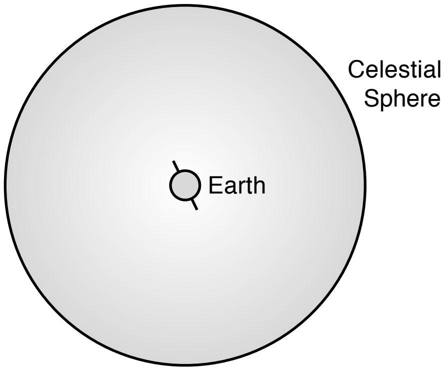
Figure 9.1: Our view of the sky



> We know that the objects we see through the window lie at different distances from us, while the objects in the picture are all painted on the same layer of canvas. Obviously, if we are trying to measure the relative distances of the houses and trees, we must use the view through the window. But if we are only concerned with the horizontal and vertical positions of these objects, we could use either the painting or the view through the window to make our measurements, whichever is more convenient. In much the same way, we will imagine the sky to be a surface, with stars glued on it. The stars' actual distances from us are unimportant at this time, and we need not consider them.

When we look up at the sky, we see stars in all directions around us. It is as if a huge bowl, lined with stars, had been turned upside-down over us. Because we know that persons on the other side of the Earth have the same experience, we extend our bowl to make it a complete sphere around the Earth. This **celestial sphere**, as we call it, is very large – so large that the Earth would be just a tiny speck in it if we were to draw it to scale.

Figure 9.2: The celestial sphere

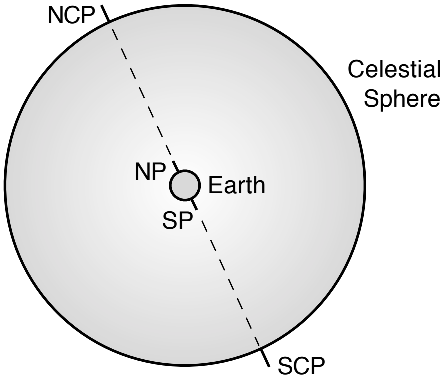


The celestial sphere is totally fictitious: there is no giant sphere around the Earth. But it is useful, for the purpose of describing the sky, to pretend that it does exist.

Within the celestial sphere, the Earth is not stationary. It rotates – as a globe does when it is spun – from west to east, or counterclockwise (CCW) as seen looking down on the North Pole. Of course we live on the Earth and rotate with it. Because of this we do not perceive the Earth's rotation; instead, it seems to us that everything else is moving. Objects in the sky seem to move in a direction opposite to the turning Earth – that is, from east to west. As a result of the Earth's rotation, the celestial sphere and the objects on it (Sun, Moon, stars, etc.) appear to move from east to west, about once per day.

We saw in Chapter 4 that the Earth rotates about an axis through the North and South Poles. We can extend that axis out into space until it intersects the celestial sphere at the **north** and **south celestial poles** – the **NCP** and **SCP** as shown in Figure 9.3.

Figure 9.3: The celestial poles



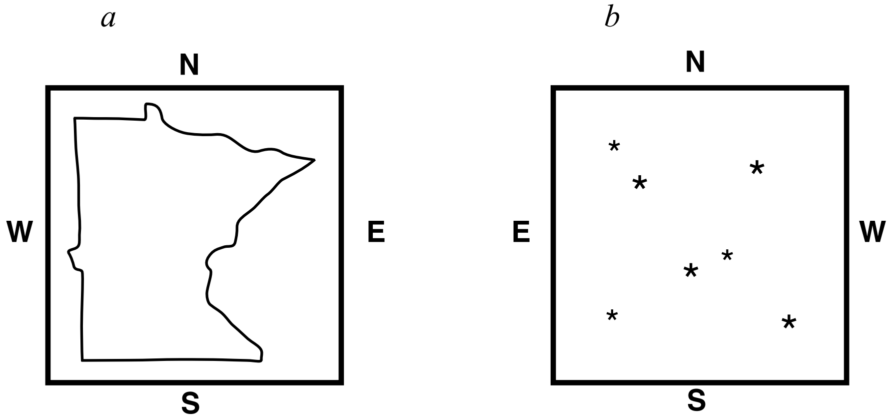
These special points on the celestial sphere are imaginary – there is no star or other celestial object located there. These points will serve as our reference points in the sky, and we can use them to locate stars, planets, and other objects.

Directions in the Sky

We have used directions – north, south, east, and west – in Chapter 4. You recall that on the surface of the Earth where we live, we defined north very simply as the direction *towards the North Pole*. South is *towards the South Pole*. East is the direction of the Earth's rotation, and west is the opposite.

In a similar manner, we can define directions on the celestial sphere. Just as it is reasonable to inquire which way is north from a given town, we can also ask which way is north from a given star. The answer is similar to that for the Earth: north is the direction *towards the north celestial pole*, south is *towards the south celestial pole*; east is still the direction of the Earth's rotation, while west is the direction of the celestial sphere's apparent motion. Thus, to someone looking through the celestial sphere at the Earth, the directions on each would match up in the same way – north with north, east with east, and so on.

Figure 9.4: Directions (a) on the Earth and (b) in the sky

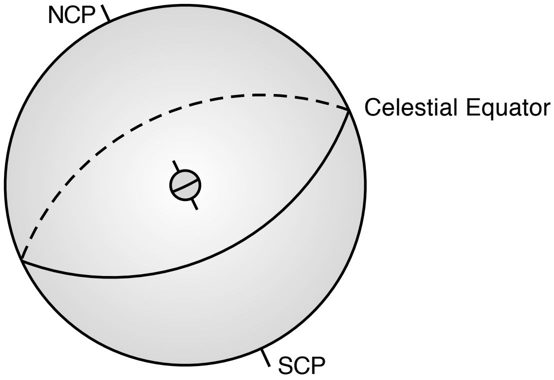


However, to an observer on the Earth's surface, located *between* the Earth and the celestial sphere, the matchup is a bit confusing. Figure 9.4a shows a map of Minnesota with north at the top, west on the left, etc. Figure 9.4b shows a map of the sky, which has north at the top and west on the right!

The reason for this apparent contradiction is simple. As you look at Minnesota on a globe, you are looking *down* at the ground, and west is on your left. But in order to look *out* at the sky, you must turn your body around, causing west to now be on your right side.

> Similarly, if you stand facing your dance partner, your right hand meets his left hand, and you are looking in opposite directions.

Figure 9.5: The celestial equator

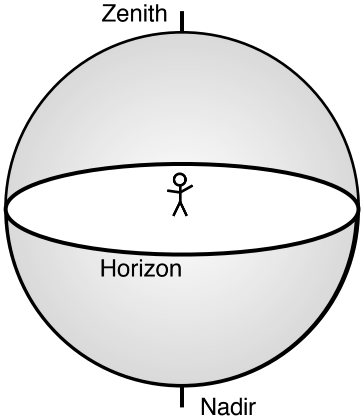


There is another set of reference points on the Earth, each of which is equidistant from the North and South Poles. We call this circle the Earth's equator. There is a similar circle around the celestial sphere, called the **celestial equator** (see Figure 9.5), which lies in the same plane as the Earth's equator. Both circles divide their respective spheres into two hemispheres – northern and southern.

Viewing the Sky

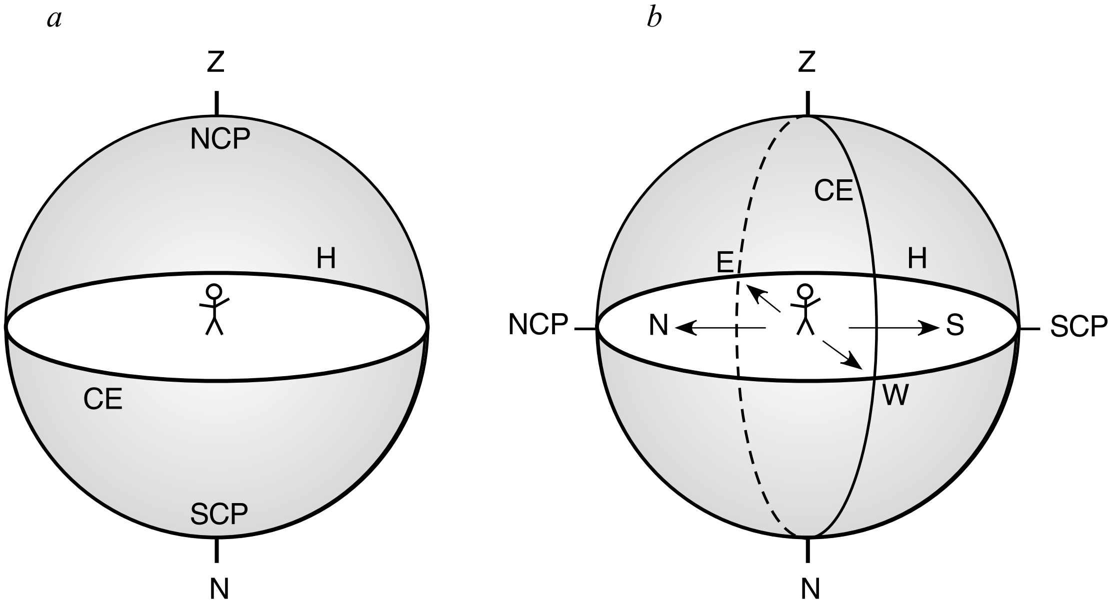
We are now ready to talk about the appearance of the sky. If you go outside on a clear night and look up and all around you at the sky, you should be able to see about half of the celestial sphere. You cannot see the other half because the Earth is in the way. In Figure 9.6 we draw the celestial sphere with a **great circle** dividing it into two halves. This circle, called the **horizon**, divides the sky from the Earth; it separates the part of the celestial sphere that you *can* see from the part that you *cannot* see.

Figure 9.6: Horizon, zenith, and nadir



This figure also shows two more special points on the celestial sphere: The point directly overhead is called the **zenith**, while the point directly below (opposite the zenith) is called the **nadir**. The zenith, nadir, and horizon are all fixed to the observer. Each person has her own personal set of these, which she carries around with her from place to place. Your zenith is very slightly different from that of your friend seated only a few feet away. (The zenith and horizon were also mentioned in Chapter 4 in our discussion of the Sun's motion in the sky.)

Figure 9.7: The sky from (a) the North Pole and (b) the Equator



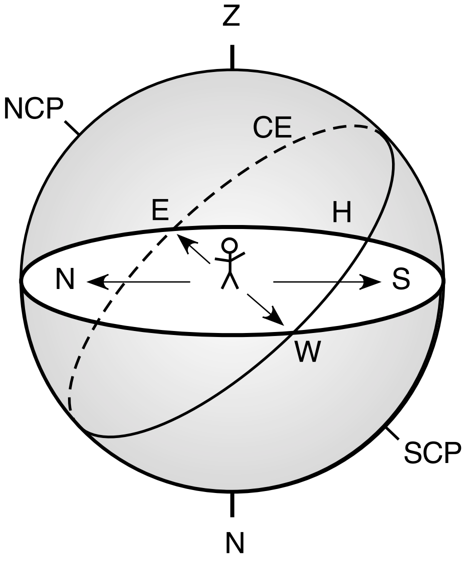
We now have two sets of reference points and circles: how do they match up? As you look at the sky, your zenith is overhead, but where is the north celestial pole? Because the NCP is aligned with the Earth's axis while the zenith is aligned with you, the relative positions of the NCP in your sky will depend on your location on Earth – specifically, on your latitude.

Figure 9.7a shows the view from the North Pole (latitude = 90°). Here the NCP is directly overhead, the SCP is at the observer's nadir, and the celestial equator circles around the horizon. From this location, only the northern celestial hemisphere is above the horizon; the southern celestial hemisphere cannot be seen.

Figure 9.7b shows the view for an observer located at the equator (latitude = 0°). For this person, the celestial equator passes overhead through the zenith and circles down through the nadir while the celestial poles lie on the northern and southern horizons. Equatorial observers can thus see half of the northern and half of the southern hemispheres at any time.

For middle latitudes the situation is more complicated. As an example, consider the view from Minnesota, located about halfway between the equator and the North Pole. As seen in Figure 9.8, the NCP will be found about halfway between the northern horizon and the zenith, the SCP will lie below the southern horizon, about halfway from the horizon to the nadir, and the celestial equator will intersect the horizon at an angle, reaching halfway up to the zenith and halfway down to the nadir. Most of the sky visible to Minnesotans is in the northern celestial hemisphere, but a small portion of the southern celestial hemisphere is also seen.

Figure 9.8: The sky from Minnesota



The precise positions and angles depend on the observer's latitude. For an observer at Mankato, Minnesota (latitude = 44° N), the NCP is 44° above the northern horizon, and the SCP is 44° below the southern horizon. The celestial equator reaches 46° above the southern horizon, dips 46° below the northern horizon, and makes an angle of 46° with the horizon where it crosses. An observer in Austin, Texas (latitude = 30°) would have the NCP 30° above the northern horizon and the SCP 30° below the southern horizon; the celestial equator would reach from 60° above the southern horizon to 60° below the northern horizon, making an angle of 60° where it crosses the horizon.

Effects of Rotation

Now that we understand how our view of the sky depends on our latitude, let us turn on the Earth's rotation – and suddenly the sky moves! Rotation of the Earth gradually varies the direction we are looking – much as a rider on a merry-go-round has a constantly changing view of the rest of the fair. Just as the rides, booths, and people at the fair seem to fly by as we ride the merry-go-round, the stars will appear to move across the sky as the Earth turns, although much more slowly. The paths the stars follow across the sky depend on their locations on the celestial sphere. The direction they move is simple: as the Earth rotates eastward, the celestial sphere appears to move westward. Thus, the stars constantly move westward across the sky (with west as indicated in Figure 9.4b).

The simplest way to picture the motion of points on the rotating celestial sphere is to observe another rotating sphere, such as a spinning globe. Begin by looking at the North Pole. As the globe spins, the North Pole remains in the same place; similarly, the NCP does not move but stays in the same place in our sky. Points on the globe close to the North Pole (such as the northern tip of Greenland) describe small circles about the pole as the globe spins, while points farther from the pole (such as the British Isles) move in larger circles. In the same manner, stars near the NCP move in small circles about it while stars farther away from it move in circles of even larger radii.

When looking directly at the equator on the spinning globe, we see that although it is certainly moving in a circle, its motion appears more as a straight line across our view. Similarly, the stars at the celestial equator will seem to be following straight paths rather than moving in circles. This is because we are at the center of the circle they follow and thus do not readily perceive the curvature.

> We have a similar problem when looking at the horizon, which extends as a huge circle around us. Despite its circular nature, any small portion of the horizon appears to us as a straight line dividing the sky from the ground (ignoring complicating effects such as mountains or hills).

Of course, the motion of the sky is very gradual because the Earth turns slowly; therefore the movement of the stars is not immediately apparent to the casual observer. Over a sufficient length of time it might be noted that a given star has changed its position (with respect to a reference point such as a tree or building on the horizon), but this observation requires that the observer remain in the same position over this interval in order to notice the effect. Relatively few people are inclined to do this these days, unless they have gone outside specifically to watch the sky.

In order to demonstrate that this motion does take place, we need either a long time base – so that changes will be quite obvious – or a device that can continuously record positional changes. For the latter case, a camera will serve quite well if it is equipped with a 'B' or 'Bulb' setting on the shutter (which allows the shutter to be locked open for any length of time). Pointing such a camera at the sky on a clear, moonless night, away from streetlights, and locking the shutter open for a period of several minutes will produce a picture showing the **diurnal** (daily) **motion** of the stars. The streaks across the film left by the stars as they move are called **star trails**. Longer exposures produce longer trails.[*]

> The advent of digital cameras has complicated this process, as such cameras are generally incapable of making long time exposures of several minutes or hours. And the decline of film cameras has made supplies of suitable film very difficult to obtain. Star trails may have become a lost art.

---

[*] See **PHOTOGRAPHING THE STARS** in the Appendix.

Star Trails

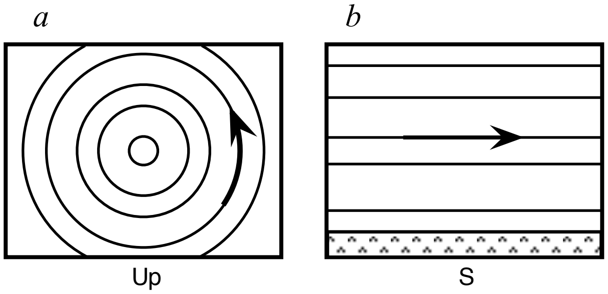
The shape of the star trails depends on which part of the celestial sphere the camera was photographing, and this in turn depends on the observer's latitude and the direction the camera was pointed. To illustrate, let us take a trip to different locations on the Earth – the same places visited just a few paragraphs above.

Our first stop is the North Pole, where the sky appears as shown in Figure 9.7a (above). At this location, we will point our camera in two different directions: straight up, and toward the southern horizon.

If we point a camera straight up at the zenith, the NCP will be in the center of our picture; because the stars appear to move in circles about the celestial poles, we should photograph circular star trails. The direction of the stars' motion will be westward, or counterclockwise about the NCP as indicated in Figure 9.9a.

