Directions: Create a document to answer Questions 1-13. That will be your report.

Galileo's Lunar Observations

Measuring the Mountains on the Moon

Overview

From the evening of Wednesday, April 29th to the evening of Thursday, April 30th, the Moon goes from slightly less than First Quarter to slightly more (a little more than half-full). This is a very good phase to repeat some of Galileo's observations and calculations from *The Starry Messenger*.

1. Context

Up until Galileo's time, it was believed that there were two realms: earthly—everything below the Moon—and heavenly—the Moon and everything beyond, which includes the other planets, the Sun and the stars. The earthly realm was imperfect and changing. The heavenly realm was divine and unchanging. In the heavenly realm everything was made of a frictionless substance called aether. In the earthly realm, the four substances (earth, water, fire, and air) made up everything in varying proportions. These are features of Aristotelian natural philosophy which had been melded into Christian understanding long before Galileo's time.

Question 1. If a meteor came crashing out of the heavens and burned up in our atmosphere, would that be made of heavenly aether or of the four earthly substances? Does the difficulty in answering this pose a problem for an Aristotelian explanation of meteors?

When we say that the heavenly realm is perfect and eternal, among the things we mean are that the planets move in perfect circles around the Earth, as do the Sun and the Moon. We also mean that the heavenly bodies are perfect spheres. You can imagine that meteors and comets, which are evidence of imperfection or change in the heavens could be seen as threatening to heavenly order.

If you saw a comet perhaps you could maintain that the heavens are unchanging by saying that the comet is actually a plume of gas from a nearby volcano.

Question 2. Suppose you got reports that people all over Europe (and maybe Asia and Africa too) saw the same comet. Does that pose a problem for the volcanic plume explanation?

The Moon is in the heavens. Therefore it must be a perfect sphere and made of aether. But even without a telescope, you can see variations in brightness of its surface.

Question 3. To cling to the perfect-sphere-of-aether theory of the Moon, what could be an explanation for the variations in brightness of the Moon's surface?

2. Seeing and Believing

If you are driving across the Central Valley, and you see the Sierra Nevada still 50 miles in the distance, but you have never been there, is seeing the peaks in the distance enough to believe they are there? Could you explain what you are seeing without assuming that there are far-off peaks rising 14,000 feet high. Maybe the mighty Sierra Nevada are actually an atmospheric effect, such as atmospheric refraction exaggerating the height of some nearby foothills that are only 1,000' high?!

Question 4. What would be a good counter-argument to the atmospheric refraction explanation? Is the counter-argument convincing?

The point of the previous question is to ask yourself, what does it mean to see and believe in something in the distance that you have never visited—maybe something that nobody has ever visited? This is precisely the situation Galileo was in with the Moon. This is possibly a springboard into even more philosophical questions.

3. Geometry

We are going to need the Pythagorean theorem to follow Galileo's reasoning, so let's get that out of the way.

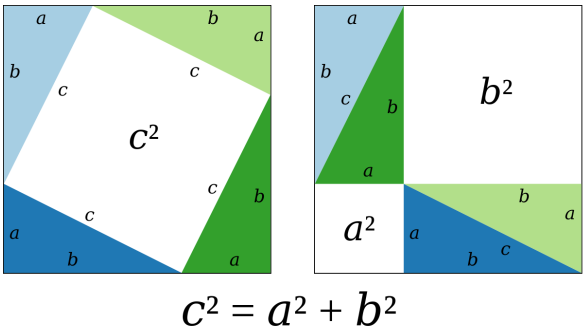

Figure 1. Proof of the Pythagorean Theorem

The figure above is all by itself quite a convincing proof of the theorem. The bottom line is,

$$c^2 = a^2 + b^2$$

where a is one of the short sides of a right triangle, b is the other short side, and c is the long side (the hypotenuse). The formula can be solved for the hypotenuse:

$$c = \sqrt{a^2 + b^2}$$

Question 5. If $a = 9$ and $b = 40$, what is c? Make a realistically-proportioned drawing of this triangle in the space below and label the three sides.

4. Naked Eye Observation of the Moon

As mentioned in the overview, we are near the First Quarter Moon. The "New Moon, First Quarter, Full Moon, Third Quarter, and New Moon (again)" naming comes from the idea of dividing the lunar month (29.5 days) into quarters. A quarter of 29.5 is more than 7 but less than 8 days.

Question 6a. If the Moon was First Quarter sometime between the 29th and 30th of April, on what date would you estimate it will be Full?

If it is after about 8:30pm where you are, it should be dark enough for you to go outside and be able to easily find the Moon. If it is earlier, and the Sun hasn't set yet, you might be surprised to find that you can still go out and find the Moon. It is in a prominent position, and the Moon is so bright, you can actually find it in daylight.

