Part I

Introducing steps to astronomy

Astronomy was the first science. Indeed, it is older than science. Thousands of years before the scientific revolution, thousands of years before telescopes and modern chemistry, geology and physics, people gazed at the sky and realized there was a lot going on up there to think about.

We begin our study of astronomy by considering what you can see with your naked eye. The daily passage of the Sun across the sky, the phases of the Moon, eclipses and the migration of the Sun across the constellations – all these regularities cry aloud for explanation, and they hint of a great cosmic structure. Early ideas of this structure – we now call it the Solar System – were formulated by ancient peoples, and they persisted for millennia.

Eventually these ideas were overthrown in the scientific revolution. We will trace briefly the course of this revolution, but in doing so our concern is not really historical. Our actual concern is to illuminate the nature of science through a study of its origins. Science is a way of thinking, a way of looking at the world, that was unique in the history of thought. Nothing more vividly illustrates the remarkable nature of science than a study of how it differs from what came before.

With the work of Isaac Newton the scientific revolution reached its climax. In his magisterial *Mathematical Principles of Natural Philosophy* this extraordinary genius set forth principles which govern the workings of the cosmos. We will devote an entire chapter to Newton's laws of motion and of gravitation, the single most important force operating in the astronomical universe.

Astronomy faces a difficulty not shared by other sciences: we cannot get our hands on what we study. The geologist can pick up a rock and examine it: the biologist can dissect an animal. But among all the objects in the Universe, only four – the Moon, Venus, Mars and a moon of Saturn – have actually been landed upon by spacecraft. The rest of the cosmos we are forced to study from afar.

Luckily, the Universe is continually broadcasting information to us, coded into light. It is by studying this light that we gain information about the cosmos. Indeed, until the advent of the space program, this was the *only* means we had of gathering information about the cosmos.

Telescopes are the very symbol of astronomy, the most important instruments at our disposal. For centuries they functioned as what might be called "giant eyes," operating as they did in the visual region of the electromagnetic spectrum. More recently new instruments such as radio telescopes and X-ray telescopes have been invented, capable of "looking" at the sky in entirely new wavelengths. Some sit on the ground: others orbit in space. Each has changed the way we do astronomy.

In recent decades the space program has made it possible to study the Moon and planets by actually visiting them. Astronauts have walked on the Moon, and robotic space probes have visited every planet of the Solar System. This entirely new way of studying the Solar System has brought back a wealth of information.

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1

The sky

Astronomy belongs to everyone. The Universe is here for all of us to see. Its study is not just the province of astronomers, with their expensive telescopes and strange, unfamiliar mathematics. In this chapter, we are concerned with astronomy that you can do with your naked eye.

Some of the most universal aspects of our lives are inluenced by astronomical phenomena. Imagine, for instance, a world in which day did not turn into night, or one in which there were no seasons! As we think about these, we will quickly realize that they are more subtle than perhaps we had thought. Indeed, even so simple a thing as the daily path of the Sun across the sky was historically explained in several different ways.

So too with eclipses and the phases of the Moon, the measurement of time and the drifting of the sun along the zodiac – we begin our voyage through the Universe with these, some of the most fundamental aspects of our everyday environment.

Rising and setting: the rotation of the Earth

Perhaps the most basic of all astronomical observations is the simple fact that day turns into night and then day again in a never-ending cycle. This perpetual alteration, caused by the passage of the Sun across the sky, is so familiar that we hardly ever stop to pay attention to it. But in fact there is more to it than many people think.

Let us begin our study of astronomy with this, perhaps the simplest of all astronomical observations: the study of the Sun's path across the sky. To perform this study you will need no advanced scientific equipment. Simply step outside just before dawn, face east, and watch what happens. What you see depends on where you live: we will concentrate on the view of the sky from the mid northern hemisphere.

Many people believe that the Sun moves straight up as it rises. Does it? You can answer this question by mentally marking the location on the horizon at which it rises – just to the right of that house across the street, perhaps, or directly over that distant tree. An hour or so later, when the Sun has risen higher, step outside again and note its new position. Does it lie directly above the point at which it rose? You will find that it does not. In fact the Sun has moved along a slanting path, upwards and to the right as sketched in Figure 1.1.