> Some people are confused by the counterclockwise motion of these stars. They recall from Chapter 4 that the Earth turns counterclockwise as seen looking down on the North Pole and reason that the stars must appear to go the opposite direction – clockwise. But remember, if you are looking *down* on the North Pole, watching the Earth turn counterclockwise, you must turn around to look *up* at the NCP to see the stars move around it. This 'turn around' reverses your left and right and turns what you thought would be clockwise motion back into counterclockwise motion. This is similar to what happened to east and west earlier in this chapter when we compared maps of the sky with maps of the Earth (Figure 9.4).

Figure 9.9: Star trails at the North Pole



At the North Pole the celestial equator lies right along the horizon. Therefore, when we look to the south – at the North Pole, *every* direction is south – the stars should be moving parallel to the horizon from east to west (left to right), and the star trails should be nearly straight lines, as in Figure 9.9b.

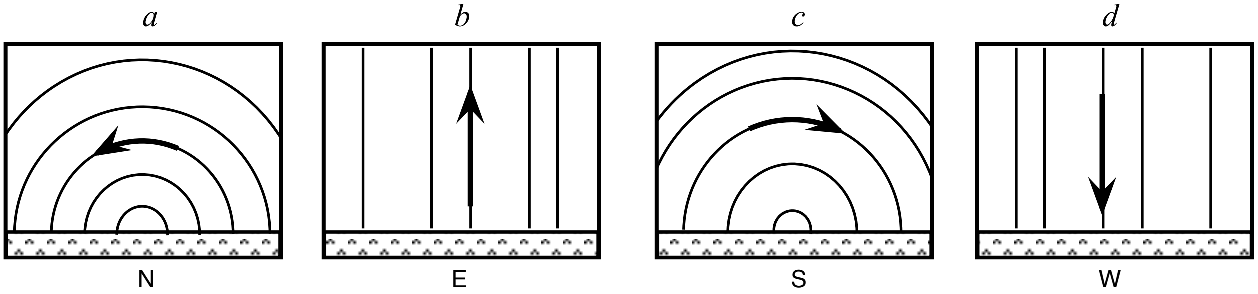
We see then that at the North Pole, the stars circle counterclockwise about the NCP and cruise parallel to the horizon from left to right (east to west), never rising or setting. The same stars – those in the northern celestial hemisphere – are always above the horizon, while the other half of the celestial sphere remains hidden from view below the horizon.

If we were to go to the South Pole, we should find a similar view, but with a few directions reversed. The stars would circle *clockwise* about the *SCP* at the zenith and cruise parallel to the horizon from *right* to *left* (but still east to west), again never rising or setting. Only southern celestial hemisphere stars would be visible, with the northern celestial hemisphere always below the horizon.

Instead of visiting the South Pole, we shall go elsewhere on the Earth. Wherever we go, certain constants will remain: the stars will always move counterclockwise about the NCP, clockwise about the SCP, and parallel to the celestial equator, always moving from east to west.

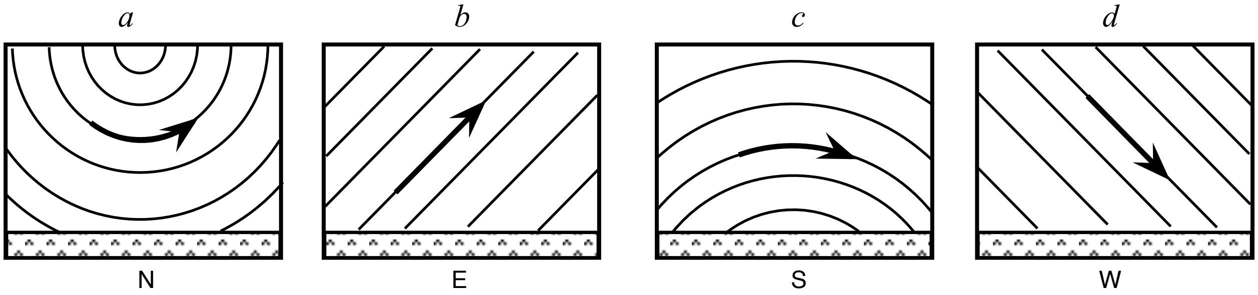
Our next stop is the equator. As Figure 9.7b shows, the NCP and SCP will be on our northern and southern horizons, respectively. Therefore, when we look north, we should see stars moving in counterclockwise circles about the NCP (Figure 9.10a) while to the south, they will be moving clockwise about the SCP (Figure 9.10c). In each case, our star trails will be semicircles. To the east or west of the equatorial observer, the celestial equator intersects the horizon at a 90° angle. Star trails in these directions will be vertical, with the stars moving upwards in the east (Figure 9.10b) and downwards in the west (Figure 9.10d).

Figure 9.10: Star trails at the Equator



Of course, relatively few people live at the poles or the equator, most preferring a more moderate latitude (and climate). For a representative view, we will again visit Mankato, Minnesota. Here we find the NCP located 44° above the northern horizon, with the SCP hidden below the southern horizon as in Figure 9.8.

Figure 9.11: Star trails in Minnesota



Pointing our camera to the north, we find the NCP at the top of, or just above our picture, and the stars moving in counterclockwise circles about it. Only the lower portions of these circles appear in our picture, as arcs that are concave upward (Figure 9.11a). With the camera pointed south, we can photograph only the upper portions of the clockwise circles about the SCP, producing trails that are concave downward (Figure 9.11c).

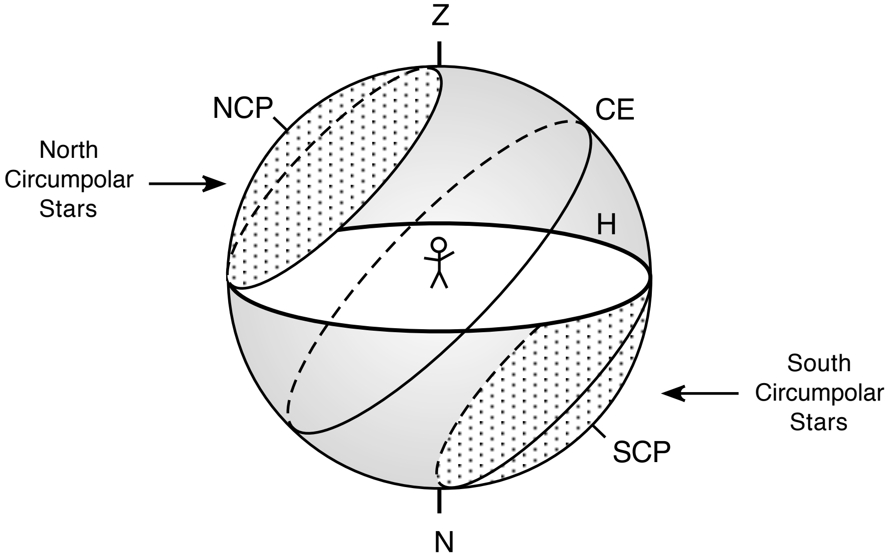
Figure 9.8 showed that the celestial equator intersects the horizon at a slant in the east and west. This slant shows up in the star trails for these directions: the stars move up and to the right as they rise along the eastern horizon (Figure 9.11b) and down and to the right as they set along the western horizon (Figure 9.11d).

Star Rise and Star Set

In general, stars rise all along the eastern horizon, move across the sky as shown by the star trails, and set all along the western horizon. A star that rises directly east will set directly west. One that rises south of east will set south of west; and one that rises north of east will set north of west.

Depending on the observer's latitude, there may be some stars that never rise or set because their star trails do not intersect the horizon. Such stars are called **circumpolar** stars because they are near the celestial poles. At the North Pole, *all* stars are circumpolar, while at the equator, *none* of them are. At other latitudes there will be *some* circumpolar stars and others that rise and set regularly. Figure 9.12 shows the location of the circumpolar stars for observers in Mankato, Minnesota, at 44° N Latitude. Because the NCP is 44° above the northern horizon at Mankato, all stars within 44° of the NCP (or within 44° of the SCP) will be circumpolar.

Figure 9.12: Circumpolar stars for Mankato, Minnesota



Stars in the dotted region around the NCP are circumpolar because they never go below the horizon. Stars in the dotted region around the SCP are also circumpolar, but they can never be seen from this latitude because the Earth's rotation never carries them above the horizon. The dotted regions of circumpolar stars would be smaller for observers at latitudes closer to the equator and larger for observers closer to the poles.

In summary, the Earth's eastward rotation causes the sky to appear to turn from east to west about us every day. Because the Earth is spherical, our view of the sky varies with latitude.

Effects of Revolution

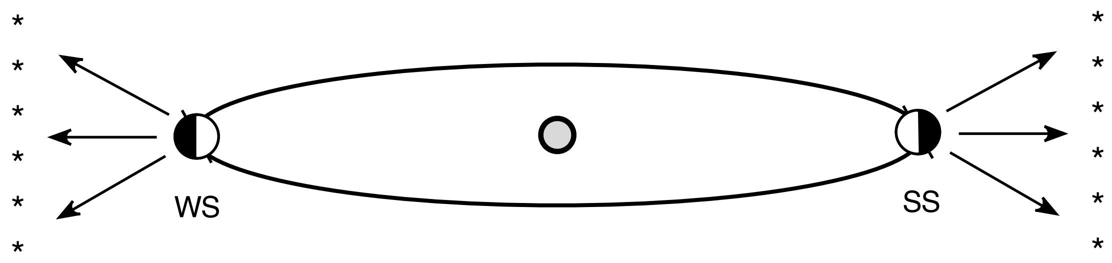
Now that we understand the changes in the night sky that are the result of the Earth's rotation, it is time to add in the changes produced by Earth's revolution. Both motions are periodic: while the rotation period is about one day, the revolution period is about one year. This means that changes in the appearance of the sky that are due to revolution will be much more gradual than the diurnal motion caused by rotation. To illustrate why revolution causes our view of the sky to change, consider the following example:

Figure 9.13 shows the Earth at two different positions in its orbit about the Sun. At the winter solstice position, a person observing the night sky would see stars as shown, on the left side of the celestial sphere.

The same person observing the night sky six months later at the summer solstice position would be looking at stars on the opposite side of the celestial sphere. Clearly, different stars are seen in different seasons as the night side of the Earth is directed toward different portions of the celestial sphere.

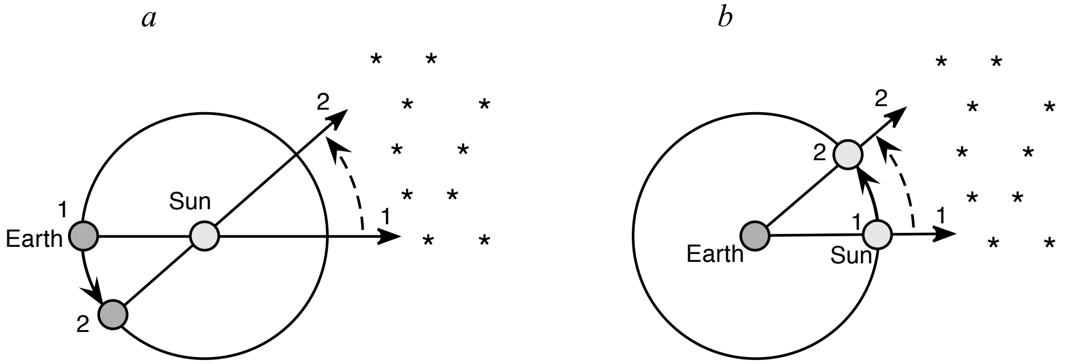
The rate of change is very gradual. From one night to the next, not much difference would be seen, but over the course of several weeks, the accumulated change becomes quite evident. If we could turn off the Earth's rotation and the diurnal changes that it causes, we would see that the net effect of the Earth's orbital motion is to cause a slow westward drift of the stars in the night sky. Thus, both rotation and revolution cause the stars to appear to move about us, but at different rates. The actual position of the stars at any given moment depends on the time of day or night (rotation position) and the day of the year (revolution position).

Figure 9.13: Sky changes due to revolution



Another way to think about the orbital changes is to consider the Sun's position among the stars. (The Sun's brilliance prevents us from seeing stars in the daytime sky, but they are out there just the same.) As the Earth orbits about the Sun, the Sun appears to change its position among the stars, as shown in Figure 9.14a. The Earth's counterclockwise motion about the Sun causes the Sun to *appear* to move counterclockwise about the Earth, or eastward with respect to the stars, as shown in Figure 9.14b.

Figure 9.14: The Sun's apparent motion through the stars

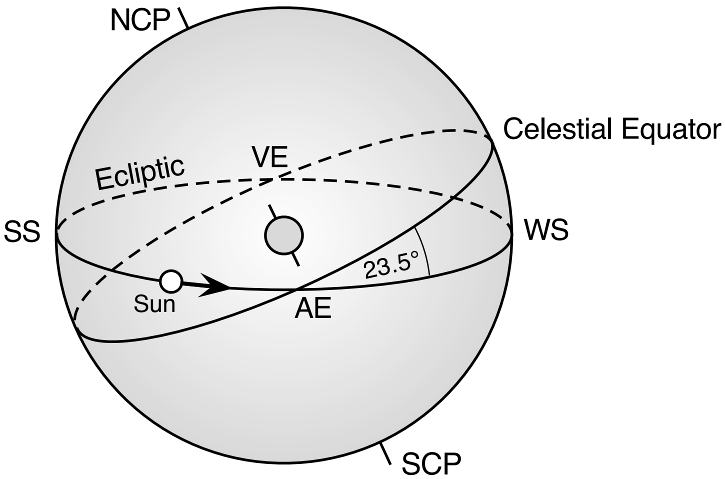


If we consider the fixed-Earth view of Figure 9.14b, we find that the Sun *appears* to travel in a circular path about the Earth. We represent this path as a circle around the celestial sphere; its name is the **ecliptic**. As seen in Figure 9.15, the ecliptic is not in the same plane as the celestial equator, but rather is inclined to it by about 23 $^1/_2$ degrees. As noted already in Chapter 4, this angle is called the obliquity, or the tilt.

The ecliptic and the celestial equator do not coincide because they are related to separate motions of the Earth. The celestial equator is determined by the Earth's rotation while the ecliptic is determined by the

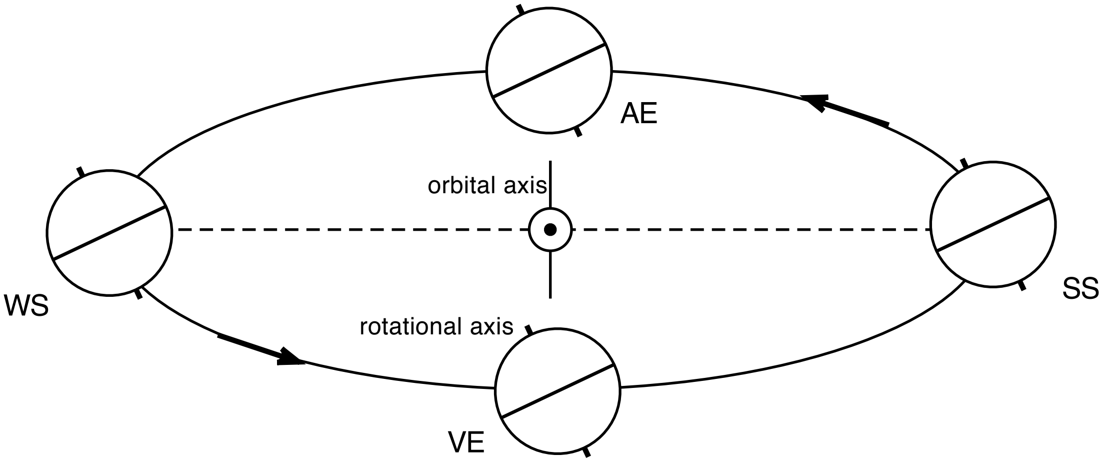
Earth's revolution. As these two motions are independent of each other, there is no reason for the ecliptic and the celestial equator to have any particular alignment.

Figure 9.15: The ecliptic



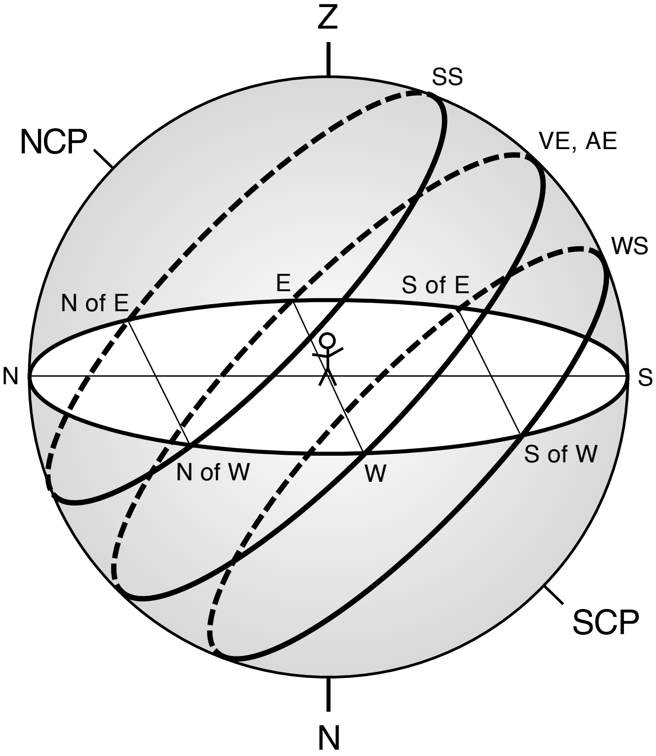
The Sun's motion in Figure 9.15 is counterclockwise around the ecliptic, from the summer solstice (SS) to the autumnal equinox (AE) to the winter solstice (WS) to the vernal equinox (VE). Note that when the Sun is at the summer solstice, the North Pole is tilted toward the Sun, while at the winter solstice, the North Pole is tilted away from the Sun. Compare this fixed-Earth view with the fixed-Sun view of Figure 4.9.