As long as there aren't clouds, take some time to go outside and take a look at the Moon with the naked eye (no telescope), and answer questions 6b and 7.

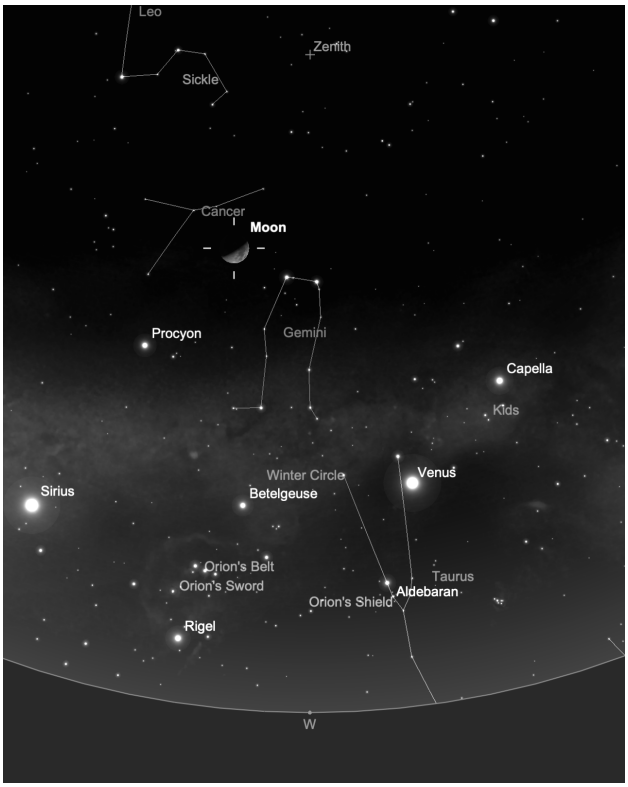

Figure 2. Sky to the West, April 29th, 8:50pm

Above is the view facing west on April 29th (and on the next page is April 30th). If it is night, find the sickle of Leo the Lion, almost directly overhead. Find Castor and Pollux (the Twins). In the West, find Venus. Venus is also so bright you might be able to find it before sunset.

Question 6b. Knowing which way West is, looking at the Moon, would you say the West side of the Moon is lit up or the East side? Does this make sense given where the Sun is?

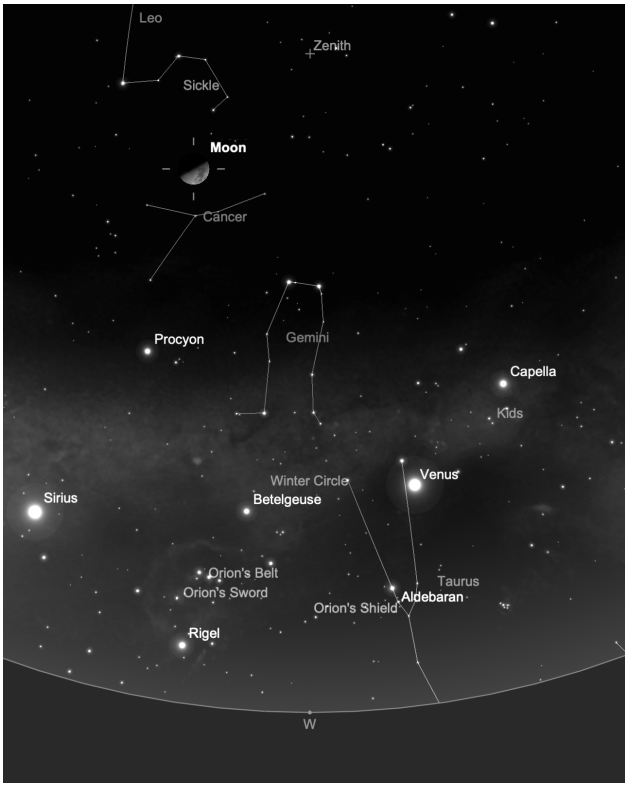

FIGURE 3. Sky to the West, April 30th, 8:50pm

QUESTION 7. There are some darkish spots on the Moon. Make a drawing in the space below that shows where the largest spots are.

Come back inside to work on the remainder of the lab.

5. Observation of the Moon

Due to this semester's circumstances, you don't have access to the College's telescopes. What revolutionized Galileo's understanding was the modest (by our standards) telescope he constructed upon hearing of its invention in a Dutch city in 1608. We are going to use a photo and one of his drawings to understand what he did. The photo will actually give you a better view than Galileo had.

FIGURE 4. Moon Day 7, Nov. 26, 2017. Illumination 53.3%. Ginger Wentrcek. Used with Permission.

For this and other photos by Ginger Wentrcek of the Brazos Valley Astronomy Club, go to:

https://brazosvalleyastronomyclub.org/moon-phases.html.