Many people also believe that at noon the Sun is directly overhead. Here too, it is worthwhile to actually make the observation. You will find that it is not: the Sun at noon lies somewhere between the overhead point and the southern horizon. At this

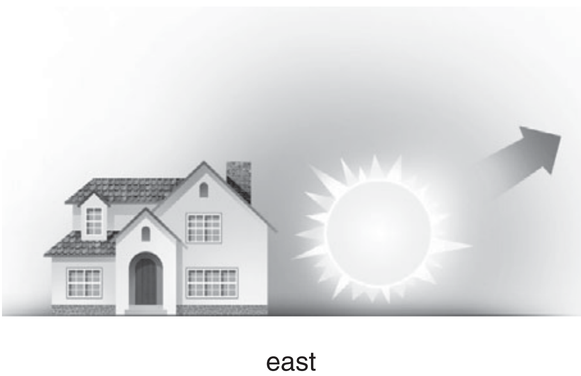

Figure 1.1 **The rising Sun moves up and to the right (in the northern hemisphere).**

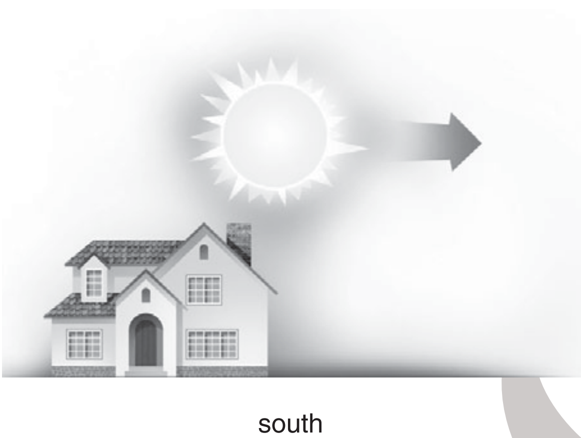

Figure 1.2 **At noon the Sun moves horizontally to the right (in the northern hemisphere).**

Figure 1.3 **The setting Sun moves down and to the right (in the northern hemisphere).**

time it is moving from left to right, parallel to the horizon as sketched in Figure 1.2.

Finally, watch the Sun set in the west. Perhaps you will not be surprised to observe that the Sun slants downwards and to the right as it sets, as sketched in Figure 1.3.

Why does the Sun rise and set?

How can we understand this intriguing behavior? We all know, of course, that the motion of the Sun is an illusion. In reality the Sun is holding still: it is *we* who move, carried by the rotation of the Earth. It is as if we were on some gigantic conveyer belt which steadily carries us up and over a hill. In fact this is a good analogy: the "hill" is the curving bulk of the Earth itself, and the "conveyer belt" is the Earth's rotation. Because the Sun rises in the east, we know that the rotation of the Earth carries us from west to east.

This simple analogy, however, does not help us understand the complexities of the Sun's path across the sky. The problem is that the analogy fails to capture the way in which we move as we are carried along by the rotation of the Earth. This motion is illustrated in Figure 1.4.

As we can see, people located on different parts of the Earth move in different ways. A person standing at the north pole spins about like a figure skater. A person standing at the equator executes a sort of "tumbling" motion. And finally, a person situated between pole and equator traces out a curious cone-shaped path over the course of one day.

The complexities of the apparent path of the Sun in the sky arise from these complex motions of the people who are observing it. Perhaps the simplest motion to think about is that of a person at the north pole: a simple spinning on one's axis. You can duplicate this motion for yourself by standing up on your toes and spinning about. If you look at a lamp as you do this, you will see it appear to move horizontally (Figure 1.5), mimicking the motion of the Sun as seen from the pole.

To mimic the motion of an observer at the equator, imagine what you would see if you were to gaze at a distant street light as you walked up and over a hill, if it were possible to remain not vertical but *perpendicular to the hill* (Figure 1.6). You would see the street light move straight up.