Figure 4.9: Solstices and equinoxes



The directions of sunrise and sunset were discussed in Chapter 4; we can now explain the observed variation in another way: When the Sun is on the portion of the ecliptic that lies in the *northern* celestial hemisphere, it will obviously be *north* of the celestial equator. Because the celestial equator rises *directly east* and sets *directly west* (see Figure 9.8), the Sun (which is *north* of the celestial equator) must rise *north of east* and set *north of west* during this period, as shown in Figure 9.16. This will occur from the vernal equinox through the summer solstice to the autumnal equinox – the seasons we call spring and summer.

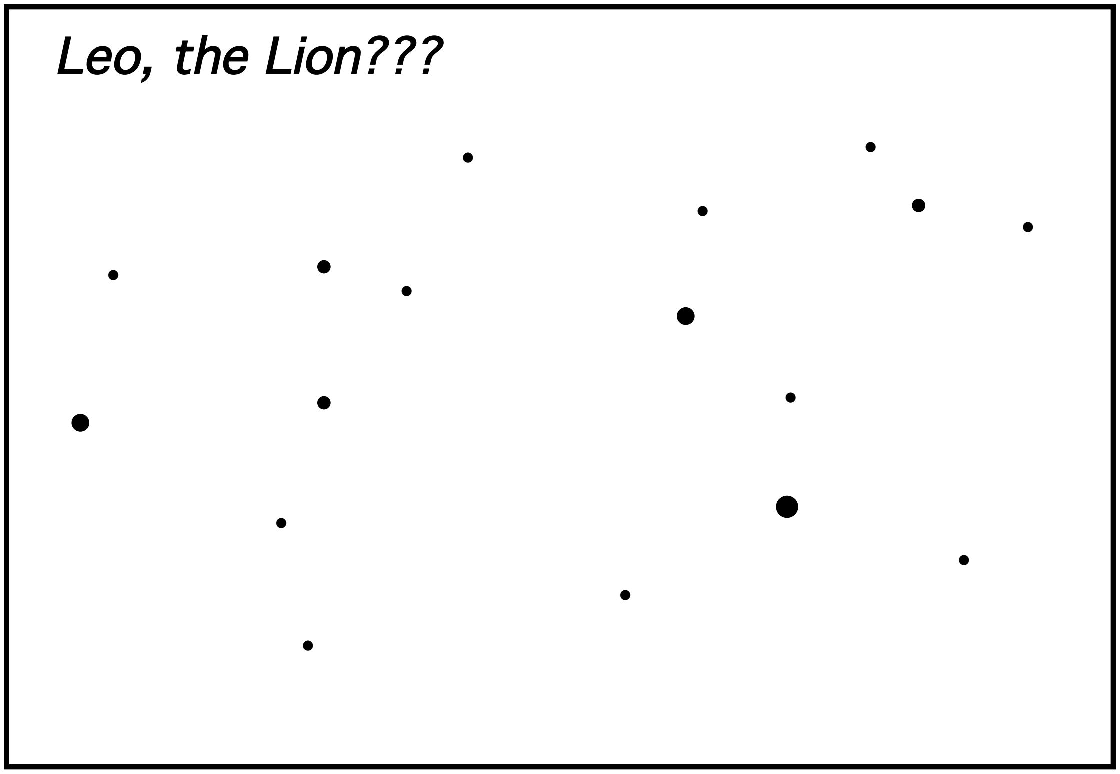
Figure 9.16: Sun's daily path across the sky, at the equinoxes and the solstices, as seen from Latitude 44° N



Similarly, during autumn and winter, the Sun travels along the *southern* portion of the ecliptic, staying *south* of the celestial equator, and therefore must rise *south of east* and set *south of west*. Only at the equinoxes will the Sun rise directly east and set directly west.

In this chapter we have seen that the appearance of the night sky is affected by both the Earth's rotation and its revolution. An observer wishing to find particular stars in the sky must take both factors into account. In the next chapter we will discuss how to locate stars, planets, and constellations in the night sky.

Chapter 10: Constellations and Star Charts



In Chapter 9 we used the celestial sphere to model the sky. This sphere, its inside surface sprinkled with stars and other celestial objects, was pictured as surrounding the Earth. In this chapter we will discover how to locate objects in the sky, again using the concept of the celestial sphere.

The first objects to consider will be the stars, of which there are a great many. The stars are all so far away that although they are moving through space at rates comparable to the Earth's orbital speed about the Sun, to us they appear to be fixed in position. For this reason, we often refer to the **fixed stars**; they will occupy fixed points on the celestial sphere.

> With very careful measurements of stellar positions made over many years, the motions of some stars can be detected. The problem is similar to measuring the growth of a tree from 50 miles away.

Constellations

Because there are so many stars, it is convenient to group them together into easily recognized patterns in the sky. These patterns are the **constellations**. They may be large or small and contain stars that are bright or faint. They have all been devised by human observers on Earth, and different cultures have invented different constellations for the same stars. The constellations in use in the United States are based primarily on those developed by the ancient Greeks. Most of these are human figures, animals, or other beasts from Greek mythology. In many cases, the brighter stars of a constellation trace out an outline or stick figure of the person or animal portrayed: a particular star might be an eye or a head; a group of stars may be an arm, leg, or tail. In nearly every case, a great deal of imagination is needed to see the person, animal, or thing that the constellation represents.[*]

The Greeks did not cover the *entire* sky with constellations, for they could not see *all* of the celestial sphere from Greece. In addition, the constellations they made did *not* fit neatly together like puzzle pieces, covering all of their visible sky. The spaces of sky in between that were not in any particular constellation were said to be 'unformed'. Because these regions did not contain any significant bright stars, that was not a problem for the Greeks. But with the invention of the telescope in 1609 came the revelation that many of the apparently starless 'unformed' regions between the constellations were actually populated by numerous faint stars. To accommodate this discovery the constellations acquired boundaries, rather than just skeletons, and expanded until they touched each other. In some cases, new constellations were invented to fill in spaces between the old ones. And as European explorers circled the globe, they labeled the extreme southern skies with additional constellations to aid in their navigation of the southern seas.

By the start of the twentieth century the celestial sphere was covered with over 100 constellations with somewhat poorly defined borders. The situation was clarified in 1928 when the number of constellations was reduced to 88, and their borders were drawn with straight lines running north-south and east-west. This is the situation we have now. Because the animals the constellations originally represented and the boundaries that now define them are both invisible, the sky that we observe is *essentially* the same as it was for the Greeks. The difference is in the star charts that we use to identify the constellations.

Star Charts

A star chart is a map of the celestial sphere; it shows the locations of the fixed stars, which do not change position significantly. Objects that are less stationary, such as the Sun, the Moon, and the planets, are generally not shown on star charts unless the chart is intended for use over a limited time interval, such

---

[*] See **CONSTELLATION HUNT** in the Appendix.

as one month. An individual star chart usually covers only a *portion* of the celestial sphere; a whole *set* of star charts, numbering anywhere from two or three to over a hundred charts, is needed to map the entire sky. There are many good sky maps on the market, and while this book will not attempt to compete with them, it *will* describe the different layouts you can expect to find.

As we learned in Chapter 9, the appearance of the night sky changes continually, due to the Earth's rotation and revolution. Additionally, the appearance of the sky depends on the observer's latitude. One type of star chart shows the night sky as it appears from a particular latitude on a particular date at a particular time of night. Because most people who observe the sky do so in the hours just after sunset, such charts are usually set for this time of night. Because most of the United States lies in a relatively narrow band of latitude (about 25° to 45°), many charts are drawn for an average value of 35° to 40°, showing a sky that is fairly accurate for most of us. This leaves only the date as a major variable: complete sky maps are often produced in sets of 12 monthly star charts as can be found in issues of *Sky & Telescope* or *Astronomy* magazines. One need only select the chart for the current month in order to begin to identify constellations.

> These charts are fine to use as long as one only goes observing shortly after sunset (or whatever time the charts are drawn for). However, an observer going out at 2 a.m. in October will find that the October star chart drawn for 8 p.m. is not a very good match for the October sky at 2 a.m. But the situation can be easily remedied: for every two hours past the recommended observing time, an extra month can be added on. As 2 a.m. is six hours later than 8 p.m., the star chart for January (three months past October) will work just fine.

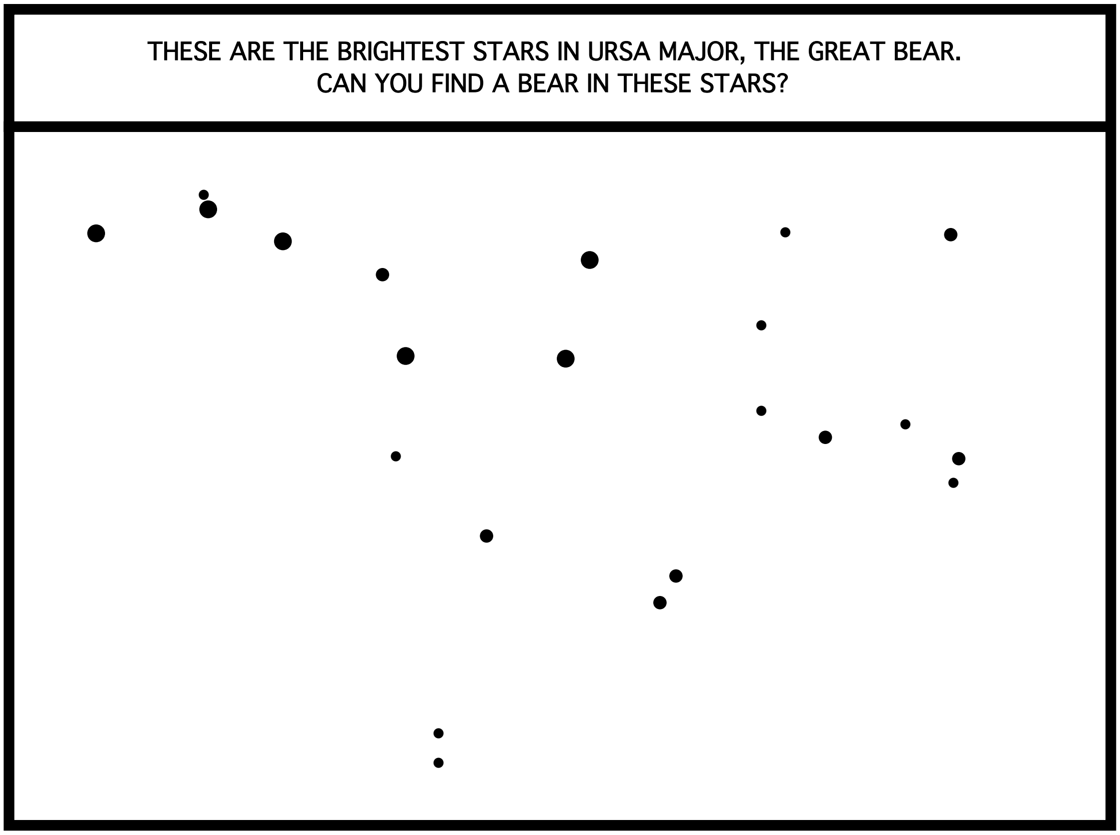
The other method of making sky maps ignores variations due to latitude, date, and time. The celestial sphere is simply divided into regions and a separate star chart is drawn for each one. For example, a chart is often made of the region around the north celestial pole showing the north circumpolar constellations; if you are outside looking at this part of the celestial sphere, you would use this particular chart. The trick is that you need to know what part of the sky you are looking at in order to know which chart to use. Simple sky maps, with only a few charts, are not too difficult to use; those with more than about ten charts can become rather confusing for the occasional observer.

> Generally, the more charts in a sky map, the greater the detail shown on each chart and the smaller the area of sky covered by each chart. In a similar fashion, we could show the United States on one map, with principal cities and highways marked; or we could show the same area on 50 state maps, with all towns, rivers, and paved roads marked; or we could collect a set of several hundred county maps from all the states, showing all the roads, streams, bridges, etc. Which maps are best to use depends on the job to be done: Is fine detail needed, or is a big picture more appropriate? The same is true of sky maps.

How does a star chart depict a constellation? Most star charts will show the stars as dots of different sizes, possibly adorned with small points or rays. The different sizes or points are meant to indicate the brightness of each star; bigger dots indicate brighter stars. If you hold the chart at arm's length, you should be able to see the biggest dots (brightest stars) most easily. Identifying constellations is simply a matter of matching stars in the sky to stars on the chart. If you are correct, the patterns should be the same. Some charts will also have a few lines connecting the stars within a constellation. These lines will not show up in the sky, but they may help you to see the bear or dog or person the constellation is supposed to be. An example of a familiar constellation is shown in Figure 10.1.

Where in the sky will the constellations be? As mentioned above, the stars are fixed. That means that they do not move around on the celestial sphere. But as we saw in Chapter 9, both rotation and revolution cause changes in our view of the celestial sphere: when we look to the east, we are not always looking at the same constellations.

Figure 10.1: The stars of Ursa Major



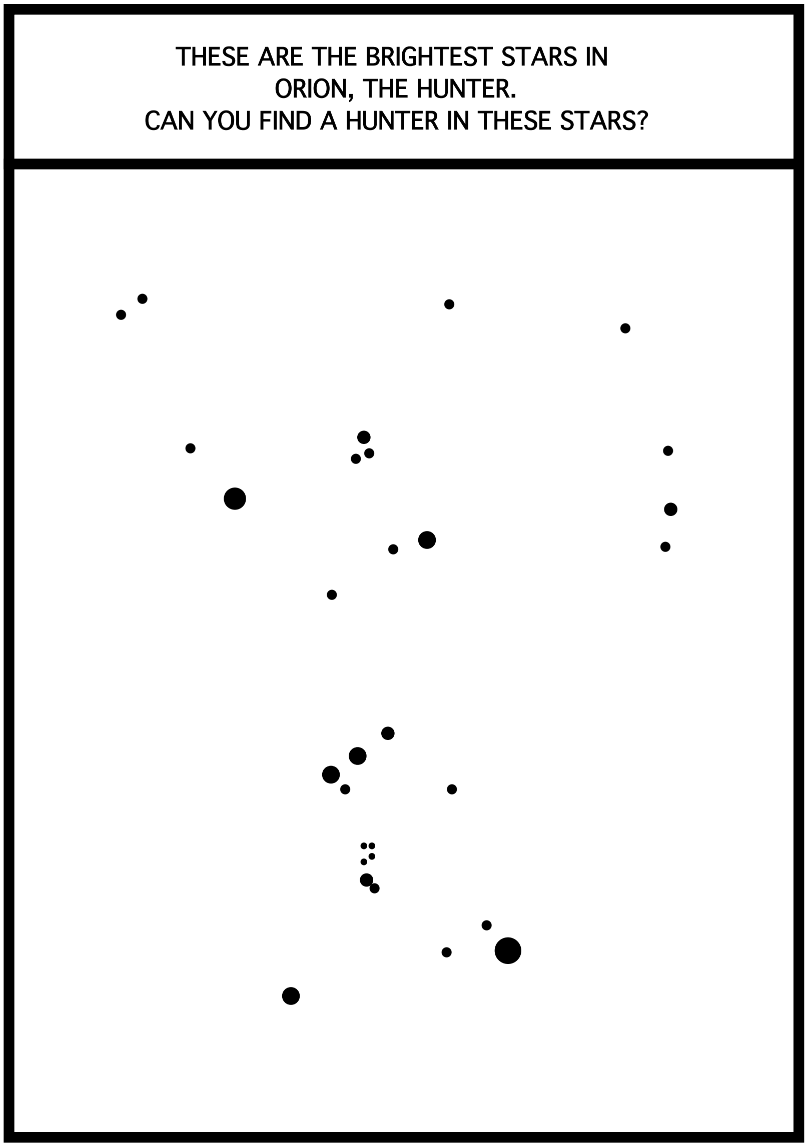
A constellation that is near the north celestial pole (such as Ursa Major) will remain near it as the Earth rotates and revolves. To find such a constellation we should look in the general direction of the north celestial pole (about 44° above the northern horizon for a person in Mankato, Minnesota) and try to match the stars we see to those on a chart of the north circumpolar region. The chart may have to be rotated to get it to match up with the sky.

