We now take it for granted that the Moon orbits the Earth and Earth orbits the Sun. But this was not always the case. Trying to determine the paths of celestial bodies while sitting on a spinning, tilted Earth that's orbiting the Sun is an extremely difficult task. Imagine trying to draw a map of your own hometown while riding the Tilt-a-Whirl at the amusement park!

Throughout the 17th century, scholars advanced several different explanations for the motions of the Sun, planets, and stars. In the absence of unambiguous scientific data, theories were often justified on aesthetic, religious, or philosophical grounds. By 1632, the controversy surrounding the many explanations of celestial motions had become so intense that Galileo was summoned before the Roman Inquisition for publishing a book describing a *heliocentric* model. At the time, a geocentric theory was the accepted explanation for the motions of objects seen in the night sky and was the model taught by the [Roman Catholic] Church. But Galileo based his argument on careful observations that he made with a newly invented tool: the telescope.

Four centuries of increasingly sophisticated astronomical observations later, we now know that Galileo's heliocentric theory was correct. But it wasn't until Isaac Newton's 1687 theory of universal gravitation that the last piece of the puzzle fell into place.

Under the influence of gravity, all the planets orbit the Sun and the Moon orbits the Earth along elliptical paths. The farther a moon or planet is from the body it is orbiting, the longer it takes to complete one orbit. For example, the Moon is 3.8×10^5 km from the Earth and it completes one round trip every 27.3 days. The Earth is 1.5×10^8 km from the Sun and it makes a complete orbit in just over 365 days. But despite the apparent simplicity of this description, the Sun, Moon, and stars follow relatively complicated paths across the sky.

You may have previously observed the motion of a planet (or the Moon) over a very short time. In this exercise, you will see the motions of the Sun and Moon over an *extended* period of time. As you watch the Sun and Moon (and planets and stars) travel through the sky, try to keep in mind that their paths are the combined result of four simple facts: (1) the positions of the stars relative to each other are nearly constant; (2) the planets orbit the Sun; (3) the Moon orbits the Earth; (4) the Earth spins.

Objectives:

- Observe positions of the sunset (or sunrise)
- Learn and explain why we have seasons
- Observe positions of the Moon along its orbit
- Determine the various periods of the Moon
- Learn and predict the phases of the Moon and why they occur

Equipment:

- Cross-staff with meterstick
- SC001 chart
- Timepiece
- View of the western (or eastern) horizon that you can access multiple times over an extended period

Set-Up:

Your instructor will give you a brief overview and introduction to this exercise, but it is conducted outside of class, on your own time. It is an outdoor observing activity over an extended period of time, so *keep up with the observations and do not procrastinate! THIS ACTIVITY CANNOT BE COMPLETED IN LESS THAN FOUR WEEKS. Plan accordingly.* It is not necessary to work with anyone else, but if it helps you, by all means do so. Remember to credit any collaborators in your write-up. Skim through the exercise before you begin and get familiar with what you'll be doing. Clearly indicate answers to questions.

I. THE CELESTIAL SPHERE (CONTINUED FROM MOTIONS I)

In the first installment of the Astronomical Motions exercise, "The Night Sky," you learned the basic features of the celestial sphere (Figure 1). As objects move through the sky, observers on the Earth can trace their motions on the celestial sphere. The distant stars seem to lie on the surface of the celestial sphere, and as the Earth spins on its axis, people on the ground see the celestial sphere rotate overhead. The Earth rotates from west to east, so the celestial sphere seems to rotate from east to west.

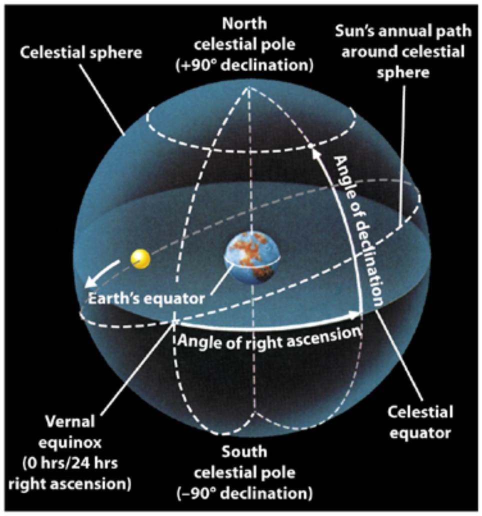

Figure 1-8
Discovering the Universe, Eighth Edition
© 2008 W.H. Freeman and Company

Figure 1. The celestial sphere.