Figure 1.4 **The rotation of the Earth moves you in different ways depending on your location.**

Figure 1.5 **Simulating the motion of an observer at the pole.**

Figure 1.6 **Simulating the motion of an observer at the equator.**

And finally, the motion of a person at some location intermediate between equator and pole is intermediate between these two situation, and yields the observed slanting path of the Sun.

THE NATURE OF SCIENCE

HYPOTHESIS TESTING IN SCIENCE: WHY DOES THE SUN RISE AND SET?

It is important to emphasize that what we have described in the above section is a *theory*, one designed to explain the observations we have made of the Sun's path across the sky. Let us call it "the Round Earth theory":

- *the Round Earth theory*: the Earth is round, and it is spinning on its axis. The Sun holds still.

But a different idea has also been held:

- *the Flat Earth theory*: the Earth is flat, and it is holding still. It is the Sun that moves.

Of course we all know perfectly well that the Round Earth theory is true and the Flat Earth theory is false. We have all seen images of the spherical globe of the Earth sent back to us from space. But let us try to ignore this knowledge for a moment, and try to put ourselves in the shoes of people who lived centuries ago, before the dawn of the space age. They might have regarded the Flat Earth theory as being perfectly good. After all, in our daily lives the ground beneath our feet certainly *looks* flat. What could they have done when faced with two different explanations for the same thing?

Scientists are continually encountering such situations. We discover something interesting, and then we think up a theory to account for it. The problem is that often we are able to think up *lots* of theories! What then? How can we choose between competing hypotheses?

The answer is that we ask each hypothesis to make a *prediction* concerning something that has not yet been observed. The different theories will make

Figure 1.7 **The rising Sun moves straight up as seen from the equator, according to the Round Earth theory.**

different predictions. We then go out and *conduct new observations*, testing to see which prediction turns out to be true.

So to choose between our two theories of the Sun's path, let us ask each of them to predict *the Sun's path across the sky as seen from different locations on the Earth*.

Predictions of the Round Earth theory. Imagine that you were to get in a plane, travel thousands of miles, and then track the motion of the Sun. What would you observe according to the Round Earth theory? As you can see from our discussion in the previous section, you would find that the slant angle at which the Sun rises and sets depends on your location. The further south you journey, the more nearly vertical would this angle become. Indeed, if you were to travel all the way to the equator you would find the Sun rising straight up (Figure 1.7) and setting straight down.

Similarly, if you were to journey to the north pole you would find that as 24 hours pass the Sun would *never* rise or set. Rather it would move in a circle from left to right, parallel to the horizon (Figure 1.8).

Predictions of the Flat Earth theory. The Flat Earth theory makes a different prediction. If the Earth were flat and the Sun moved across the sky, the Sun's path would be the same no matter where you were. So this theory predicts that if you were to get in a plane, travel thousands of miles, and then track the motion of the Sun, you would find everything to be the same.

Testing the predictions. Experience confirms that the predictions of the Round Earth theory are born out, and the predictions of the Flat Earth theory are not. The path of the Sun across the sky does indeed depend on where you are.

In this way we accept one hypothesis and reject the other. And in later chapters, we will find that the process is always the same: scientists are forever testing their theories by forcing them to make predictions, and they choose the best theory by finding the one which makes the most sucessful predictions.

A SCIENTIFIC THEORY MUST MAKE PREDICTIONS

It is essential to hypothesis testing that *a theory has to make a definite prediction*. If you have an idea which does not make a prediction, your idea is not a theory.

As an example, consider yet a third idea about the Sun's path.

- *The Free Will Idea*: the Sun moves across the sky because it wants to.

We would not say that this is a legitimate theory: it is not a hypothesis but a vague notion. It makes no predictions about anything. Even if we granted that the Sun could "want" something, there is no way we could test this idea.