A constellation located along the celestial equator (such as Orion) will rise in the east, move across the southern sky and set in the west (for a northern hemisphere observer); because of its motion, there is no single, simple direction to give for finding Orion in the sky – in fact half of the time it is not even above the horizon. Orion is most easily found by noting its distinctive pattern of stars (see Figure 10.2) and watching for it in the part of the sky where the celestial equator lies at your latitude. It also helps to know the time of the year when Orion *should* be visible in our evening sky (December through April).

Star Names

Individual stars can be identified fairly easily once the constellations have been found. The brighter stars usually have proper names, such as Sirius, Pollux, or Alamak. Many stars are also assigned Greek letters as names (with the genitive form of the Latin name of the constellation added): Sirius (in Canis Major) is *α Canis Majoris*; Pollux (in Gemini) is *β Geminorum*; Alamak (in Andromeda) is *γ Andromedae*. Knowing a few stars by name will make it easier to identify the constellations; it will also make it easier to find the planets, which often masquerade as bright stars.

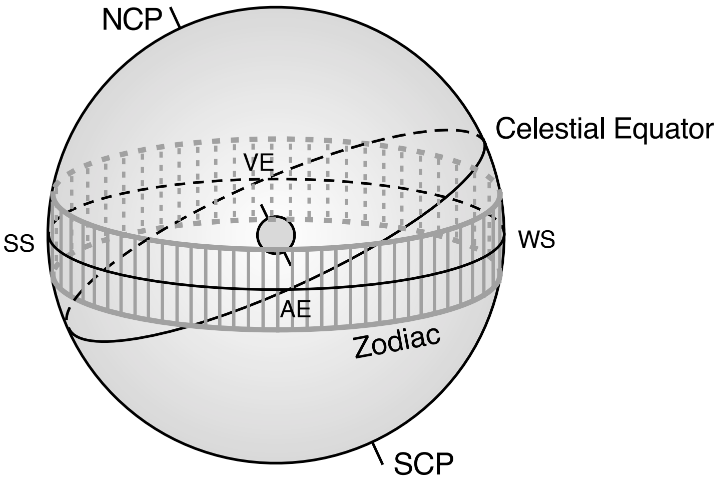
Figure 10.2: The stars of Orion



The Zodiac

Whereas the stars have fixed locations on the celestial sphere, the Moon and the planets do not. They move around the sky in an orderly, predictable fashion, passing stars as they go. We have seen that the Sun has a similar motion, moving around the ecliptic each year. We also noted in Chapter 6 that the Moon's orbit is inclined by 5° to the Sun's orbit; thus, the Moon never strays very far from the ecliptic in its monthly journey around the sky. We learned in Chapter 7 that the solar system is somewhat disk-shaped, with the planets' orbital planes all lying fairly close to the plane of the ecliptic. This keeps the planets near the ecliptic as they travel around the sky. The region of sky through which the Sun, Moon, and planets move is called the **zodiac**. The zodiac is a band around the celestial sphere – 18° wide and centered on the ecliptic, as shown in Figure 10.3.

Figure 10.3: The zodiac



Locating planets can often be as simple as determining in what zodiacal constellations they currently reside. The following table lists the zodiacal constellations, along with the positions of the equinoxes and solstices:

Zodiacal Constellations

Pisces, the fishes	**>>**	**contains the vernal equinox**
Aries, the ram		
Taurus, the bull		
Gemini, the twins	**>>**	**contains the summer solstice**
Cancer, the crab		
Leo, the lion		
Virgo, the maiden	**>>**	**contains the autumnal equinox**
Libra, the scales		
Scorpius, the scorpion		
Sagittarius, the archer	**>>**	**contains the winter solstice**
Capricornus, the sea-goat		
Aquarius, the water bearer		

The Moon is easy to find if you know its current phase; we discussed in Chapter 5 how the times of moonrise and moonset vary with phase. Crescent moons are found near the Sun while gibbous moons are found more nearly opposite the Sun. Waxing moons are found to the east of the Sun, and waning moons are found to the west of the Sun. The Moon changes its position gradually, moving eastward through the stars about 13° per day. Because the Moon is relatively large and distinctive, there will be no problem identifying it.

Planets, on the other hand, will usually appear as bright stars. The brightness of each planet varies as our distance from it varies and/or as its phase changes. Uranus, Neptune, and Pluto are difficult or impossible to see without a telescope, but Mercury, Venus, Mars, Jupiter, and Saturn can be among the most prominent objects in the sky.

As we saw in Chapter 7, Mercury and Venus always remain relatively close to the Sun in the sky and must be viewed during or close to twilight. They will be found in the zodiac, to the east or west of the Sun, depending on their current configurations.

Mars, Jupiter, and Saturn travel slowly all around the zodiac and may appear anywhere along it with respect to the Sun. Their locations will also depend on their current configurations.

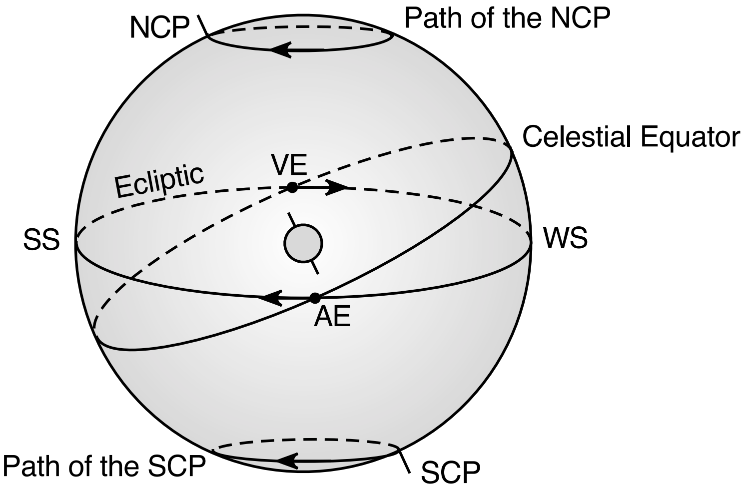
> It should be pointed out that the planets are not visible *every* night. Like the Moon, they spend half of the time below our horizon, invisible to us. In addition, when they are near conjunction, they cannot be seen due to the glare of the Sun, much as the new moon is not seen.

Locations of the planets and the Moon in its different phases can be found online or in each month's issue of *Sky & Telescope* or *Astronomy* magazines. Usually the planets' positions will be marked on star charts of the equatorial regions of the celestial sphere; they will appear in the sky as bright 'stars' in the zodiacal constellations, where no stars are marked on the regular star charts.

Precession

Until now we have considered the Earth's axis to have a fixed orientation in space, always pointed to the north celestial pole, near Polaris. For most casual observing, this picture is accurate enough. However, the fact is that the Earth's axis is *not* fixed in space: it slowly changes its alignment, with the north celestial pole describing a huge circle on the celestial sphere every 26,000 years as shown in Figure 10.4.

Figure 10.4: Precession



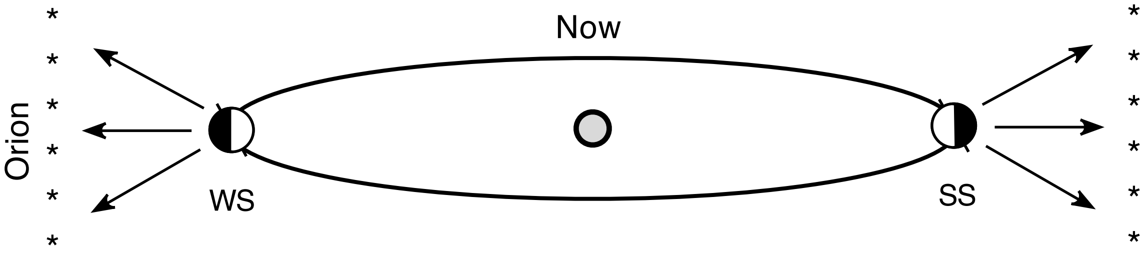
This motion is called **precession**; it can be demonstrated by spinning a gyroscope or a top and observing the changing position of the spin axis. Just as the axis of the spinning top points to different locations on the ceiling as it precesses, the Earth's axis points to different locations on the celestial sphere. The north celestial pole, which today is about 0.9° away from the North Star, is currently getting closer to Polaris and will pass within about 0.5° of it in another hundred years or so. Following that, the NCP will drift farther away from Polaris, making it a poorer North Star as time goes on.

> Some people think that the North Star is the brightest star in the sky; it is not – it is just the closest bright star to the NCP. Polaris has not always been our North Star: in the time of the ancient Egyptians, the NCP was quite close to Thuban (*α Draconis*), making it the North Star. In another 12,000 years or so, the North Star will be the very bright Vega (*α Lyrae*), which will be an excellent northern beacon.

As a result of precession, both celestial poles move in circles on the celestial sphere, and the equinoxes move westward around the ecliptic, as shown in Figure 10.4; this means that the vernal equinox is slowly moving with respect to the stars. That is why the **tropical year** and the **sidereal year** have different lengths (see Chapter 4): the former measures the Sun's motion with respect to the vernal equinox while the latter measures it with respect to the stars. The 26,000-year cycle of precession results in a 20-minute difference in the lengths of the two years.

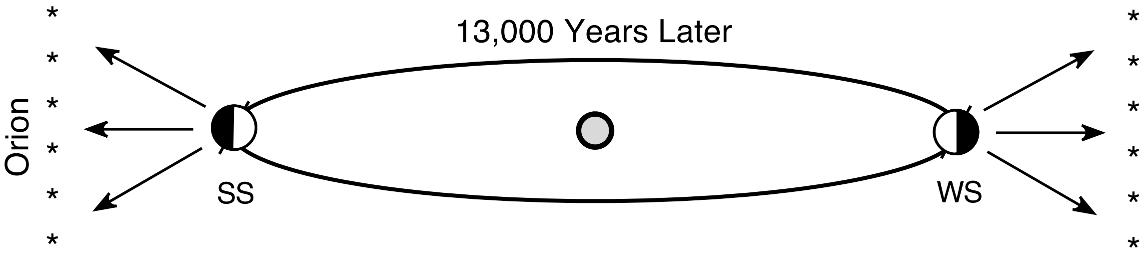
Precession causes no noticeable changes over a short length of time. But over several *hundred* years the changes become significant, and over several *thousand* years they become dramatic. Recall that our seasons are determined by the tilt of the Earth's axis towards or away from the Sun. Consider the present situation as we have drawn it before, shown in Figure 10.5. In this sketch, the 'winter constellations', such as Orion, would be on the left side of the celestial sphere.

Figure 10.5: Current orientation of the night sky



Over time, precession causes the Earth's axis to shift its orientation such that 13,000 years later it will point as shown in Figure 10.6. The stars are in approximately the same positions, Orion is still on the left side of the celestial sphere, but because the solstices have switched, Orion and the other current 'winter constellations' would then be viewed in the *summer*.

Figure 10.6: Future orientation of the night sky



This means that any star chart will eventually become obsolete, due to precession. For this reason, the better star charts identify the year, or epoch, for which they are designed (e.g. 1950 or 2000). However, for most observing needs, the popular star charts available today will serve the amateur astronomer quite well for many years to come.

Precession is a bit confusing for most people and not especially important for viewing the sky. But it does have one interesting application to everyday life.

Astrology

Many people pay attention to their horoscopes – those blurbs found in the newspaper that purport to offer words of wisdom about your future, based on your astrological sign. Astrology has been around for a long time – two or three thousand years – and even then it served the same purpose it does now: to allow astrologers to make a living by telling people their fortunes.

The astrology story is simple: the positions of the Sun, Moon, and planets at the time of your birth have some effect on your future, including your day-to-day activities. The nature of this effect has been neither identified nor proven, but that does not stop the astrologers from making money.

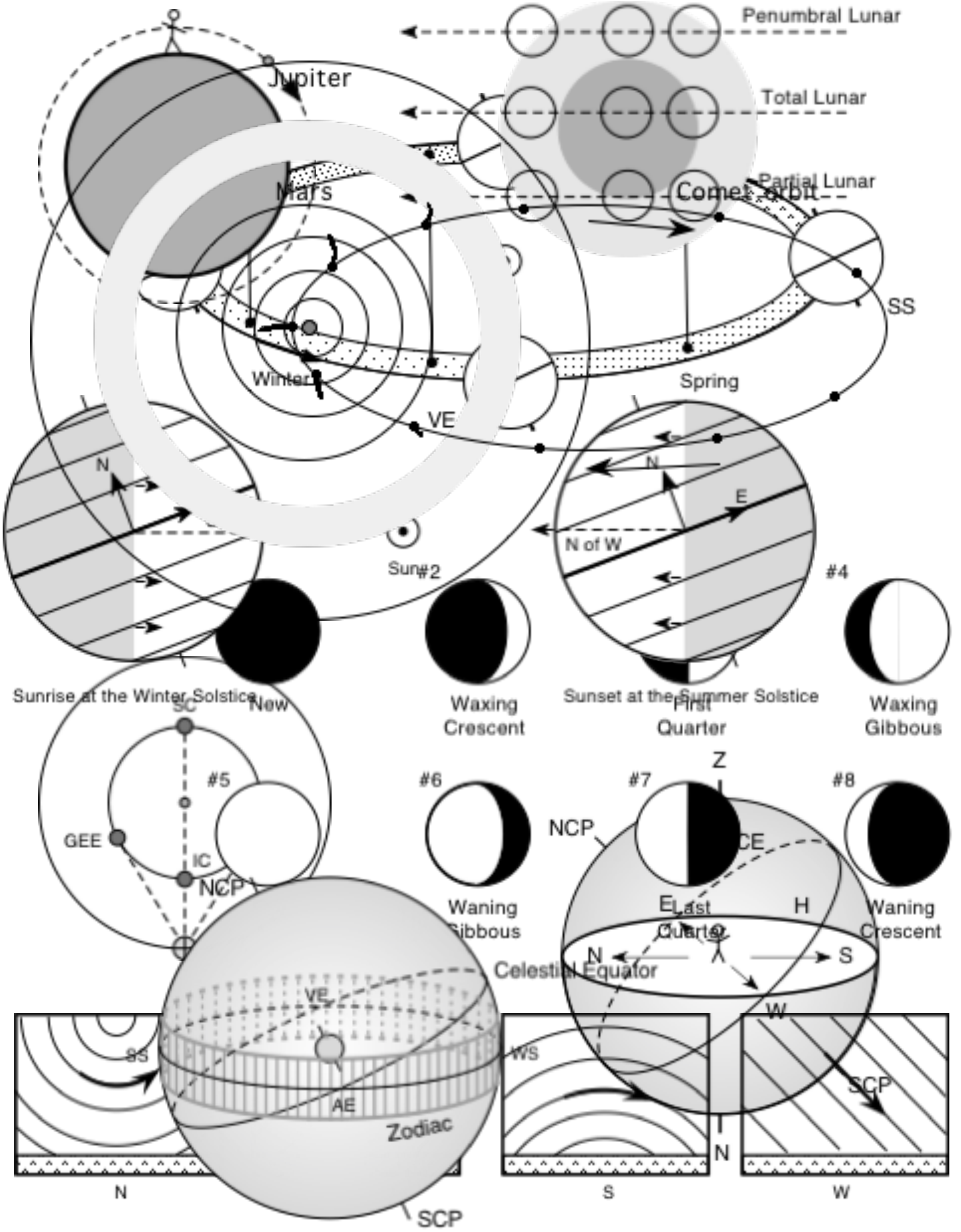
To figure a person's horoscope, the early astrologers needed to know the position of the Sun among the stars at the time of the individual's birth. Of course, few people were sufficiently cognizant at the time of their birth to make note of such important information for future use, which meant that the astrologers had a difficult time making money. In order to save their jobs, they had to make the horoscope process easier; this they did by observing that the Sun moved around the celestial sphere once per year, passing through the same constellations on the same dates each year. They established the zodiacal signs (based on the 12 zodiacal constellations) and figured horoscopes based on these signs. Because the Sun entered each zodiacal sign on the same date each year, the astrologer needed only learn the *birth date* of his customer to determine his sign and hence, his horoscope. The astrologers were in business.

In the following centuries, astronomers continued to wrestle with their own problem of finding a calendar that matched the motion of the Sun, made difficult by the non-integral number of days in a year (see Chapter 4). They finally were able to make one that fit, adjusting the frequency of leap years to make the seasons begin on about the same date each year. But the seasons are actually determined by the equinoxes (spring begins on the vernal equinox, etc.), and the equinoxes are constantly shifted by precession. This produces the following strange result:

> The zodiacal signs, which originally were aligned with the stars they represent, became fixed instead to the calendar dates, which were then linked to the seasons, which are determined by the equinoxes, which move among the stars due to precession. That is, the zodiacal signs move with respect to the stars they supposedly represent! This motion is continual and has been going on for two or three thousand years, resulting in a shift of about 30° so far, or about one zodiacal sign. And the problem will get a lot worse before it gets better as precession continues its relentless motion.

What does this mean for your sign? It is really quite simple: if your sign is Aries, the Sun was in Pisces when you were born; if your sign is Pisces, the Sun was in Aquarius when you were born; and so on. What does this mean for your horoscope? Don't worry – it is just as accurate and useful and worthwhile as it has ever been.