QUESTION 8. Compare the darkish spots you drew in response to question 7 with the darkish spots in the photo. Does your naked eye observation correspond to Ginger Wentrcek's photo? If not, what are some unexpected differences?

On the next page is one of Galileo's drawings of the Moon.

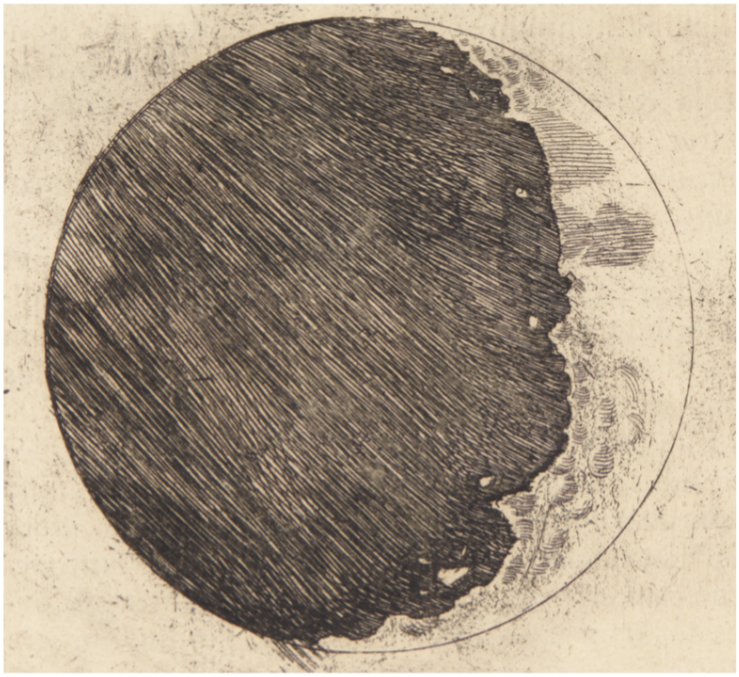

FIGURE 5. Galileo Drawing of Waxing Crescent Moon

In Galileo's drawing the Moon has not yet reached half-full. Galileo sees a large crater the lower right of his drawing and some darkish spots in the upper right.

QUESTION 9. Which large crater and which large darkish spots in the photo correspond to the features in Galileo's drawing?

The "terminator" is the line separating light from dark on the Moon. Notice that there are bright spots to the left of the terminator in Galileo's drawing. These are not a mistake by Galileo or the engraver.

QUESTION 10. Can you think of any reason why bright spots might be in the otherwise dark region?

Galileo argued that the bright spots that were on the dark side of the terminator were mountain peaks, surrounded by darkness. He notices that with persistent observing, over the course of hours, these gradually expand as the terminator approaches them and are eventually fully lit up. He argues that this is exactly what you'd expect if a mountain peak were lit up before sunlight comes to the plain around it, and then sunlight envelopes the whole mountain as sunrise continues.

Return to Ginger Wentrcek's photo. Study the dark area to the left of the terminator. Look for light spots like Galileo found. Note a few that are the farthest to the left of the terminator.

QUESTION 11. Treating the full diameter of the Moon as 100%, what percentage of a diameter is the furthest light spots to the left of the terminator? Take your time estimating this percentage. It is the most important number going into your final answer.

6. Computing the Height of the Mountains on the Moon

You have to completely change gears now! Imagine that instead of looking down on the mountains you have circled, you are looking at them from the side. This is really quite a twist in perspective. Study the diagram below until you understand how the perspective has changed.