It is also essential to hypostheis testing that the theory must be able to make a prediction about something *that has not yet been observed*. In our present case, we must ask each theory to make its prediction before we had actually gotten in a plane and travelled to a new location. Only in such a circumstance would we have conducted a fair test of the competing hypotheses.

Figure 1.8 **The Sun neither rises nor sets as seen from the north pole, according to the Round Earth theory.**

This is easy for us nowadays, but in ancient times it was an exceedingly difficult proposition. In the past, cultures which did not engage in long-distant voyages of exploration had no way to decide between the Round Earth and Flat Earth hypotheses. Similarly, in modern science we often encounter situations in which we are not yet able to conduct observations which would allow us to choose between competing theories. We therefore live in a state of perpetual uncertainty, in which we are forced to suspend judgement, and tentatively hold in our minds a set of mutually exclusive explanations.

Hypothesis testing is a universal aspect of science. We will encounter it again and again throughout this book.

"Rotation" of the sky: circumpolar stars

It is not only the Sun that rises and sets. Every object in the sky – the Moon, the planets, the stars – appears to move. You can prove this to yourself by going outside at night and glancing at the sky to the East – and then returning a few hours later and looking again. You will find that everything which used to be close to the Eastern horizon has now risen higher and to the right. A little thought shows why this should be so: we view the entire sky from the rotating Earth, and everything in it undergoes the same kinds of motion as does the Sun.

But this does not mean that everything rises and sets. Indeed, there is a group of stars – so-called "circumpolar stars" – which never rise or set. They are always above the horizon.

Figure 1.5 illustrated how a person at the north pole moves, carried along by the rotation of the Earth. In Figure 1.9 we illustrate how the sky appears to move as seen by this person. As you can see, this person sees every star moving in a circle. The center of this circle, the so-called *celestial pole*, lies directly above the observer. It is the location on the sky towards which the rotation axis of the Earth points. We can think of the sky as a gigantic dome peppered with stars: as seen from us on Earth, this dome appears to rotate about an axis passing through the celestial pole. The North Star lies almost exactly at this pole. Notice that in Figure 1.9 stars appear to move parallel to the horizon. So none of them rise or set. We see that from the Earth's poles *every* star is circumpolar.

Figure 1.10 does the same for a person located on the Earth's equator. A person on the equator is tilted by 90° relative to one at the pole, so that as seen from the equator the dome representing the sky appears to be tilted by 90°. Thus from the equator the celestial pole lies on the horizon to the north. As illustrated, from the equator the stars appear to move perpendicularly to the horizon, so that they rise straight up. Furthermore, all of them rise and set: from the Earth's equator *no* star is circumpolar.