Chapter 11: Conclusion



If you have arrived at this final chapter after reading all or part of this book, you will have been exposed to a fair amount of basic astronomical information. Perhaps some of it was already familiar to you; perhaps *all* of it was brand new to you; either way, you should have found some tidbits that will help you to present astronomy in your classroom or answer questions from your own children.[*]

Do not worry if you did not retain or understand *everything* that you read – you probably will not be able to use *all* of this information in your class. Go back and reread if necessary, to concentrate on the material that relates to your lessons. Keep the book handy, to find answers to questions you or your students may have.

Most of the material in the book is unlikely to become obsolete in the near future because most of it is fairly timeless. Future planetary missions will undoubtedly refine some of the data about the planets and their satellites, but seasons, moon phases, eclipses, planetary configurations, and constellations are not apt to change significantly in your lifetime. Keep a pencil handy to update your copy as new moons are discovered.

For those who feel that this was a lot of astronomy to digest, it should be noted that this is only the tip of the iceberg. The astronomy in this book is the practical, everyday, down-to-earth astronomy that you can experience without fancy equipment and understand without a degree in physics. It is typically discussed in the first few weeks of a college freshman's *'Intro to Astronomy'* course. That leaves plenty of areas of astronomy to discover if you are interested and have the time – but do not expect to encounter those topics in elementary classrooms.

As a next step in studying astronomy, you might explore the properties of matter and learn how atoms create, and interact with, light. You could then understand how, by analyzing the starlight collected by their telescopes, astronomers can deduce the composition and temperature of a star. By measuring the brightness of a star and the distance to it (not easily done!), they can determine the luminosity, or power output, of a star. This data permits calculation of the size of the star, while observations of binary stars – two stars orbiting about each other – provide the means to find the star's mass. Thus, most of the basic properties of stars can be determined by making the appropriate observations.

With the properties of a star and an understanding of the physical laws that govern matter and radiation, astronomers can construct a computer model of a star that yields the temperature, density, pressure, etc. at each point inside the star. Nuclear physics reveals how most stars generate enough energy by nuclear reactions to last for billions of years. (Our Sun, for example, is about halfway through its ten-billion-year lifetime.)

The computer models show how stars will change with time, due to gradual conversion of their hydrogen to helium by nuclear fusion. Armed with these models, astronomers can follow a star's history, from its birth at the center of a huge cloud of gas and dust (pulled together by gravitational forces), through its middle age (as the Sun is now), to its ultimate death when its nuclear fires die out. Most stars will die quietly, turning into tiny white dwarfs that gradually fade away as they cool. Others (such as the Sun) will swell up to become red giants before ejecting their outer layers and forming white dwarfs from what remains. A few stars will become huge supergiants before suffering violent explosions, blowing themselves apart as supernovae and leaving behind such exotic bodies as neutron stars and black holes.

---

[*] See **SCIENCE FAIR PROJECTS** in the Appendix.

Some astronomers study the huge collection of a few hundred billion stars that we know as the Milky Way Galaxy. Our Sun and essentially all of the stars we see in the night sky are part of this galaxy, which is bound together by the mutual gravitational forces of all the matter that comprises it. Our galaxy must contain many other planetary systems (we have detected a few hundred around nearby stars) and possibly other planets that harbor life – perhaps even intelligent life such as ourselves. Our galaxy is but one of billions of galaxies in the universe, which is obviously a very big place. The study of the nature, origin, and evolution of the universe is the branch of astronomy called cosmology.

Most of the topics mentioned in the previous paragraphs are not particularly easy to understand, although many of them are extremely interesting. All of them can be appreciated at the college freshman level, but most require some additional background in physics and mathematics for adequate comprehension. If you have the inclination, you should explore some of the rest of astronomy at an introductory level; it may not be appropriate to present to third-graders, but it will certainly give you a fresh perspective on your place in the universe. And that is probably the best reason for studying astronomy.

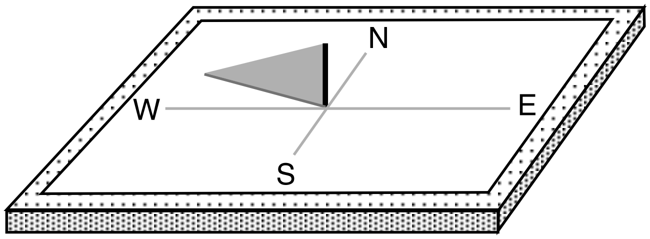
As for the topics in this book, do the best job you can to learn them and present them to your class. Most students do not take an astronomy course in high school or college; the mental images and ideas of the Sun, Moon, planets, and stars that most students carry are formed during their elementary school years. The astronomy concepts you convey in your classroom may well be remembered for a lifetime: try to make the most of your opportunity.

Appendix

- Shadow Experiments
- Moon Rotation Demonstration
- Phalse Phases
- Solar Viewing Tube
- Photographing the Stars
- Constellation Hunt:
  - Ursa Major and Cygnus
  - Cetus and Pegasus
  - Gemini and Taurus
  - Leo and Draco
  - Orion and Scorpius
  - Canis Major and Aquila
- Science Fair Projects

SHADOW EXPERIMENTS

A simple shadow-measuring device can be constructed by tapping a one-inch finishing nail (which has a very small head) into the center of a short board. The board should be large enough (about 9" x 12") to allow long shadows to fall on its surface. The board can be covered with a sheet of paper to record the shadows, and the paper can be changed for each new set of observations. The long end of the board should be oriented east-west, as the shadows will be longer in these directions. The edges of the paper should be labeled with the directions, to insure proper orientation for each measurement.



Careful shadow observations can be used to follow two different motions of the sun:

1. The daily westward drift of the sun across the sky.
2. The annual north-south migration of the sun with the seasons.

To record the westward drift, orient the shadow board in the sunshine and mark the position of the head of the nail at regular intervals during the day. (Be sure to use the same orientation for the board each time.) The shadow should become shorter toward midday, then lengthen in the afternoon. Local noon will occur when the shadow points north; this will probably not occur at noon by the clock. In spring and summer, a line connecting the shadow tips should be concave toward the south; in fall and winter it should be concave toward the north.

Repeating the experiment the next day should produce essentially the same results. However, a repeat made after a week or two should show subtle changes in the shadow lengths and directions for corresponding times, due to the northward or southward seasonal motion of the sun.

This annual motion can best be shown by marking one shadow tip at the same time of day, on one day each week over the course of the year. Use the same sheet of paper for the whole year. As the sun moves south for the winter, the shadow tip will move north. The maximum shadow length should occur on the winter solstice, after which the sun will head back to the north. To generate the complete path of the shadow tip (a figure-8 shape called an analemma) the students will have to continue the project throughout the summer months.

These experiments offer great potential for teaching science, as they involve studying a particular concept, predicting what should happen, building equipment to test the predictions, making the measurements, interpreting the results, and analyzing the whole process for errors. These projects can be adapted to various grade levels by emphasizing different aspects of the scientific method.

MOON ROTATION DEMONSTRATION

1 Choose two participants -- one **Moon**, one **Earth**.
- The audience is the distant **Stars**.

2 **Earth** stands in center of demo area.
- Ask **Earth** to demonstrate ROTATION. (Spinning on an axis)

3 Ask **Stars** if **Earth's** motion is correct.
- How can we tell when ROTATION occurs? (We see all sides of **Earth**.)
- Did **Earth** ROTATE in the correct *direction*? (Should be CCW.)

4 Now ask **Moon** to demonstrate REVOLUTION about **Earth**.
- Ask **Stars** if direction is correct. (Should be CCW.)

5 Ask **Earth** whether **Moon** ROTATED. (**Earth** probably wasn't watching – if so have **Moon** repeat REVOLUTION.)
- If **Earth** gives incorrect answer at this point, ask **Earth** how she can tell whether ROTATION occurred. (Did you see all sides of **Moon** or not?)
- Continue until correct answer (which could be either YES or NO, depending on what the **Moon** did) is reached.

6 Next ask **Stars** whether **Moon** ROTATED. (Answer should be opposite that given by **Earth** – lead them to the right answer.)

- The **Moon** probably REVOLVED while keeping one side/face toward either the **Earth** or the **Stars**.

7 Now ask **Moon** to REVOLVE again while facing either (a) the **Earth** (if **Stars** the first time) or (b) the **Stars** (if **Earth** the first time).

8 Again ask **Earth** whether **Moon** ROTATED. (Try to get the opposite answer from the first time.)
- Then ask **Stars** whether **Moon** ROTATED. (Again, their answer should be opposite the **Earth's**.)

9 Note that whether the **Moon** ROTATES or not depends not only on how the **Moon** actually moves, but also on whom we ask.

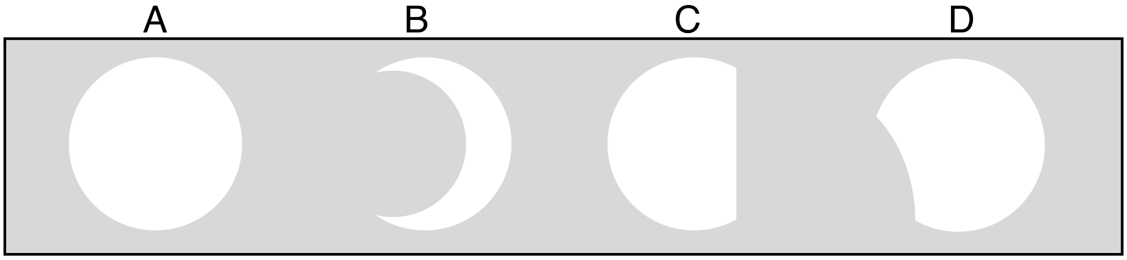
10 In reality, which way *does* the **Moon** REVOLVE? – facing **Earth** or facing the **Stars**? (Facing **Earth**)
- Ask **Moon** to demonstrate this method once again.

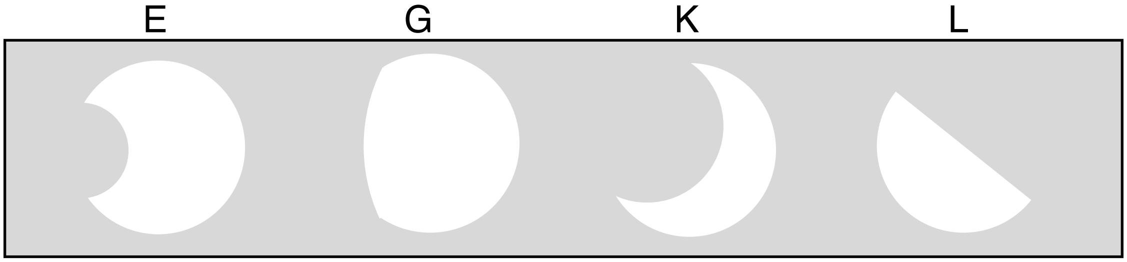
11 For this motion, **Earth** should claim that **Moon** does *not* ROTATE (because she sees only *one* side), while **Stars** should say it *does* (because they see *all* sides of the **Moon**).
- Who is right? Whom should we believe? What should we put in the Books?

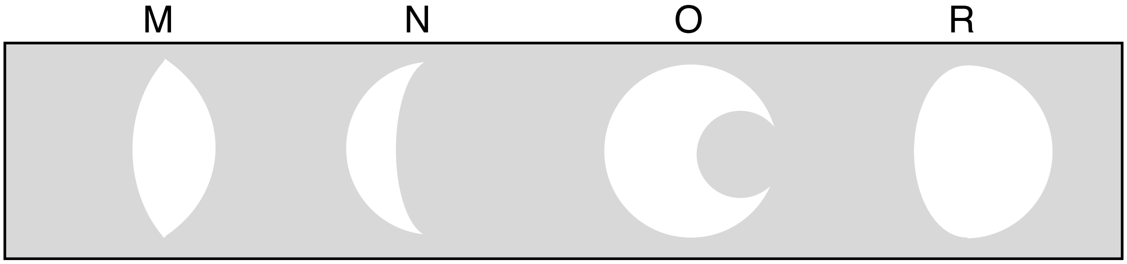
12 Because the **Earth** itself moves, it is not always a reliable witness. (Remember, it looks to *us* as though the Sun is going around the **Earth**.)
- Therefore, astronomers measure ROTATION and REVOLUTION with respect to the distant **Stars**, which do not seem to move.
- That is why we say that the **Moon** *does* ROTATE, and it ROTATES at the same rate and in the same direction that it REVOLVES.

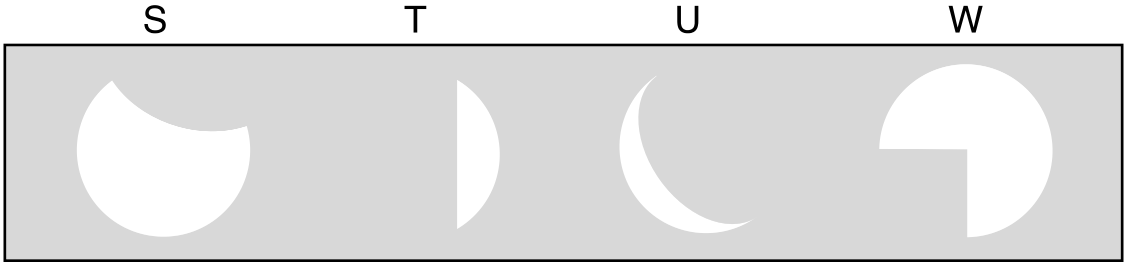
PHALSE PHASES

Which of these sketches represent *possible* moon phases?[*]









---

[*] See Chapter 5 for solution.

SOLAR VIEWING TUBE

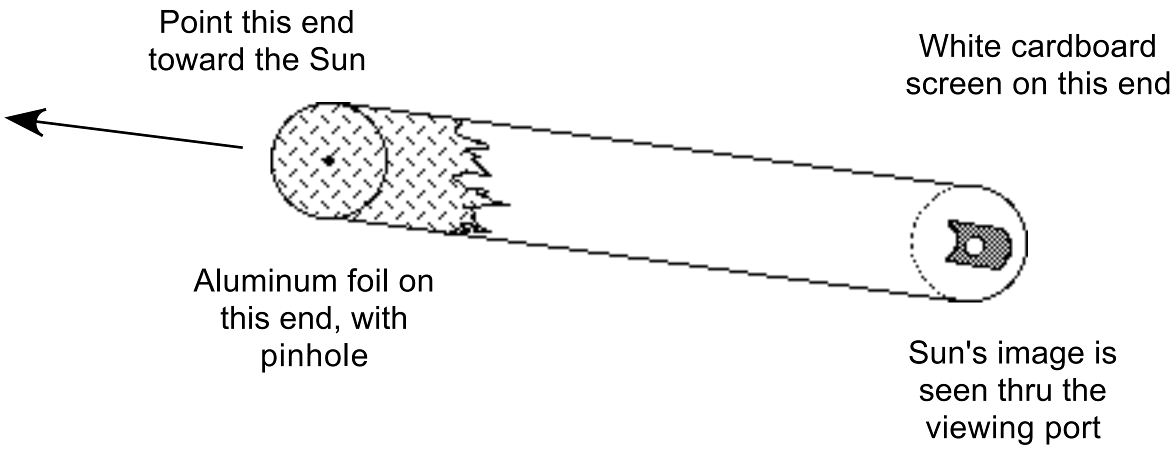
This is a good, safe way to view the sun, during an eclipse, a transit, or any time.

Get a long cardboard tube.

Cover one end with aluminum foil and make a pinhole in the foil.

Cut a viewing port in the side of the tube near the other end.

Cover this end (but not the port) with white cardboard.



Try it out!

Stand with your back to the sun. (Do not look at the sun.)

Hold the port end in one hand and rest the foil end on your shoulder (like a soldier on parade).

Now for the tricky part: Move your hand until the sunlight shines directly down the tube and the sun's image appears on the white cardboard, as seen thru the viewing port.

[Hint: How will the shadow of the tube look when the image is visible thru the port?]

Compare your viewing tube with those of your friends: what effect does each of these have on the sun's image?

The diameter of the tube?

The length of the tube?

The size of the pinhole?

PHOTOGRAPHING THE STARS

A GUIDE TO TAKING STAR TRAILS PICTURES WITH A *FILM* CAMERA

You will need the following:

1. a camera that has a shutter with a B or Bulb setting.
2. a locking cable release.
3. a tripod or other support for the camera.
4. a clear night.
5. a dark sky, free from streetlights, car headlights, and moonlight.

You may also wish to bring these:

6. a watch for timing exposures.
7. a notebook and a pen for recording settings.
8. a flashlight to see what you are recording.
9. warm clothing or mosquito repellent, depending on the season.

What to do:

1. Load your camera with film. Use color film for best results -- stars are colored. Slides are better than prints, as most automatic processors will not print dark pictures. Any speed can be used; ambient lighting will be held in check better by slow film, but fainter objects can be recorded with faster film. A smaller diameter lens requires faster film to record the fainter stars.

2. Set the camera on the tripod and point it at a group of bright stars.

3. Set the aperture wide open -- to the lowest f number, usually about f/1.4 or f/1.8 for a 50 mm lens. If ambient lighting is strong, stop the lens down to f/2.8 or so.

