The Moon

I. OBJECTIVES

The Moon is the second brightest object in our sky and the nearest to our planet. The Moon's motion relative to the background stars is easy to observe. By charting the motion and phases of the Moon, ancient astronomers were able to predict eclipses without the benefit of Kepler's laws of planetary motion. Throughout the course of the semester, you will observe the Moon's motion. Using your observations, you will:

- learn lunar geography;
- determine the mass of Earth;
- determine the angular diameter of the Moon;
- determine the diameter of the Moon;
- determine the distance to the Moon.

II. PREPARATION

A. CONCEPTS. Before attempting the activities in this lab, you should be familiar with the heliocentric (Sun-centered) model of the solar system. You should also be familiar with the celestial sphere and the celestial coordinate systems.

Read **Section III** to familiarize yourself with the Moon, its motions, and its effects on Earth.

B. APPARATUS. This lab is devoted to naked eye and telescopic observations of the Moon and what you can learn from them. You will have access to lab telescopes on dates specified by your instructor. One observation of the full Moon will require paper and a ruler for determining the Moon's angular diameter.

You will have access to the Macintosh computers in the lab. You may use **Voyager II** to obtain moon declinations, and **DeltaGraph** will be available for making the plots required in the **Data Analysis** section.

Appendix A at the end of this lab identifies major geographical features on the Moon; however, you may want to consult other texts for different perspectives or better maps. For those who are ambitious, the Space Imagery Center on the fourth floor of the Space Sciences building has lunar globes!

C. OBSERVATIONS. You will make at least one telescope observation of the Moon. It is strongly suggested that you make this observation during the quarter or gibbous Moon phase to maximize the detail that can be seen.

At least twice a week you will need to make naked eye observations of the Moon. You must note the date, time, altitude, azimuth, phase, and weather conditions for each observation. The naked eye observations should not be made on consecutive nights. Rather, they should be spaced 2-3 days apart to eliminate major gaps in your phase record. ***During one full Moon observation, you will need to determine the Moon's angular diameter.***

D. MATHEMATICS. In the **Data Analysis** section, you will be required to make several computations. The **Math Help!** appendix should be consulted as a reference. You must be familiar with simple geometry and trigonometry. Be able to manipulate algebraic equations.

E. DATA ANALYSIS. Using Kepler's third law of planetary motion, the mass of a primary can be determined by observing the behavior of its satellites. In this lab, you will use your observations of the Moon to determine the mass of Earth.

III. BACKGROUND

Superficially, the Moon and Earth have little in common. Earth is a vibrant, colorful world while the Moon is barren and desolate with no atmosphere, no water, and no life. Earth's surface is covered with oceans and a soft soil of rock and organic matter. The Moon's surface is covered by a gray layer of broken rock and dust called ***regolith***. Earth's atmosphere keeps its surface temperature in a very narrow range that permits the presence of liquid water. On the Moon, however, daytime temperatures can rise to over 200 °F while nighttime temperatures fall to -300 °F. Earth is geologically active; its surface is constantly being modified by plate tectonics and erosion. The Moon is geologically dead; its surface has remained virtually unchanged for billions of years. Why did two such apparently different bodies form a double-planet system?

A. FORMATION OF THE MOON. The formation of the Moon is one of the great puzzles of planetary science. Did the Moon and Earth form together; is the Moon a captured body that formed elsewhere; or did the Moon come from Earth itself?

Prior to the Apollo space program, there were three competing hypotheses to explain the Moon's origin. One hypothesis stated that the Moon was a small planet originally orbiting the Sun that was captured by Earth. This implied that the Moon's composition should be very different from Earth's since they would have formed in different parts of the solar nebula. A second hypothesis suggested that the Moon and Earth formed as "twins" from the same cloud of gas and dust. In this scenario, lunar and terrestrial compositions should be similar since both objects would have formed in the same region of the nebula. The last hypothesis stated that the Moon was ripped from a rapidly spinning Earth like cookie batter from an electric beater. In this case, the Moon and Earth should have nearly identical compositions.