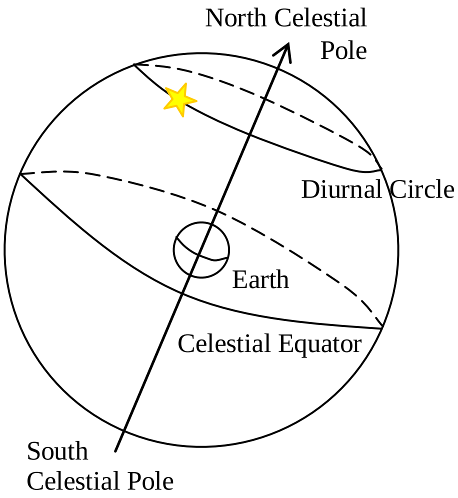

Figure 2. The diurnal circle of a star in the northern hemisphere of the celestial sphere.

Points on the celestial sphere seem to follow circles around the earth's rotation axis. Only two points on the sphere, the north and south celestial poles, which lie at the extensions of the Earth's north and south poles, respectively, remain stationary. Points on the celestial sphere trace out circles on the sky called *diurnal circles* (diurnal = daily). For observers in the northern hemisphere, objects that are south of the celestial equator are visible less than half of the time and objects that are north of the celestial equator are visible more than half of the time.

The apparent position of an object's diurnal circle in the sky depends upon your geographic

(a) **(b)** **(c)**

Figure 3. Star trails (diurnal circles) in the skies. (a) As seen from the equator. (b) As seen from the North Pole. (c) As seen from an intermediate latitude.

location. If you are standing at the equator, points on the celestial sphere rise from the east along a path perpendicular to the horizon and cross the sky due westward before setting straight over the western horizon (Figure 3a). If instead you happen to be standing at either the north or south pole, the objects on the celestial sphere would circle the sky around the celestial pole, parallel to the horizon (Figure 3b).

At intermediate latitudes, the motions of the celestial bodies are slightly more complicated. In the northern hemisphere, objects rise up from the eastern horizon along a path that moves towards the south, at an angle equal to the observer's latitude (Figure 3c). For example, the latitude of Murfreesboro, TN, is about 35° N, so stars rising there follow a trail that makes an angle of 35° with respect to a line drawn perpendicular to the eastern horizon. The same stars, when setting, will approach the western horizon moving to the north at an angle of 35° with respect to a line drawn perpendicular to the horizon.

II. THE SUN AND SEASONS

The *ecliptic* is the projection of the plane of the solar system onto the celestial sphere (Figure 4). It is in this plane (approximately) that the eight planets of our solar system orbit the Sun. Since the Earth's axis of rotation – which defines the celestial poles and equator – is tipped relative to the plane of the solar system by 23.5°, the ecliptic is tilted by 23.5° with respect to the celestial equator. As a consequence, objects which move in the plane of the solar system pass north and south across the celestial equator. For example, as the Earth orbits the Sun, the Sun's position on the celestial sphere changes. On the summer and winter solstices, the Sun reaches its highest and lowest points in the sky, respectively. [*Solstice* is from the Latin "sol" and "sistere" which mean "sun" and "to be still," respectively.] On the northern hemisphere's winter solstice, the sun is 23.5° south of the celestial equator, and on the summer solstice it is 23.5° north of the celestial equator (Figure 5). Similarly, the Moon's orbit around the Earth and the other planets' orbits around the Sun carry them through different hemispheres of the celestial sphere.

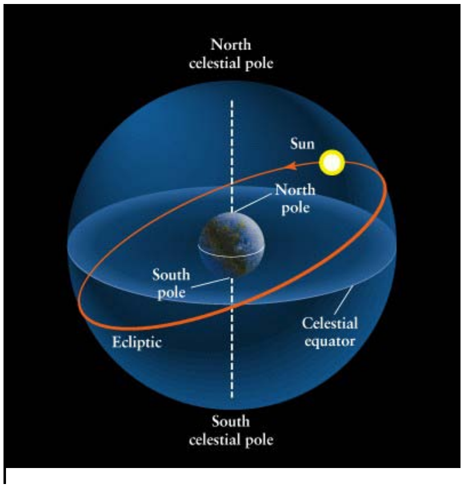

Figure 4. The ecliptic on the celestial sphere.