4. Set the focus to infinity (∞).

5. Set the shutter speed to B. This means the shutter will remain open as long as the button is pressed down.

6. Install the locking cable release on the shutter release button – on most cameras it simply screws in. (Be sure you have practiced using this gadget before – it's too late now.)

7. Cock the shutter and check the viewfinder for proper aiming. Don't expect to see very much through the viewfinder. If you don't see anything, take off the lens cap.

8. Push the cable release button and lock it down. You should hear the shutter click open. Note the starting time.

9. Wait patiently for some length of time. If skies are dark, wait up to several hours. If in town, try five minutes. Experiment with exposure times to get the desired effect. If you stroll around in the dark while you wait, be careful not to trip over the tripod. Do not bring a large clumsy dog or a small active child.

10. Unlock the cable release; hopefully you will hear the shutter click shut. If not, your cable release did not lock or your shutter was not set on B.

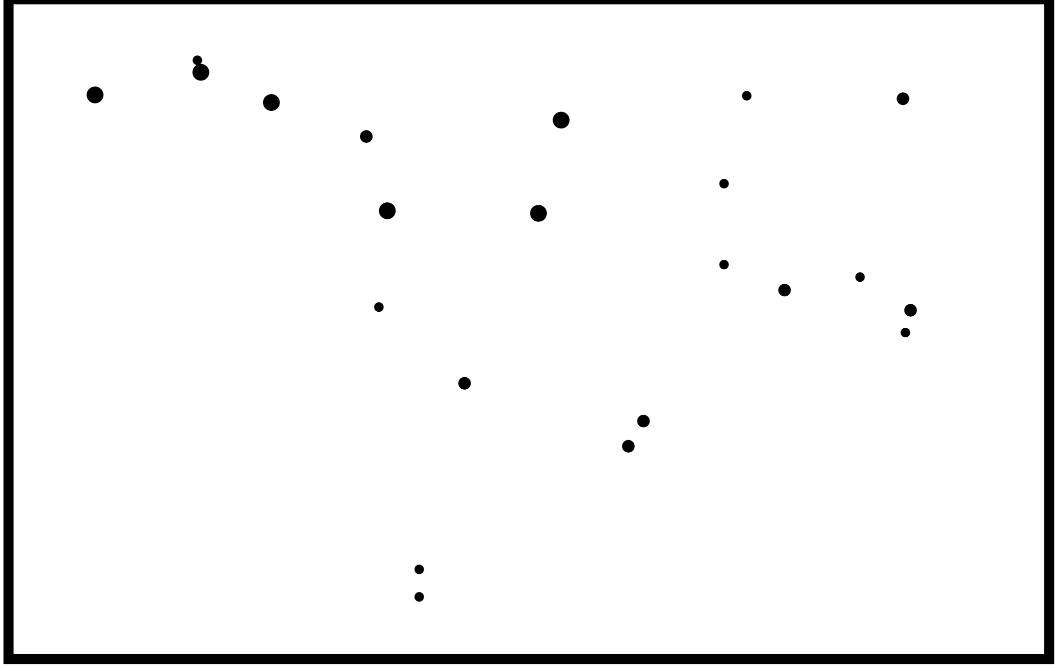
11. Record the date, time, location, film speed, lens, aperture, exposure time, direction of target, and its name (if you know your constellations). Then find a new target and do it all again.

When you have finished a roll, be careful in getting your film developed. Some developers will note your dark pictures with dots or streaks and assume you are just another photographic loser. They may damage or destroy your entire night's work. Before turning in a whole roll of star trails, you should try one or two shots on a roll of regular pictures to see what the developer's response will be. It is also a good idea to write a short note on your film envelope warning that these are astrophotos.

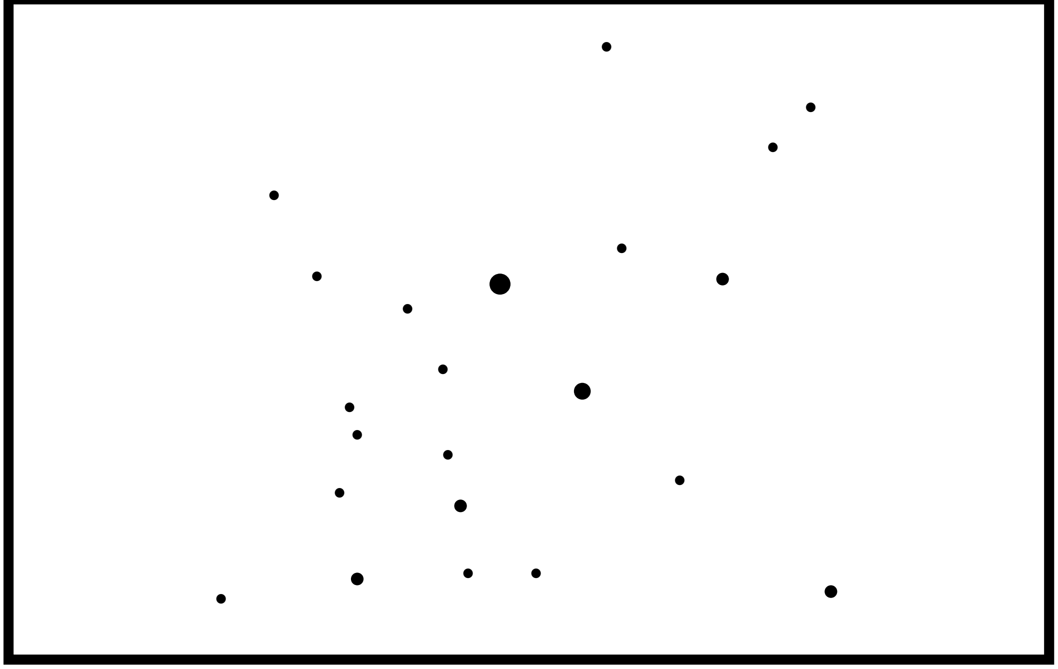
When you get your pictures back, record on each slide (or on the back of each print) the date, film speed, lens, etc., and as your collection grows, you'll have the pertinent information along with each picture.

CONSTELLATION HUNT: UMA & CYG

THESE ARE THE BRIGHTEST STARS IN URSA MAJOR, THE GREAT BEAR.
CAN YOU FIND A BEAR IN THESE STARS?
SKETCH THE BEAR THAT YOU FIND.

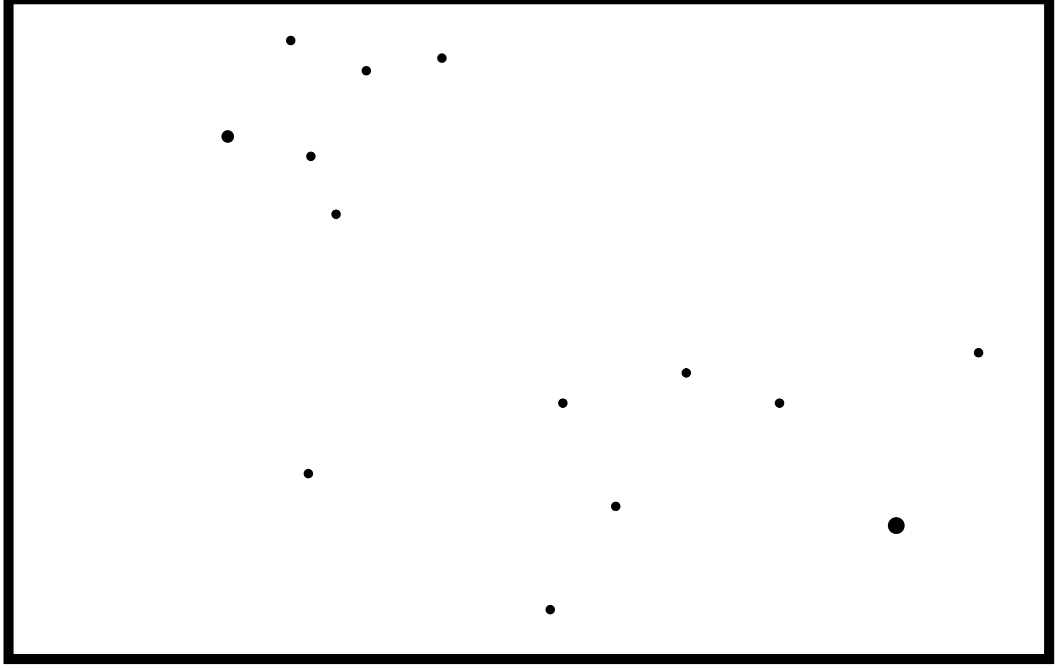


THESE ARE THE BRIGHTEST STARS IN CYGNUS, THE SWAN.
CAN YOU FIND A SWAN IN THESE STARS?
SKETCH THE SWAN THAT YOU FIND.

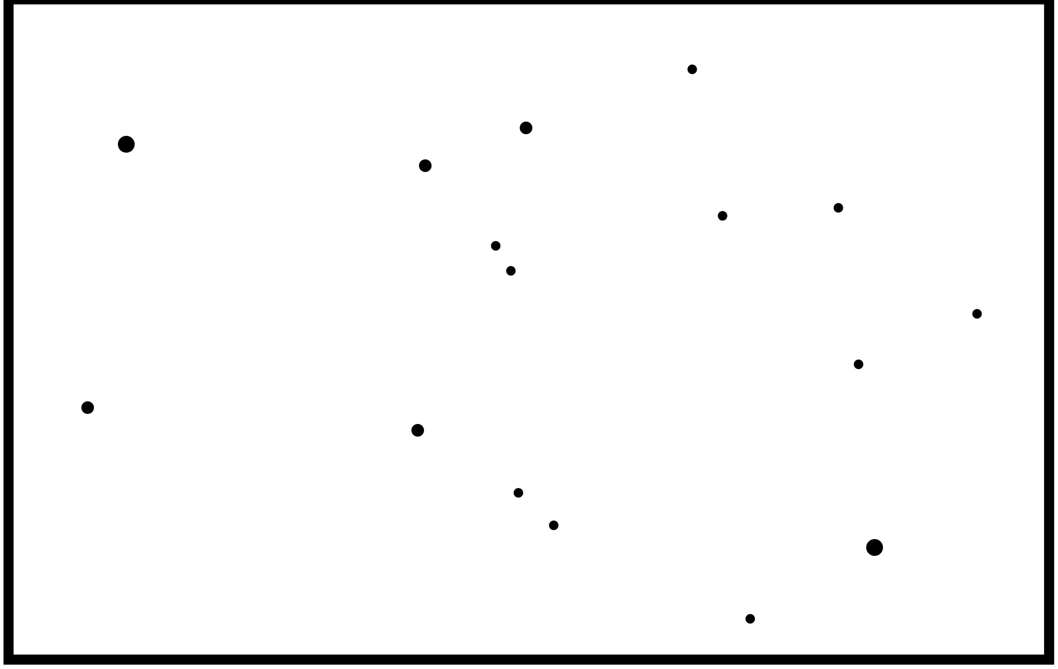


CONSTELLATION HUNT: CET & PEG

THESE ARE THE BRIGHTEST STARS IN CETUS, THE SEA MONSTER.
CAN YOU FIND A SEA MONSTER IN THESE STARS?
SKETCH THE SEA MONSTER THAT YOU FIND.

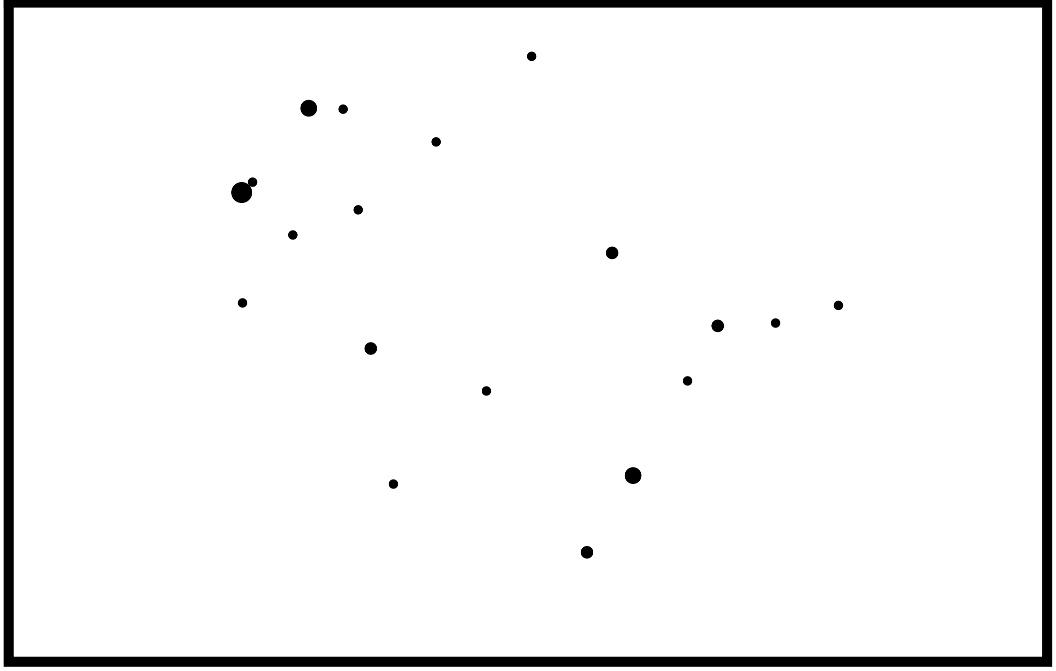


THESE ARE THE BRIGHTEST STARS IN PEGASUS, THE WINGED HORSE.
CAN YOU FIND A WINGED HORSE IN THESE STARS?
SKETCH THE WINGED HORSE THAT YOU FIND.

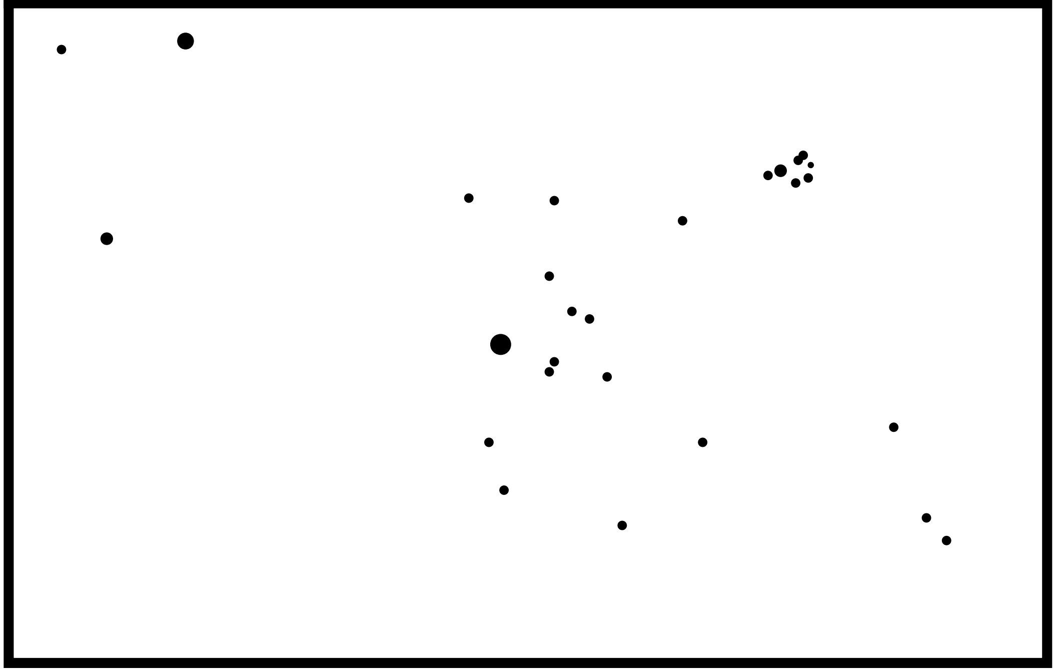


CONSTELLATION HUNT: GEM & TAU

THESE ARE THE BRIGHTEST STARS IN GEMINI, THE TWINS.
CAN YOU FIND THE TWINS IN THESE STARS?
SKETCH THE TWINS THAT YOU FIND.