From 1969-1972, the Apollo astronauts landed on the Moon and brought back lunar rocks. These rocks were the first direct samples of the Moon that scientists could study. Analyses of the lunar rocks showed that some elements of the lunar composition are nearly identical to Earth's while others are substantially different. For example, the Moon is rich in high melting point materials like gold but very poor in low melting point (***volatile***) materials like water. Curiously, though, it is lacks one important high melting point (***refractory***) element - iron! None of the three hypotheses described above could explain all of these observations and it was not until the late 1970's that a new hypothesis capable of explaining all of the observations was developed.

A giant impact hypothesis was first proposed in the late 1970's, but it was not seriously considered by planetary scientists until a 1984 conference where new computer simulations verified its plausibility. According to the giant impact hypothesis, a Mars-size object colliding with the primitive Earth splashed rocky material from Earth's crust and mantle into orbit. Volatile materials like water were vaporized and dispersed in the impact leaving little to be incorporated into the Moon. The remaining rocky material condensed and accreted to form the Moon. Since the impact splashed out only crust and mantle material from Earth, the iron core was virtually untouched so no iron was available to be incorporated into the Moon. The giant imapct hypothesis also explains why the Moon does not orbit in Earth's equatorial plane and may account for the tilt of Earth's axis.

B. LUNAR GEOGRAPHY. The photos in **Appendix A** at the end of this lab identify the major geographic features of the Moon. You should become familiar with these features!

There are two types of terrain on the lunar surface. The smooth, relatively uncratered, dark regions are called ***maria*** (singular ***mare***), which is Latin for "seas." When Galileo first observed them through his telescope, he thought they were large bodies of water. In fact, maria are lava plains that fill large impact basins. The brighter ***highland*** regions of the Moon are older and more heavily cratered terrains.

C. LUNAR PHASES. Like Earth, the Moon does not *produce* light. It "shines" by reflecting Sunlight.

The Moon orbits Earth as Earth orbits the Sun. From the perspective of the Sun, the Moon can be (1) in front of Earth, (2) behind Earth, or (3) beside Earth. Let us consider the same geometries from the perspective of Earth (see Figure 1).

The first geometry creates the ***new moon*** phase. When the Moon is positioned between Earth and the Sun, only the far side of the Moon is illuminated. The side of the Moon facing Earth is completely dark. Since the new Moon is between the Sun and Earth, it rises at sunrise and sets at sunset.

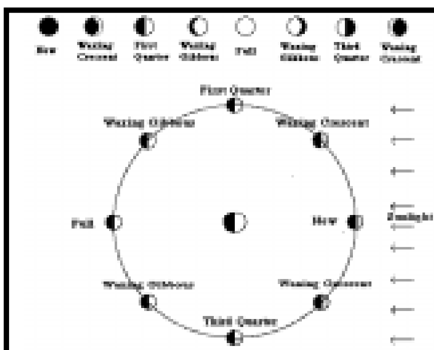


FIGURE 1: Phases Of The Moon

The second geometry produces the ***full moon*** phase. In this case, Earth is between the Moon and the Sun. As seen by an observer on Earth, the Sun illuminates the Moon's entire nearside. Since the Moon and the Sun are on opposite sides of Earth, the Moon rises at sunset and sets at sunrise.

The third geometry can produce anything between the new and full Moon. If the angle formed by the Moon and the Sun is between 0° and 90°, only a small fraction of the nearside is illuminated and it appears as a ***crescent***. If the angle formed by the Moon and the Sun is between 90° and 180°, most of the nearside is illuminated and it is said to be ***gibbous***. At exactly 90°, the nearside is exactly half-illuminated producing a ***quarter Moon***.