Figure 1.9 **"Rotation" of the sky as seen from the north pole.**

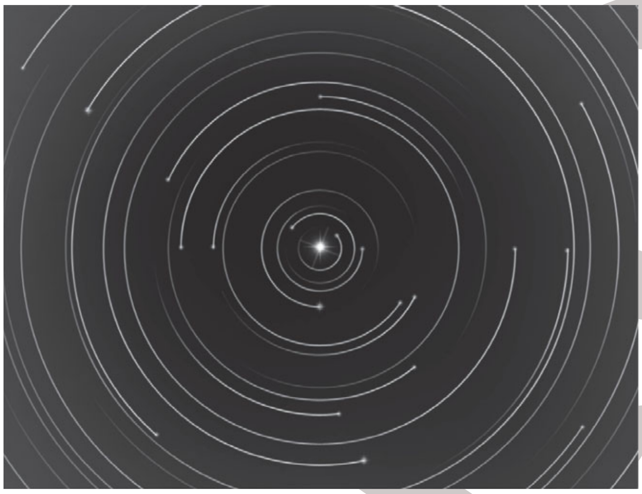

Figure 1.10 **"Rotation" of the sky as seen from the equator.**

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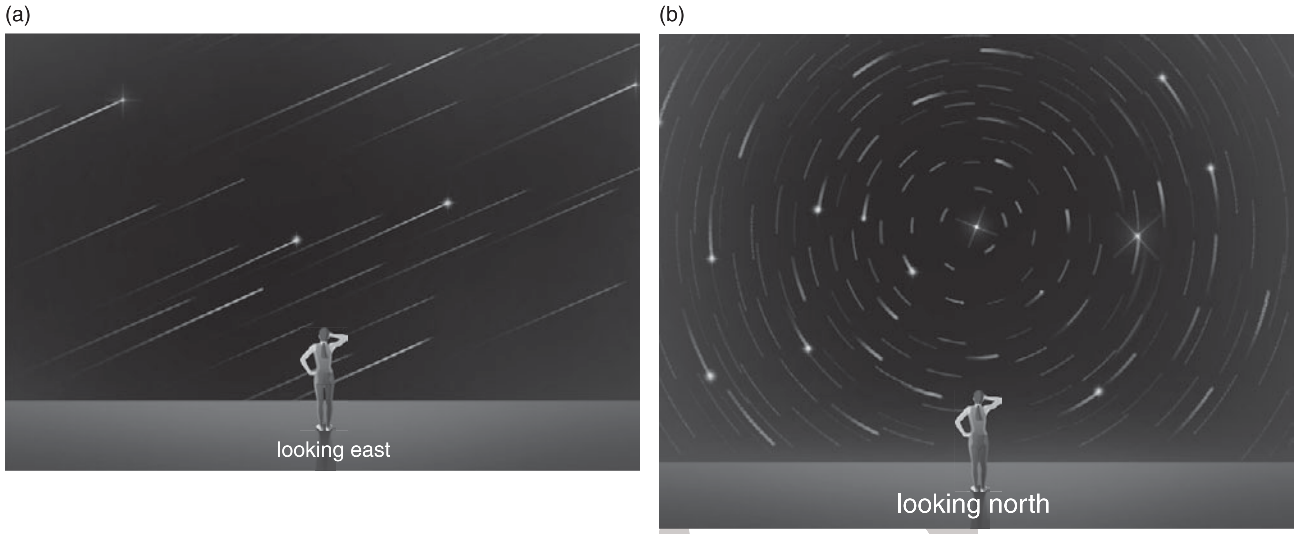

Figure 1.11 **"Rotation" of the sky as seen from intermediate latitudes.**

The "rotation" of the sky as seen from somewhere lying in between these two extremes is intermediate. It is illustrated in Figure 1.11. The dome representing the sky appears to be tilted, with the celestial pole lying above the northern horizon. If we look to the east we see stars rising, but if we look to the north we see stars appearing to rotate about the celestial pole. Those stars whose paths never pass below the northern horizon are circumpolar.

How rapidly does the Earth rotate?

Although we do not feel it, we are all moving, carried along by the rotation of the Earth. Let us calculate how rapidly we are moving.

The calculation is easiest if we concentrate on a person situated on the equator. As you can see from Figure 1.4, this person is moving in a circle whose radius is the radius of the Earth.

The logic of the calculation

Velocity is distance divided by time. The distance the person moves is the circumference of the Earth, and the time required to move this distance is one day. So the steps in the calculation are as follows.

Step 1. Find the circumference of the Earth.
Step 2. Divide this by one day to find the velocity.

As you can see from the detailed calculation, a person at the equator is moving at a bit more than a thousand miles per hour.

Now let us transfer our attention from the equator to the north pole. As we can see from Figure 1.4, this person is not moving in a circle at all – she is simply spinning about on an axis. So the velocity at the north pole is not a thousand miles per hour, but zero.

This is enough to tell us that the velocity at which we are moving must depend on our location. It is greatest at the equator, and zero at the pole. In Problem 8 at the end of this chapter we study this further.

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Detailed calculation

We will begin with a rough calculation, and then do it more carefully.

Rough calculation

Step 1. Find the circumference of the Earth.

The Earth's circumference is about 24 000 miles.

Step 2. Divide this by one day.

There are 24 hours in a day, so the velocity is roughly

V = 24 000 miles/24 hours = 1000 miles/hour.