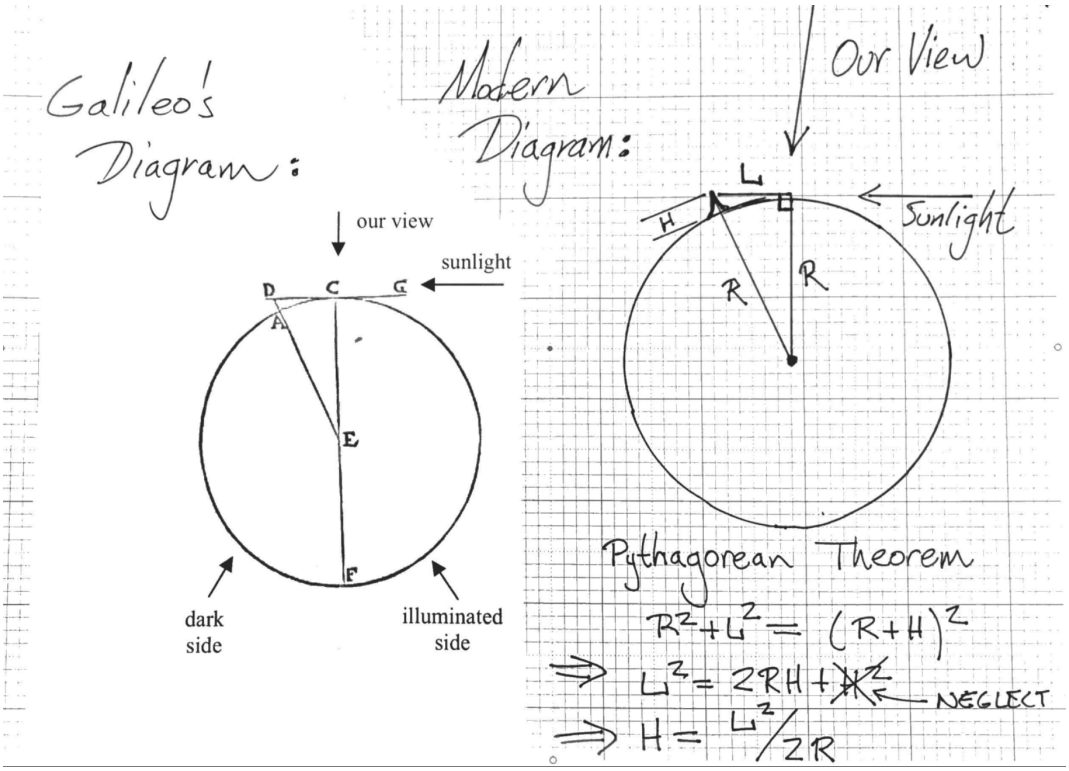

FIGURE 6. Geometry applied to the Height of Mountains on the Moon

In Galileo's diagram, the mountain peak is at D. The height of the mountain is the length of the line segment AD. In the modern diagram, this is H. In both diagrams, the sunlight comes in from the right and "our view" is looking down from the top. The terminator is marked C in Galileo's diagram. In Galileo's diagram, AE and CE are both radii of the Moon (the Moon's radius is 1080 miles). In the modern diagram these radii are both labeled R.

Do you see the right triangle ECD? In the modern diagram, the hypotenuse has length $H + R$, one side has length R, and the other side has length L. This is begging to have the Pythagorean theorem applied. Below the modern diagram, the algebra is done (using an approximation, which isn't essential—it can also be solved exactly). The bottom line is that by knowing L and R you can get H!

QUESTION 12. The Moon's radius is 1080 miles and its diameter is 2160 miles. Using the percentage you found in the previous question and multiplying the percentage by the Moon's diameter, how many miles is the furthest light spot from the terminator?

The distance you found in Question 12 is labeled L in Figure 5. R is the radius of the moon, 1080 miles. The formula you need to put these into is:

$$H = \frac{L^2}{2R}$$

QUESTION 13. Plug L and R in to the formula to get H. What is the height of the highest peak you found?

Galileo claimed that lunar mountains are several times taller than the highest mountains on Earth. The tallest mountain on Earth is Mount Everest and it is six miles high. That's about what Galileo got for the highest mountains on the Moon. The mountains near where Galileo lived in central Italy only get to be about 1 mile high. So maybe it isn't fair to say he overestimated. He may not have known about Mount Everest and that it is comparable.

7. Conclusion

In modern astrophysics, astronomical observations and laboratory physics experiments go hand in hand. We have stood Aristotelian philosophy on its head: we now believe that all of the laws of physics we observe on Earth apply equally to the rest of the cosmos.

If Galileo's argument that there are mountains on the Moon seems obvious now, and you find it strange that it wasn't quickly accepted by his contemporaries, it is only because we have had 400 years to get used to the idea of the non-specialness of our place in the universe. It also helps settle the question (if there were

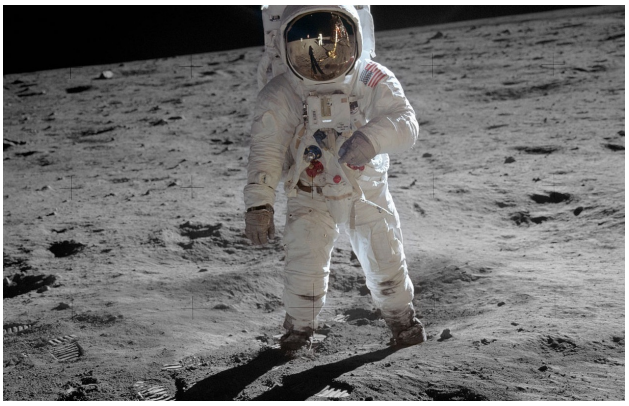

FIGURE 7. Buzz Aldrin Moonwalk, July 20, 1969, photo by Neil Armstrong

any remaining doubt) that 50 years ago, Neil Armstrong and Buzz Aldrin walked on the Moon and personally verified that it is neither perfectly spherical nor made of aether.