As the phase of the Moon grows from new to full, the Moon is said to be ***waxing***. The quarter Moon between new and full is called ***first quarter***. As the phase of the Moon shrinks from full to new, the Moon is said to be ***waning***. The quarter Moon between full and new is called ***third*** (or ***last***) ***quarter***.

The Moon rises approximately 50 minutes later each day. The waxing crescent rises in the morning, first quarter at noon, and the waxing gibbous in the afternoon. In contrast, the waning gibbous rises in the evening, third quarter at midnight and the waning crescent after midnight.

The Moon completes one orbit about Earth every 27.3 days and one cycle of phases every 29.5 days. The difference between the Moon’s orbital period and the period of the phases arises because Earth moves about 1/12 of the way along its orbit around the Sun in the time it takes for the Moon to complete one orbit about Earth. In order to complete the cycle of phases, the original Earth-Moon-Sun alignment must occur again. Since Earth moves in its orbit, the Moon must not only complete its 27.3 day orbit about Earth, it then must orbit another 2.2 days to “catch up” with Earth’s motion about the Sun. Hence it takes 29.5 days to recover the original Earth-Moon-Sun alignment. As an example, suppose that a new moon occurs in the constellation Virgo at 9 AM on September 1. At this point, the Moon is directly between Earth and the Sun and the Sun sits directly in front of the constellation Virgo. In 27.3 days, the Moon would have traversed the sky and would again arrive in Virgo on September 28 at 4 PM. However, because Earth has moved in its orbit around the Sun, the Sun is no longer directly in front of Virgo, but is now directly in front of Libra (the next constellation in the zodiac). The Moon must orbit another 2.2 days before it arrives in Libra where it can again come between Earth and the Sun. Hence the next new moon occurs on September 30 at 9 PM.

D. ECLIPSES. Both the Sun and the Moon have approximate angular diameters of 0.5° on Earth’s sky. This peculiarity in size treats Earth to spectacular events called eclipses. An ***eclipse*** occurs when one astronomical body casts its shadow on another astronomical body. ***Solar eclipses*** occur when the Moon passes directly in front of the Sun (see Figure 2) as seen from Earth. ***Lunar eclipses*** occur when the Moon passes into Earth’s shadow (see Figure 3).

Eclipses are rare because the Moon’s orbit is inclined with respect to the ecliptic plane. Without the inclination, we would experience a solar and a lunar eclipse every month. Instead, the shadows of the Moon and Earth usually fall on empty space (see Figure 4). However, when the new Moon is near the ecliptic, it casts a narrow shadow on Earth’s surface. Observers within the Moon’s shadow, or ***umbra***, will see a solar eclipse. Observers in regions surrounding the Moon’s shadow are in the Moon’s ***penumbra*** and they will see a ***partial solar eclipse***.