Careful calculation

Our above value for the circumference of the Earth was not exact: we should do the calculation more carefully. Furthermore, throughout this book we will be using the MKS system (the meter/kilogram/second system), so we need to work in these units.

Step 1. Find the circumference of the Earth.

The Earth's radius R is 6378 kilometers, or 6.378×10^6 meters. Its circumference is then

$C = 2R = (2)$ $(6.378 \times 10^6$ meters$) = 4.01 \times 10^7$ meters.

Step 2. Divide this by one day.

We need to express the length of the day in seconds: we get one day = (24 hours/day)(60 minutes/hour)(60 seconds/minute) = 8.64×10^4 seconds.

So the velocity is

$V = 4.01 \times 10^7$ meters/8.64×10^4 seconds = 464 meters/second.

How good was our rough calculation?

We can find out by converting the result of our careful calculation into miles per hour: we find

464 meters/second = 1038 miles/hour.

Our rough calculation had been pretty good!

NOW YOU DO IT

Measure the diameter of a basketball. Now spin it once per second. How rapidly is a point on its equator travelling? Can you run this fast?
(A) Explain the logic of the calculation you will do.
(B) Do the detailed calculation.

The Sun is 6.96×10^8 meters in radius. And although it is not obvious to the naked eye, the Sun actually rotates on its axis: it does so once every 25.4 days. How rapidly is a point on its equator moving? (A) Explain the logic of the calculation you will do. (B) Do the detailed calculation.

The phases and motion of the Moon

Our simple observations of the Sun have led to some interesting results. Now transfer attention to the Moon. As we have already emphasized the Moon, like the Sun, rises and sets, and it follows a path across the sky which depends on your location on the Earth. But there is more to the Moon than this.

Not long ago I decided to study the Moon, and I observed it carefully over the course of a month. Here is what I saw.

First observation. Early one morning I stepped outside just before dawn. A brilliant glow marked the point at which the Sun was about to rise. Close to the Sun was a thin crescent Moon (Figure 1.12)

Second observation. This was performed about a week later. At about noon I noticed that the Moon was rising in the East. It was in its half phase (Figure 1.13).

Third observation. The was performed about a week after the second. As the Sun was setting I noticed that the Moon was rising in the East. It was full (Figure 1.14).

The fourth observation was performed about a week after the third. I noticed that the Moon was rising in the East at about midnight. It was in its half phase (Figure 1.15).

The entire cycle repeats endlessly, taking just 29 1/2 days to be completed – the *lunar month*. Indeed, our word "month" comes from the word "moon."

These observations tell us a number of things about the Moon.

(1) *The bright portion of the Moon is always oriented towards the Sun*, as you can see from Figures 1.12–1.15.

(2) *The Moon rises at different times of day.* Indeed, the time of moonrise undergoes a regular progression as the lunar month proceeds. Initially (Figure 1.12) the Moon rises more or less when the Sun rises. But as the month rolls, by the Moon rises later and later each day.

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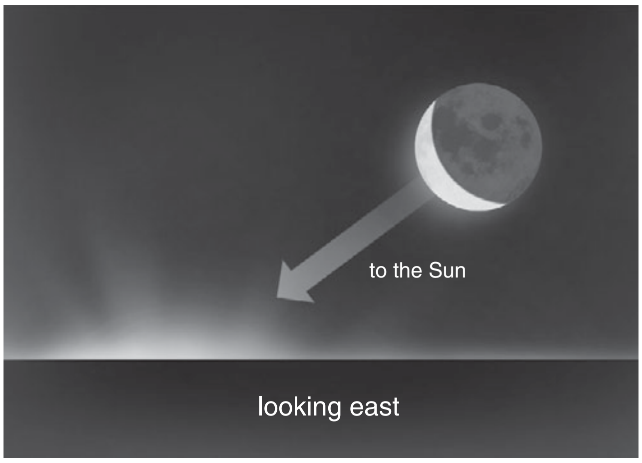