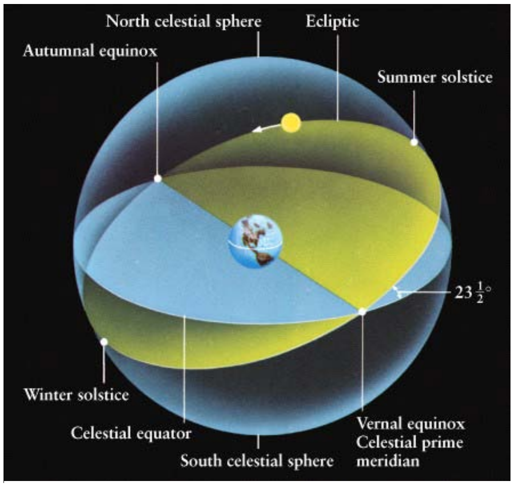

Figure 5. Motion of the Sun on the celestial sphere.

The ecliptic and the celestial equator coincide at two points on the celestial sphere: the *vernal* and *autumnal equinoxes* (Figure 5). [*Equinox* comes from the Latin "equus" and "nox," literally translating to "equal night." *Vernal* comes from the Latin "vernus" which means "of spring."] The Sun crosses the vernal equinox around March 21 and the autumnal equinox around September 22. Because of their motions along the ecliptic, the portions of the Sun's and Moon's (and planets') diurnal circles that are visible to us change. For example, in the northern hemisphere's winter, the sun is south of the celestial equator so less than half of its diurnal circle is visible above the horizon. That is why the days are shorter in the winter. At either equinox, the Sun lies on the celestial equator so exactly half of its diurnal circle is

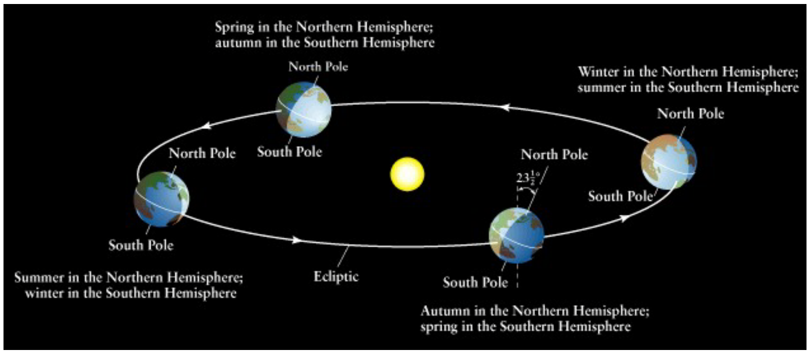

Figure 6. Why we experience seasons.

above the horizon. Thus on the equinoxes, day and night are supposed to be the same length (though this is rarely the case due to local topographical features).

The large seasonal variation in the Earth’s surface temperature is caused by the change in the position of the Sun in the sky (Figure 6). During summer in the northern hemisphere (when the Earth is physically farthest from the Sun), the northern tip of the Earth’s axis is tipped towards the sun, which increases the length of the day and allows the sun to shine more directly down on the Earth’s surface. Both effects raise the surface temperature in the northern hemisphere. As the Sun moves around toward our winter, both hemispheres are equally exposed to the sunlight, causing us to experience fall while the southern hemisphere gets warmer (spring). In the northern hemisphere’s winter (when the Earth is physically closest to the Sun), the Earth’s axis is tilted away from the Sun so it gets less direct sunlight, shorter days, and a lower average surface temperature.

ANSWER THE FOLLOWING QUESTIONS AS COMPLETELY AS POSSIBLE.

1. **What is the ecliptic and why is it different from the celestial equator?**
2. **We have seen that in our winter months, the northern hemisphere receives less sunlight than in the summer months when it is warm. Why is this so?**

III. The Moon: It’s Just Going Through a Phase

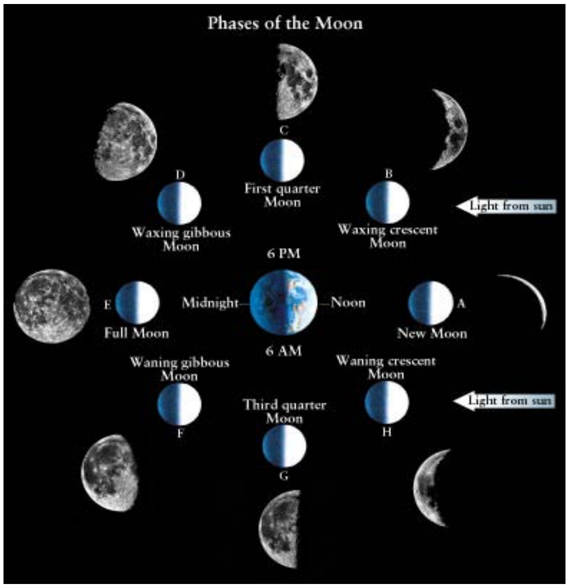

Figure 7. Lunar phases (but incorrect at “new”).