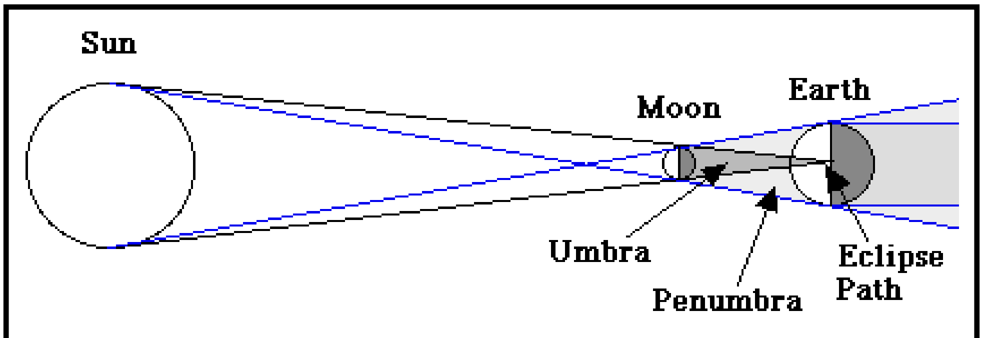


FIGURE 2: Solar Eclipse

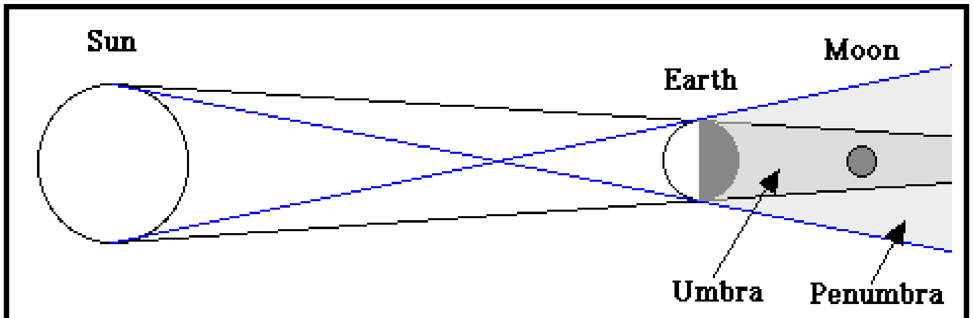


FIGURE 3: Lunar Eclipse

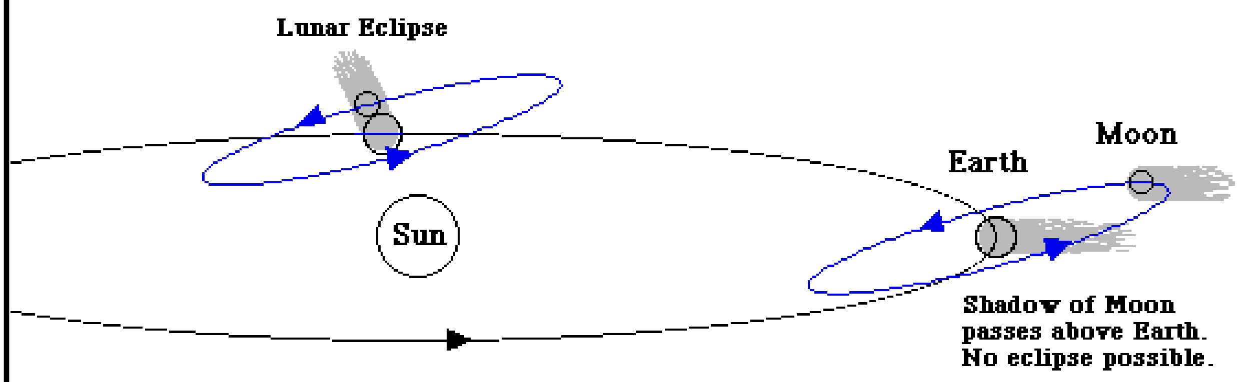


FIGURE 4: Shadows of the moon and Earth

The Moon's orbit is elliptical so its distance from Earth varies. If a solar eclipse occurs when the Moon is near ***perigee*** (the point in it's orbit where it is closest to Earth), its disk is slightly larger than the Sun's disk. The Sun's light is completely blocked revealing the Sun's bright corona (see Figure 5). This is called a ***total solar eclipse***.

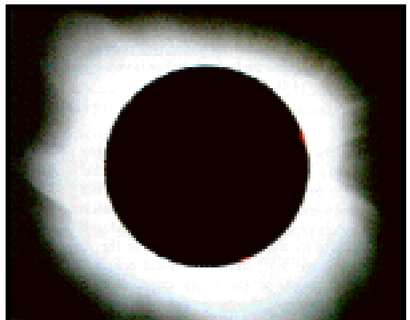


FIGURE 5: Total Solar Eclipse

If the Moon is near ***apogee*** (the point in it's orbit where it is farthest from Earth), its disk is slightly smaller than the Sun's. When the Moon passes in front of the Sun, a thin circle of sunlight remains visible. This is called an ***annular solar eclipse***.