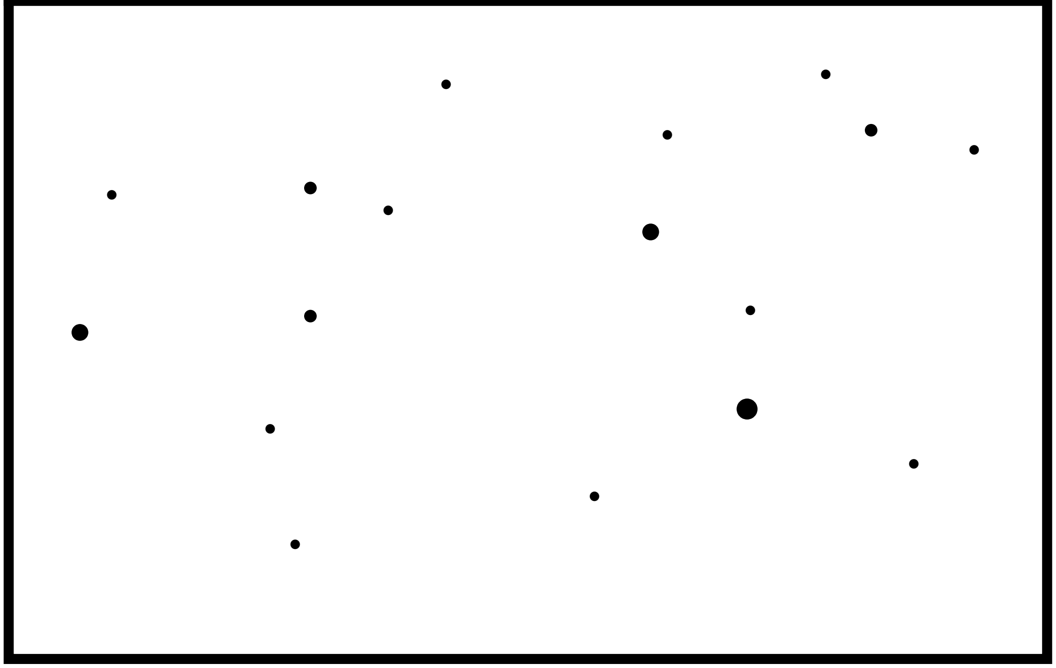


THESE ARE THE BRIGHTEST STARS IN TAURUS, THE BULL.
CAN YOU FIND A BULL IN THESE STARS?
SKETCH THE BULL THAT YOU FIND.

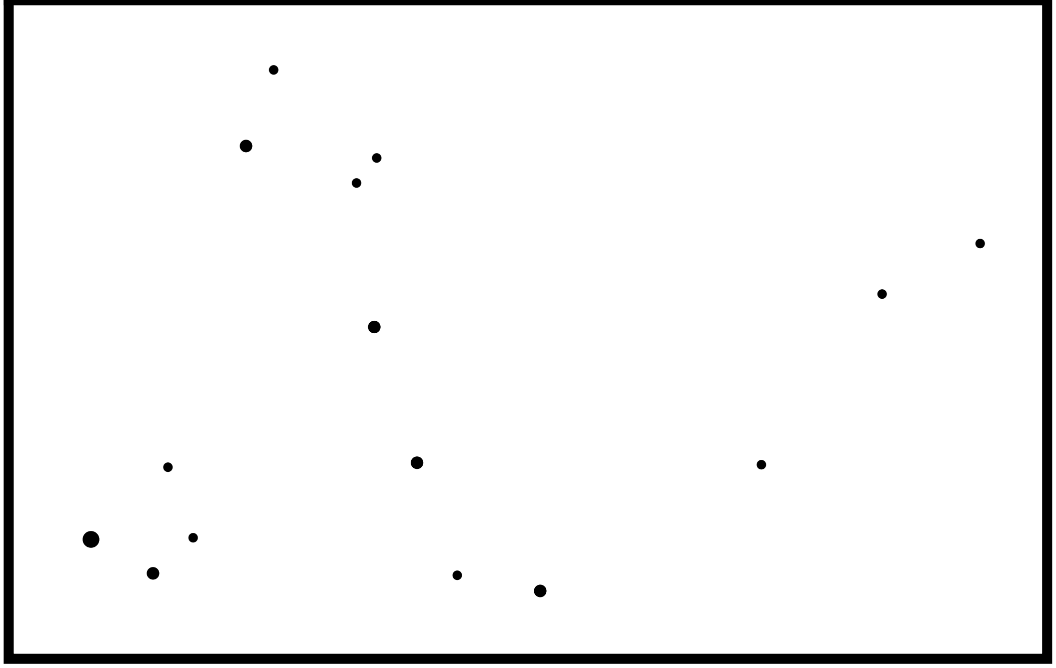


CONSTELLATION HUNT: LEO & DRA

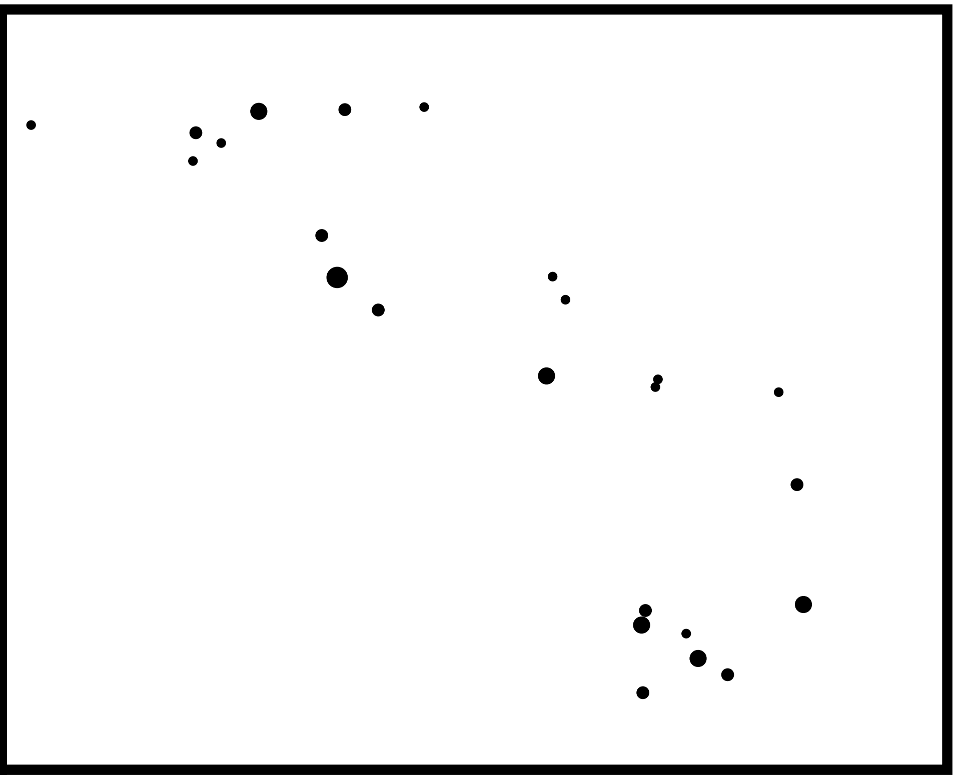
THESE ARE THE BRIGHTEST STARS IN LEO, THE LION.
CAN YOU FIND A LION IN THESE STARS?
SKETCH THE LION THAT YOU FIND.



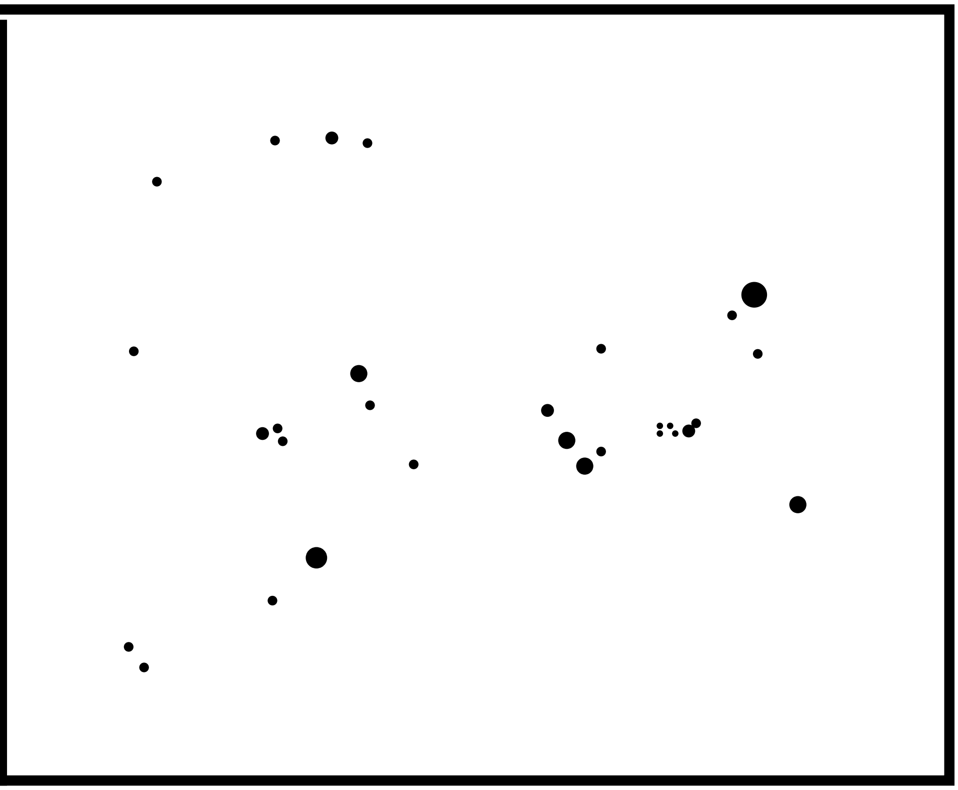
THESE ARE THE BRIGHTEST STARS IN DRACO, THE DRAGON.
CAN YOU FIND A DRAGON IN THESE STARS?
SKETCH THE DRAGON THAT YOU FIND.



CONSTELLATION HUNT: ORI & SCO



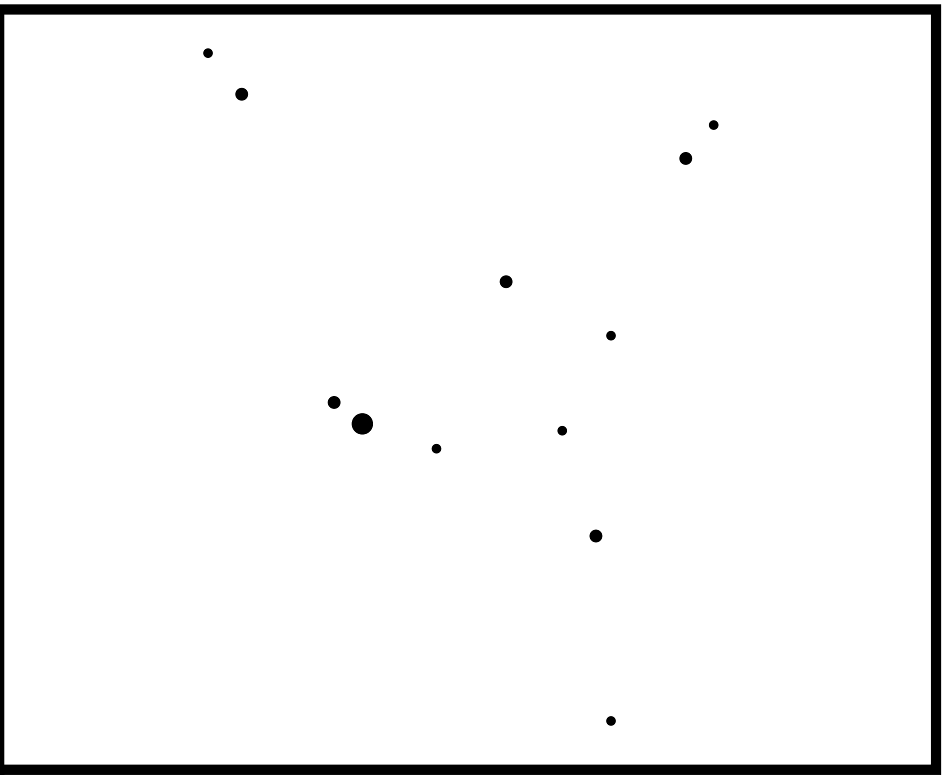
THESE ARE THE BRIGHTEST STARS IN SCORPIUS, THE SCORPION.
CAN YOU FIND A SCORPION IN THESE STARS?
SKETCH THE SCORPION THAT YOU FIND.



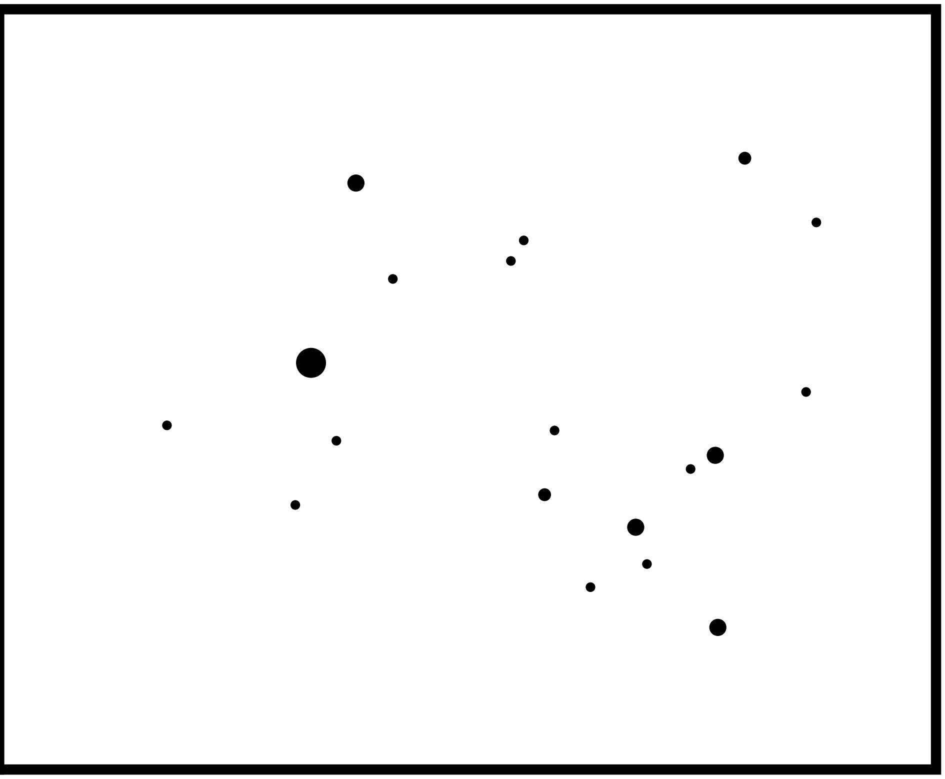
THESE ARE THE BRIGHTEST STARS IN ORION, THE HUNTER.
CAN YOU FIND A HUNTER IN THESE STARS?
SKETCH THE HUNTER THAT YOU FIND.

CONSTELLATION HUNT: CMA & AQL

THESE ARE THE BRIGHTEST STARS IN
AQUILA, THE EAGLE.
CAN YOU FIND AN EAGLE IN THESE STARS?
SKETCH THE EAGLE THAT YOU FIND.



THESE ARE THE BRIGHTEST STARS IN
CANIS MAJOR, THE GREATER DOG.
CAN YOU FIND A DOG IN THESE STARS?
SKETCH THE DOG THAT YOU FIND.



SCIENCE FAIR PROJECTS

The scientific method is based on observation and experimentation. Good science fair projects should be based on these activities as much as possible. Following is a list of astronomy experiments and observations that can be performed with a minimum of equipment. Many will require a few weeks to perform, as astronomical phenomena cannot be rushed. All should result in the generation of data that will provide the experimenter with a clue to the workings of our corner of the universe.

1. In what direction does the sun rise and set? How does a sundial work? Use shadows to trace the sun's motion. Measure length and direction of the shadow of a standard gnomon (e.g. a vertical pole) and record this data as a function of (a) time and (b) date. This will reveal (a) the sun's diurnal (E-W) motion and (b) its annual (N-S) motion in our skies.
2. When is the earliest sunset? When is the latest sunrise? When is the longest day? Measure and record the time and direction of sunrise and sunset over several weeks or months and plot the results.
3. In what direction does the moon rise or set? When is the moon visible in the sky? Measure and record the time and direction of moonrise and moonset over several weeks. Try to predict where and when the moon will rise and set next. Can you predict where the moon will be seen after several cloudy days? What shape will it have?
4. Can you read by the light of the moon? Devise a method to measure the brightness of the moon (perhaps use a light meter, or measure the distance at which you can read a standard size of print by moonlight) and record its brightness as a function of phase and altitude in the sky.
5. Why does the moon appear larger at some times? Some claim the moon appears larger when near the horizon. Record the variation in the moon's angular diameter as a function of altitude and phase. You should see variations due to the moon's changing distance from earth. From your data, try to determine when apogee and perigee occurred. Compare with published dates.
6. How fast does the moon move through the stars? Record the position of the moon with respect to the sun and stars, and from the variation in its orbital rate, try to determine the dates of apogee and perigee. [See Kepler's 2nd Law.]
7. At what rates and in which directions do the planets move among the stars? Measure and record the positions of visible planets with respect to the stars. From this data, calculate their orbital periods and compare with published data. Watch out for retrograde motion.
8. How soon after sunset does the sky become dark? Determine the length of twilight at different times of the year by observing the time at which certain bright stars first appear and comparing with the sunset time. (Beware of variations due to the stars' different altitudes. Try using Polaris as a standard.) Also note the time at which automatic streetlights turn on. Determine how soon after sunset stars of different magnitude (brightness) appear.
9. Which stars appear brightest to you? Devise your own scheme for measuring the brightness of a star (don't use magnitudes). Use it to measure the brightness of a variety of stars, bright and faint, and compare your results with published values. Compare your brightness values with published magnitudes.