The Moon is a nearly spherical chunk of rock that orbits the Earth approximately once every four weeks, nearly in the ecliptic plane. It generates no light of its own and so would be invisible if it did not reflect sunlight. Fortunately, one half of the Moon’s surface is always lit up by light from the Sun. However, we can’t always see the entire illuminated part (sometimes we see none of it at all).

There are four primary phases of the Moon: full, new, first quarter, and third (or last) quarter (see Figure 7; but note that the actual image of the new moon is incorrect). When the Earth is between the Sun and Moon, we see the entire lit face: a full moon. We “see” a new moon when the Moon passes between the Earth and the Sun; only the unlit side faces the Earth. Quarter phases occur exactly halfway between the new and full phases.

As the Moon moves from new to first quarter, only a small sliver of the sunlit portion is visible from Earth. This phase is called a *waxing crescent* because the size of the visible part increases as the moon gets closer to first quarter.

Later in the month, the Moon orbits from third quarter back to new. This phase is called a *waning crescent* because the size of the crescent is decreasing. We see a *gibbous* moon when the Moon passes between the first and third quarters, on either side of the full moon. During this part of the Moon's orbit, more than half of the sunlit side of the Moon is visible from the Earth. From the first quarter to full, the size of the gibbous moon is increasing, so it is called a *waxing gibbous* moon. From full to third quarter, we see a *waning gibbous* moon.

ANSWER THE FOLLOWING QUESTIONS AS COMPLETELY AS POSSIBLE.

3. **Briefly explain why the Moon goes through phases.**
4. **Do you think that planets can go through phases? Why or why not? [Hint: Think specifically of planets in our solar system and make a sketch.]**

IV. MOTION OF THE SUN

Find a safe place outside to observe where you can see the western (or eastern) horizon. Make sure you can access this *exact* location several times per week at about the same time each day. You will probably find it easiest to mark your spot with tape, chalk, or some other temporary mark. ***It is critical that you make your solar observations from exactly the same location each time!*** In your lab notebook, draw a representation of your horizon, making sure to label the cardinal directions and sketching in major landmarks such as distant buildings, trees, microwave towers, etc. You will use this map to chart the location of the sunset (or sunrise) over an extended period of time.

Go outside to your particular observing spot several minutes before sunset (sunrise) and make sure you can orient yourself with your own drawing, i.e. get your bearings. Use your cross-staff to measure the angular separation between the location of the sunset (sunrise) and a stationary object to one side of that location, making sure to note which side (since it may cross over during the course of your observations). Record both the angular separation and the time you make the measurement. Keep your measurements in a table similar to that in Figure 8. In the time you have to complete this activity, you must make **at least 12 observations** of the sunset (sunrise). Do not wait until the last 12 days of the assignment to take your measurements – bad weather isn't an excuse. Additionally, measurements made either too far apart or too close together (i.e. daily) will make it more difficult to obtain reliable results.

On your horizon drawing, plot the positions of your suns. ***Put all the data on one drawing!*** The point is to observe changes. Thus, having separate drawings makes no sense!

Observation	Date	Time (CST)	Measure (cm)	Sight Width	Angular Separation (deg)
1	2001 Feb 15	18:57	6.75	medium	41.0 S
2					
3					
4					
5					
⋮					
12					

Figure 8. Sample data table for solar observations.

ANSWER THE FOLLOWING QUESTIONS AS COMPLETELY AS POSSIBLE.

5. **Did the Sun move along the horizon over the course of your observations? If so, which direction did it move (N-to-S or S-to-N)?**
6. **Roughly how many degrees per week did the Sun appear to move? How did you determine this number? (You must use <u>all</u> the data!)**

7. **Based on what you know about celestial motions and the time of year, do your observations support this knowledge? Explain why or why not.**

V. MOTION OF THE MOON

Before you begin any observations, you should make sure you understand how to read and use the SC001 chart. There is supplementary material on the course website. If you need help, ask a classmate or your instructor.

The Moon is one of the most prominent objects in the sky and nearly everyone is aware of its phases. Yet few people study it critically enough to note how it moves among the stars, or to recognize how both position and time relate to its phases. Over the course of the next few weeks, observe the Moon with respect to the stars as often as possible, plotting its position on the SC001 chart and recording the date, time, and phase of each observation including a sketch of that phase. Note that as the Moon moves through its cycle, you may have to adjust the time at which you observe it (you should already know this from your lecture class). This is the reason you should not let too many days pass without at least finding the Moon – you might otherwise lose it. Record your data in a table similar to that in Figure 9.