The alignment between Earth, the Moon, and the Sun is preserved for a short period of time; so every solar eclipse is accompanied by a lunar eclipse either two weeks earlier or two weeks later. Unlike a solar eclipse which is visible from only a very narrow strip on Earth's surface, a lunar eclipse is visible everywhere in the nighttime hemisphere of Earth. To an observer on Earth, lunar eclipses are typically visible every two to three years. Solar eclipses are much less commonly observed than lunar eclipses because the observer must be in the narrow band traced out by the Moon's shadow.

The duration of an eclipse from first contact to last contact with the shadow is generally a few hours. Totality usually lasts only a few minutes. ***Totality*** occurs when the object is completely immersed in the shadow.

IV. OBSERVATIONS.

STEP 1: Study the major features of the Moon in **Appendix A**. Your sketch of the Moon viewed through a telescope should include these features properly labelled. Concentrate on large craters and the maria.

STEP 2: Observe the Moon at least twice a week for two months and sketch your observations. Your sketches should include the phase of the Moon and its position relative to the background stars or a fixed point on Earth. Note the dates and times of your observations as well as the altitude, azimuth, declination (you can get this from **Voyager II**), phase, and weather conditions. ***A journal section for recording your sketches is included at the end of the lab.***

STEP 3: Cut a hole 5 millimeters in diameter (2.5 mm in radius) in the center of a piece of paper. Hold the paper at arm length. Look through the hole and adjust the paper until the entire disk of the full Moon just fits into the hole. Have someone measure the distance from your eye to the paper. Record the measurement. Compute the angular diameter, θ, of the Moon from Equation 1. Consult the **Math Help!** appendix if necessary. *(Note: Make sure the hole diameter and the eye-to-paper distance are in the same units!)*

EQUATION 1:

$$\theta = \tan^{-1}\left(\frac{\text{Diameter of hole}}{\text{Distance from eye to paper}}\right)$$

V. DATA ANALYSIS

A. THE MOON'S ORBIT. Use **Voyager II** to obtain accurate declinations of the Moon for the days that you observed it. You should compare these to your estimated declinations. Remember to convert from degrees and minutes into a decimal format.

Plot the declinations of the Moon versus the dates of your observations. (**DeltaGraph** has a template you can use for graphing this data.) Fit a smooth curve to the observations.

B. THE MASS OF EARTH. Using Kepler's third law, it is possible to determine the mass of a planet by observing the motions of its satellites. Using your observations, you can determine the distance to the Moon and the mass of Earth.

Kepler's third law can be expressed mathematically as Equation 2. In this equation, p is the orbital period of the Moon, a is the Earth to Moon distance, M_E is the mass of Earth, and G is the gravitational constant.

EQUATION 2:

$$\frac{p^2}{a^3}M_E = \frac{4\pi^2}{G}$$

1. Estimate the orbital period of the Moon from your observation of its phases. Your period should be expressed in *seconds* for these calculations.

2. Look up the radius of the Moon in the **Units and Conversions** appendix. Set up similar triangles as shown in Figure 7. Use Equation 3 to determine the distance between the Moon and Earth.

EQUATION 3:

$$\frac{\text{Diameter}_{\text{hole}}}{x} = \frac{\text{Diameter}_{\text{moon}}}{a}$$