Glossary

acceleration analemma annular solar eclipse annulus Antarctic Circle aphelion apogee Arctic Circle asteroid asteroid belt astronomical unit atmosphere autumnal equinox axis barycenter celestial equator celestial pole celestial sphere centrifugal force centripetal force circumference circumpolar comet configuration conjunction constellation crescent moon diameter diurnal motion dwarf planet earthshine eastern quadrature eccentricity eclipse eclipse season eclipse track ecliptic ellipse elongation equator equinox first quarter focus force friction full moon galaxy gas gibbous moon gravity great circle greatest eastern elongation greatest elongation greatest western elongation greenhouse effect horizon inclination inferior conjunction inferior planet Jovian planet kilogram last quarter liquid lunar eclipse maria mass matter meridian meteor meteor shower meteorite meteoroid midnight sun nadir new moon newton node north celestial pole North Pole oblateness obliquity opposition partial lunar eclipse partial solar eclipse penumbra penumbral lunar eclipse perigee perihelion perpendicular pi planet position pound precession quadrature radiant radius revolution revolution period rings rotation rotation period satellite scientific notation sidereal day sidereal month sidereal period sidereal time sidereal year slug small solar system body solar corona solar day solar eclipse solar system solid south celestial pole South Pole speed star star chart star trails summer solstice superior conjunction superior planet synodic month synodic period temperature terrestrial planet thermal lag third quarter total lunar eclipse total solar eclipse tropic of Cancer tropic of Capricorn tropical year umbra universe vector velocity vernal equinox waning crescent waning gibbous waning moon waxing crescent waxing gibbous waxing moon weight weightless western quadrature winter solstice zenith zodiac

acceleration
the rate of change of velocity; includes direction

analemma
the figure-8 shaped path traced over the course of a year by the Sun at a particular time of day

annular solar eclipse
a solar eclipse in which the Sun's disk appears as a ring around the new moon

annulus
ring shape

Antarctic Circle
66 1/2° south latitude; the northernmost points in the southern hemisphere where the Sun can remain above (or below) the horizon for 24 hours at the solstices

aphelion
the point in an object's orbit around the Sun where the object is farthest from the Sun

apogee
the point in an object's orbit around the Earth where the object is farthest from the Earth

Arctic Circle
66 1/2° north latitude; the southernmost points in the northern hemisphere where the Sun can remain above (or below) the horizon for 24 hours at the solstices

asteroid
small, rocky chunk of matter orbiting the Sun; also called a minor planet; classed as SSSB

asteroid belt
the region of space between Mars and Jupiter where most asteroids orbit

astronomical unit (AU)
the mean distance between the Earth and the Sun; equal to about 93 million miles (150 million kilometers)

atmosphere
layer of gases surrounding an astronomical body

autumnal equinox
the point on the ecliptic where the Sun crosses the celestial equator from north to south; the date on which this occurs; the start of autumn in the northern hemisphere

axis
the line about which a body rotates or revolves

barycenter
the center of mass in a system of two orbiting bodies

celestial equator
all points on the celestial sphere that are equidistant from both celestial poles

celestial pole
one of two points that mark the intersection of Earth's rotational axis with the celestial sphere; the north celestial pole (NCP) is directly above the North Pole while the south celestial pole (SCP) is directly above the South Pole

celestial sphere
a huge, imaginary sphere around the Earth, used to model the positions and motion of celestial bodies

centrifugal force
a reaction force to a centripetal force

centripetal force
the force acting upon a body moving along a curved path that is directed toward the center of curvature of the path and constrains the body to the path

circumference
the distance around a circle

circumpolar
never rising or setting for an observer at a particular latitude

comet
mass of frozen gases revolving around the Sun, often in a highly eccentric orbit; classed as SSSB

configuration
the relative position of bodies in space

conjunction
configuration in which two objects appear close together in the sky

constellation
a group of stars that form some pattern in the sky; one of 88 regions of sky that make up the celestial sphere

crescent moon
a phase between new and quarter moons that shows a surface that is less than half illuminated

diameter
a line segment that joins two points of a circle and passes through its center; also, the length of this line segment

diurnal motion
any daily motion of the Earth or sky associated with the rotation of the Earth

dwarf planet
a celestial body with a nearly round shape that is in orbit about the Sun, is not a satellite of a third body, and has not "cleared the neighborhood" around its orbit; Pluto and Ceres are examples

earthshine
sunlight reflected from Earth that illuminates the dark face of a crescent moon

eastern quadrature
configuration in which a planet has an eastern elongation of 90°; planet is 90° east of the Sun along the ecliptic

eccentricity
a quantity (e) that measures the shape of an orbit; $e = 0$ for a circle, $0 \leq e < 1$ for an ellipse, $e = 1$ for a parabola, and $e > 1$ for a hyperbola.

eclipse
an event in which the shadow of one celestial body falls on another, resulting in the darkening of the second body or the obscuration of the source of light (normally the Sun)

eclipse season
a month-long time interval when eclipses occur at new or full moons; normally two eclipse seasons occur each year, about six months apart

eclipse track
the path of the Moon's shadow along the surface of the Earth during a solar eclipse; marks the region on Earth from which the solar eclipse may be observed

ecliptic
the Sun's apparent path on the celestial sphere; also, the plane of the Earth's orbit

ellipse
a conic section with eccentricity less than 1; the approximate shape of planetary orbits

elongation
the angle in the sky between the Sun and another celestial object (planet, comet, etc.) as seen from Earth

equator
all points on the surface of a rotating spherical body that are equidistant from the body's rotational poles

equinox
the time when the Sun crosses the celestial equator; also, the position of the Sun on the celestial sphere at this moment

first quarter
the lunar phase occurring when the waxing Moon appears half illuminated

focus
one of two fixed points used to create an ellipse; plural = foci

force
a push or a pull

friction
a force that opposes – and is caused by – motion

full moon
the lunar phase occurring when the Moon is on the opposite side of the Earth from the Sun and appears completely illuminated (except during a lunar eclipse)

galaxy
a collection of (typically) billions of stars, together with gas and dust, all bound together by gravity

gas
matter composed of particles that are fairly independent of each other; has a free volume and a free shape

gibbous moon
a phase between full and quarter moons that shows a surface that is more than half illuminated

gravity
an attractive force that acts between all objects (with mass) in the universe

great circle
a circle on a sphere that has its center at the center of the sphere

greatest eastern elongation
configuration in which a celestial object has reached its maximum eastern angular separation from the Sun and begins to move westward back toward the Sun

greatest elongation
the maximum angular separation a celestial body may have from the Sun

greatest western elongation
configuration in which a celestial object has reached its maximum western angular separation from the Sun and begins to move eastward back toward the Sun

greenhouse effect
process by which a planetary atmosphere absorbs outgoing radiation, thus maintaining higher temperatures on the surface of the planet

horizon
a great circle on the celestial sphere that divides the sky and the Earth for a given observer; celestial objects below your horizon are hidden from view by the Earth

inclination
the angle between two orbital planes

inferior conjunction
configuration in which a planet is in line with the Sun and lies between the Earth and Sun

inferior planet
a planet with an orbit inside Earth's orbit: Mercury or Venus

Jovian planet
a Jupiter-like planet

kilogram
the metric system's unit of mass, approximately equal to the mass of 1000 cubic centimeters of water; on the surface of the Earth a mass of one kilogram has a weight of about 9.8 newtons – about 2.2 pounds

last quarter
the lunar phase occurring when the waning Moon appears half illuminated; same as third quarter

liquid
matter composed of particles bound weakly together; has a fixed volume and a free shape

lunar eclipse
an event that occurs when the full moon intercepts the Earth's shadow, resulting in a darkening of all or part of the Moon's surface

maria
huge lava-filled basins on lunar or planetary surfaces

mass
a measure of the amount of matter contained in a body

matter
the substance that comprises physical objects

meridian
a line on the celestial sphere running from the north celestial pole through the zenith to the south celestial pole, that divides the observer's sky into eastern and western halves

meteor
the luminous trail of heated air produced by a meteoroid's passage through Earth's atmosphere

meteor shower
an event caused by the Earth's passage through the orbit of a comet, where it will collide with an increased number of meteoroids; happens at the same point in Earth's orbit – and thus, on the same date – every year

meteorite
a meteoroid that reaches the surface of the Earth or another planet or moon

meteoroid
a rock in space on a collision course with the Earth; sources of meteoroids include comets and colliding asteroids

midnight sun
the phenomenon of the Sun's remaining above the horizon at midnight (and throughout a 24-hour period); occurs only for observers north of the Arctic Circle or south of the Antarctic Circle

minor planet
see **asteroid**

nadir
the point on the celestial sphere directly beneath the observer (and opposite the zenith)

new moon
the lunar phase occurring when the Moon is between the Earth and the Sun and appears completely dark

newton
the metric system's unit for measuring weight and other forces; the amount of force required to give a mass of one kilogram an acceleration of one meter per second per second (1 m/s^2)

node
a point where the Moon's orbit intersects the ecliptic; the nodes are not fixed but migrate along the ecliptic

north celestial pole (NCP)
the point on the celestial sphere that is directly above the North Pole

North Pole
one of the two points where the Earth's rotational axis intersects its surface; the Earth rotates CCW as seen from above the North Pole

oblateness
a measure of the degree to which a body's shape deviates from a sphere – which has an oblateness of 0

obliquity
the angle between a planet's rotational axis and its orbital axis; aka the tilt

opposition
configuration in which a planet is on the opposite side of the Earth from the Sun

partial lunar eclipse
an eclipse that occurs when the Moon is only partly immersed in the Earth's umbra, producing a dark 'bite' out of the Moon

partial solar eclipse
an eclipse that occurs at points on the Earth that are within the Moon's penumbra, where a dark 'bite' out of the Sun can be seen

penumbra
the lighter shadow produced by an opaque body's blocking of some of the light from an illumination source

penumbral lunar eclipse
an eclipse in which the Moon enters the Earth's penumbra (but not its umbra); the lunar surface appears shaded but not significantly darkened

perigee
the point in an object's orbit around the Earth where the object is closest to the Earth

perihelion
the point in an object's orbit around the Sun where the object is closest to the Sun

perpendicular
meeting at right angles (90°)

pi (π)
the ratio of the circumference of a circle to its diameter; approximately 3.141592654359

planet
a celestial body in orbit about the Sun that has a nearly round shape and has "cleared the neighborhood" around its orbit; Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune

position
location with respect to a reference point

pound
the British system's unit for measuring weight and other forces; the amount of force required to give a mass of one slug an acceleration of one foot per second per second (1 ft/s^2)

precession
the slow wobble of the Earth's rotational axis and the gradual change in the positions of the equinoxes, solstices, and celestial poles that it causes

quadrature
configuration of a superior planet in which its elongation is 90°

radiant
the point in the sky from which a meteor shower appears to radiate

radius
the distance from the center of a circle to a point on the circle; distance from the center of a sphere to a point on the surface of the sphere

revolution
the orbiting motion of one body about another

revolution period
the time it takes a body to complete one orbit

rings
systems of numerous tiny particles orbiting a planet in the same plane

rotation
the spinning motion of a body about an axis through the body

rotation period
the time required for a body to complete one rotation

satellite
an object orbiting about another

scientific notation
the system of expressing a number as the product of (1) a number between 1 and 10 and (2) a power of 10

sidereal day
the interval between successive alignments of a star, the observer, and the Earth's axis – about 23^h 56^m 4^s

sidereal month
the interval between successive alignments of a star, the Moon, and the Earth – about 27.32 days

sidereal period
the time it takes a body to complete one orbit or rotation with respect to the stars

sidereal time
the system of time based on the position of the stars with respect to the observer

sidereal year
the interval between successive alignments of the Earth, the Sun, and a star – 365^d 6^h 9^m 10^s

slug
the British system's unit of mass, equivalent to approximately 14.6 kilograms; on the surface of the Earth a mass of one slug has a weight of about 32.2 pounds

small solar system body (SSSB)
a celestial body that is in orbit about the Sun, is not a satellite of a third body, does not have a nearly round shape, and has not "cleared the neighborhood" around its orbit; comets and most asteroids are examples

solar corona
a faint halo of gases around the Sun that is visible during a total solar eclipse; the outer portion of the Sun's atmosphere

solar day
the interval between successive alignments of the Sun, the observer, and the Earth's axis – 24^h

solar eclipse
an event that occurs when portions of the Sun are obscured by the Moon, as seen from the Earth's surface

solar system
the Sun and all of the objects – planets, moons, comets, asteroids, etc. – that orbit about it

solid
matter composed of tightly bound particles; has a fixed volume and a fixed shape

south celestial pole (SCP)
the point on the celestial sphere that is directly above the South Pole

South Pole
one of the two points where the Earth's rotational axis intersects its surface; the Earth rotates CW as seen from above the South Pole

speed
rate of change of distance; does not include direction

SSSB
see **small solar system body**

star
one of many points of light in the night sky that maintain nearly constant positions on the celestial sphere; a massive, gaseous sphere, heated by gravitational compression and/or thermonuclear fusion and radiating visible light

star chart
a map of the celestial sphere showing locations of stars and other objects

star trails
streaks made by stars on photographs of the sky, due to Earth's rotation

summer solstice
the northernmost point on the ecliptic, where the Sun is directly above the tropic of Cancer; the date on which this occurs; the beginning of summer in the northern hemisphere

superior conjunction
configuration in which a planet is in line with the Sun and lies on the opposite side of the Sun from the Earth

superior planet
a planet with an orbit lying outside the Earth's orbit: Mars, Jupiter, Saturn, Uranus, or Neptune

synodic month
the interval between successive similar alignments of the Sun, the Moon, and the Earth; the interval between successive new moons – about 29.53 days

synodic period
the time it takes for an inferior planet to lap the Earth, or for the Earth to lap a superior planet as they orbit the Sun

temperature
a measure of the energy content of matter

terrestrial planet
an Earth-like planet

thermal lag
the time required for an object to heat up or cool down in response to changes in the rate of incoming heat

third quarter
the lunar phase occurring when the waning Moon appears half illuminated; same as last quarter

total lunar eclipse
an eclipse that occurs when the Moon is completely immersed in the Earth's umbra, where practically no sunlight can reach it

total solar eclipse
an eclipse that occurs at points on the Earth that are within the Moon's umbra, where all of the Sun's disk is blocked from view

tropic of Cancer
the latitude that marks the northern limit at which the Sun can be seen at the zenith – about $23^1/_2$° N

tropic of Capricorn
the latitude that marks the southern limit at which the Sun can be seen at the zenith – about $23^1/_2$° S

tropical year
the interval between successive alignments of the Earth, the Sun, and the vernal equinox – $365^d\ 5^h\ 48^m\ 46^s$

umbra
the dark shadow of an opaque body, where direct light from the source of illumination is completely blocked

universe
everything there is, including radiation and matter in the form of billions of galaxies

vector
a physical quantity that is described by both magnitude and direction

velocity
rate of change of position; includes speed and direction

vernal equinox
the point on the ecliptic where the Sun crosses the celestial equator from south to north; the date on which this occurs; the start of spring in the northern hemisphere

waning crescent
lunar phase between last quarter and new, in which the Moon appears less than half illuminated

waning gibbous
lunar phase between full and last quarter, in which the Moon appears more than half illuminated

waning moon
any phase during which the illuminated fraction of the Moon's face decreases (from full to last quarter to new)

waxing crescent
lunar phase between new and first quarter, in which the Moon appears less than half illuminated

waxing gibbous
lunar phase between first quarter and full, in which the Moon appears more than half illuminated

waxing moon
any phase during which the illuminated fraction of the Moon's face increases (from new to first quarter to full)

weight
a reaction force that opposes the gravitational pull on an object; if no such reaction force is present, the body will accelerate, resulting in a free falling or orbiting body and a condition of weightlessness

weightless
having no reaction force opposing gravitational pull, as during free fall or orbit

western quadrature
configuration in which a planet has a western elongation of 90°; planet is 90° west of the Sun along the ecliptic

winter solstice
the southernmost point on the ecliptic, where the Sun is directly above the tropic of Capricorn; the date on which this occurs; the beginning of winter in the northern hemisphere

zenith
the point on the celestial sphere directly above the observer (and opposite the nadir)

zodiac
a band around the celestial sphere, extending 9° either side of the ecliptic, that contains the paths of the Sun, Moon, and planets

Index

About the Author

Dr. James N. Pierce is emeritus professor of astronomy at Minnesota State University, Mankato, where he taught astronomy, physics, and mathematics for 32 years. His regular astronomy offerings ranged from general education courses to classes for astronomy majors. The numerous summer workshops and in-service courses that he designed and taught for grade K-6 teachers provided the impetus for the creation of this book.

Elementary Astronomy was originally published in 2000 by Good Apple as ISBN 0-7682-0318-X. This current edition has been redesigned, updated, and generally improved.

Other books by Dr. Pierce:

Life in the Universe: The Abundance of Extraterrestrial Civilizations (2008), BrownWalker Press.

Notes on Stellar Astrophysics (2013).

Dr. Pierce's web pages: Search '*pierce astronomy mankato*' for current sites.