Observation	Date	Time (CST)	Ang Sep from what	Phase
1	2001 Feb 15	18:43	~13 deg SW of Rigel	waxing crescent
2				
3				
4				
5				
⋮				
12				

Figure 9. Sample data table for lunar observations.

Draw a circle with a number in it at the correct position on the SC001 chart, rather than trying to draw in the phase. Remember to make accompanying drawings in your lab notebook that illustrate the phase you observed. Label them accordingly. You may either visually estimate the position of the Moon or try to measure the angle and direction between it and a few bright stars. The star chart is labeled in both RA and DEC so you can determine angular positions relatively accurately. If you choose to “eyeball” your lunar positions rather than measure them, you will not need the next to last column in the table above!

<u>Continue to observe the Moon until it returns to and passes the phase that it had when you first began your observations. If it has not yet passed the location in the sky with respect to the stars that it had when you initially observed it, continue following it until it does.</u> You will get better results if you follow the Moon through more than one complete cycle. You must make **a minimum of 12 measurements**.

ANSWER THE FOLLOWING QUESTIONS AS COMPLETELY AS POSSIBLE.

8. **In what direction does the Moon travel in its orbit? What does its path tell you about the plane of the Moon’s orbit?**
9. **Roughly how many degrees per day did the Moon move? How did you determine this? (You must use <u>all</u> the data!) Use this rate to calculate how long it would take the Moon to make a full 360° circuit with respect to the stars. This is called the *sidereal* period of the Moon (Fig. 10).**

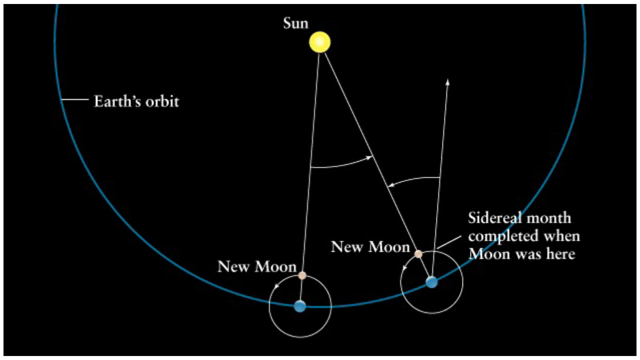

Figure 10. Sidereal period of the Moon.

10. The *synodic* period of the Moon is the time it takes to go from one particular phase back around to that same phase (Fig. 10). Based upon your data, how long is the synodic period of the Moon?
11. When the Moon returns to the same point in the sky *with respect to the stars*, does it have the same phase as it did when it was last at that point?
12. When the Moon returns to the *same phase* that it had when you started your observations, is it located at the same point with respect to the stars?
13. Are the sidereal and synodic periods you calculated the same? Should they be? Why or why not? (Hint: look at Figure 10.)
14. Based on your data, when would you expect the next new moon, first quarter, full moon, and third quarter? *Be specific: include the date and approximate times visible (rise-set range).*

VI. SUMMARY

Do not forget to fasten loose pages into your notebook. Make sure that your data is just that – yours. Simulations are not acceptable. Make sure you have the minimum number of required measurements for both the Sun and Moon and that your Moon observations meet the phase and position requirements stated in that section.

ANSWER THE FOLLOWING QUESTIONS AS COMPLETELY AS POSSIBLE.
15. What fundamental quantity(ies) could you measure from these simple observations and how might such observations be important, especially to a hunter-gatherer or farming-dependent cultures?
16. How do your results on the motions of the Sun and Moon compare with what you would have expected to see prior to taking this class?

VII. REFERENCES

anonymous. *Astronomy 102 Laboratory*, Vanderbilt University, 2000.
Gay, P.L. & Tufts, J.R. *AST 103L Observational Astronomy Course Handbook*, University of Texas, 2000.
Hemenway, M.K. & Robbins, R.R. *Modern Astronomy: An Activities Approach*, Revised Edition, University of Texas Press, 1991.
Hoff, D.B., Kelsey, L.J., & Neff. J.S. *Activities in Astronomy*, 3rd Edition, Kendall/Hunt Publishing Company, 1992.
Kaufmann, III, W.K. & Freedman, R.A. *Universe*, 5th Edition, W.H. Freeman & Company, 1999.
Walker, C. *Nighttime Activities for Natural Sciences 102*, University of Arizona, 1999.