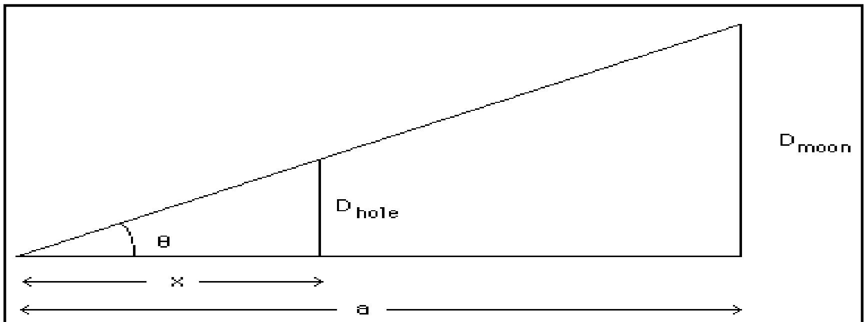


FIGURE 6: Similar Triangles

3. Plug the period of the Moon's orbit and the Earth to Moon distance into Equation 2 to determine the mass of Earth. Compare your result to the mass of Earth given in the **Units and Conversions** appendix. Determine the percentage error between your mass of Earth and the "true" mass of Earth using the equation given in the **Experimental Error** appendix.

4. What part of the computation provides the greatest source of error? How might you reduce the error? Would you consider a 10% error to be good or bad for this problem? Why?

VI. DISCUSSION.

A. MOON OBSERVATIONS.

- Address any problems (*e.g.* weather) that may have interfered with or influenced your observations.
- Explain why you observed the Moon through the telescope at quarter or gibbous phase rather than at full moon. Where do you see the most detail? Why?
- Describe the similarities and differences between your naked eye observations and your telescope observation.
- Based upon your telescope observation, why do you think the maria look darker than the highlands?
- If you observe some special events (*e.g.* an eclipse), you should describe them in detail.

B. THE MOON'S ORBIT.

- Interpret your plot of Moon observations.
- Sketch the Moon's orbit about Earth based upon information contained in your graph. You

should be able to determine the tilt of the Moon's orbit with respect to Earth's equator and the direction the Moon travels.

- Also try to either visualize and/or sketch the difference between the Moon's orbital period and the period of its phases.

C. THE MASS OF EARTH.

- Understand and be able to describe your calculations in detail. Address potential sources of error (*e.g.* using phase period rather than orbital period) and how you might eliminate them. Consider carefully the information you were given and the assumptions you made in addition to your observations. (**Hint:** In Equation 2, the simplifying assumption that $M_E + M_M = M_M$ was made where M_M is the mass of the Moon. Under what condition(s) is this true?) How might you improve the calculation?

D. SUMMARY.

- Use your observations and your analyses to critically examine what you now know about the Moon. Look for patterns or relationships that may not have been obvious to you before (*e.g.* the Moon's orbital and phase periods are very nearly a month).

- Consider specifically how and why the Moon influences you today and speculate about the effects it had on peoples of ancient times. You might even consider trying to devise scientific explanations for some common superstitons about the Moon.

E. PLANETARY SCIENCE.

- **(Gravitational Acceleration)** Compute the gravitational acceleration of the Moon as you did for Earth in the **Gravitational Acceleration** lab. You will find appropriate values for the mass and radius of the Moon in the **Units and Conversions** appendix. Compare this to Earth's gravitational acceleration. What are the implications?