Figure 1.12 **The crescent Moon rises at dawn.**

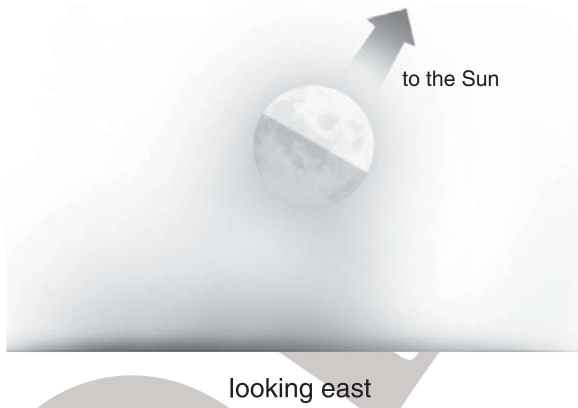

Figure 1.13 **The half Moon rises around noon.**

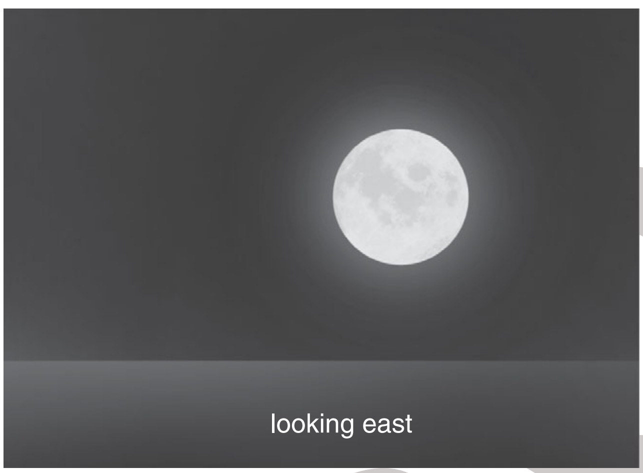

Figure 1.14 **The full Moon rises around Sunset.**

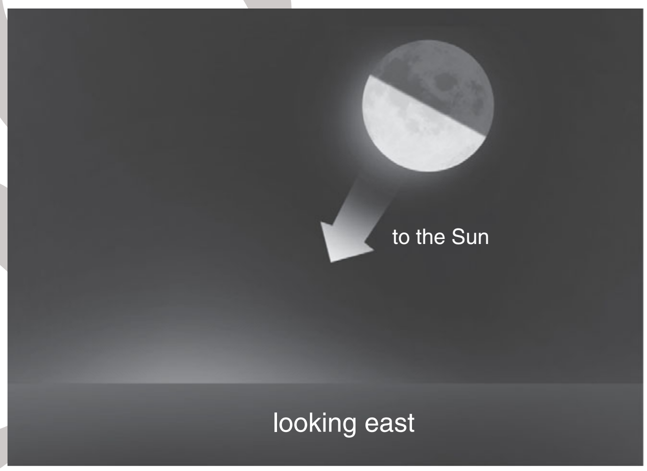

Figure 1.15 **The next half Moon rises around midnight.**

(3) *The phase of the Moon is connected to when it rises.* As you can see from the above observations, the phase of the Moon undergoes a regular progression, synchronized with the progression in its time of rising.

Let us see if we can understand these three points.

The part of the Moon that we can see is the part which is illuminated by the Sun. If you could go to the Moon and stand on the bright part, you would be in daytime. Similarly, if you could stand on its dark part, you would be in nighttime. Clearly, at the various phases of the Moon we are seeing differing portions of its daylight and nighttime parts. When the Moon is in its crescent phase, we are seeing mostly its night side and only a little bit of its day side. Similarly, when the Moon is in its half phase, we are seeing half of its dark side and half of its day side.

Let us make a model of the Moon illuminated by the Sun. The Moon, of course, is spherical, so our model must be too. Let's say that our model is an orange. In your room, turn out all the lights but one, and study how this orange is illuminated by that one remaining light. As diagrammed in Figure 1.16, *half of any sphere is illuminated by a distant light, and half is not.* This is true for your orange, and it is true of the Moon as well.