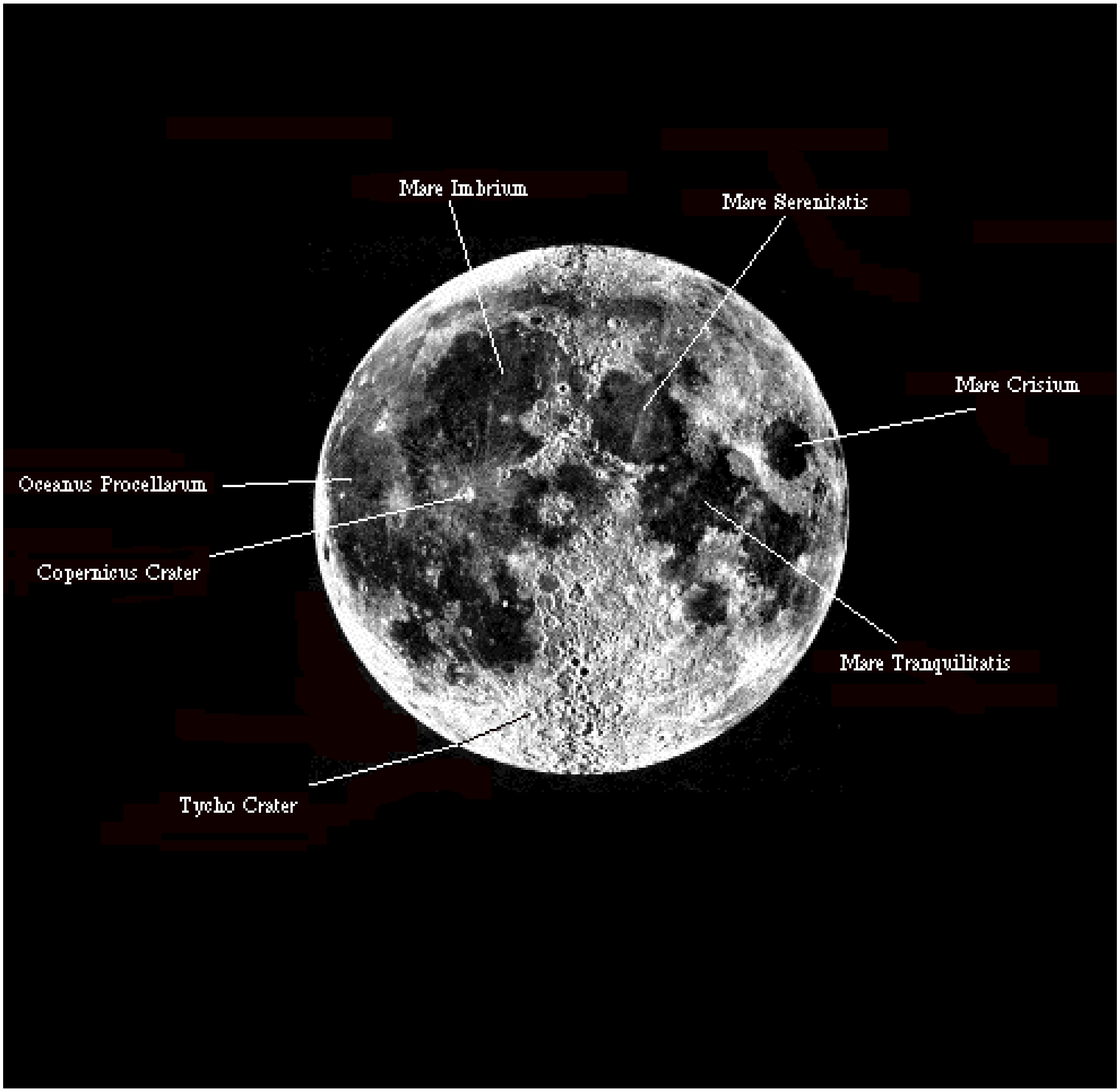
- **(Impact Cratering)** From your telescope observation, you know that the maria and the highlands look very different. Based upon the impact cratering record, which type of surface do you think is younger? Why?

- **(Volcanism)** What evidence suggests the Moon was volcanically active at some point in its history?

- **(Meteorites)** Would you expect to find lunar meteorites on Earth? Why or why not? Use the previous three bullets to justify your answer.

APPENDIX A

Lunar Geography



Moon Observation Page

Object ____________________ Date ____________________ Time ____________________

Altitude ____________________ Azimuth ____________________ Lens ____________________

Observation Location ____

Weather/Sky Conditions ____

Description of Object:

Sketch of object and surrounding sky.

Journal of Moon Observations

Moon Phase: Date: Time: Altitude: Azimuth: Weather: Declination: Sketch:	Moon Phase: Date: Time: Altitude: Azimuth: Weather: Declination: Sketch:
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Journal of Moon Observations

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