Lunar Lab #4-ASTR101

Exploring the Night Sky (University of Victoria)

Lunar Lab

Date of Lab: November 2nd, 2021

OBJECTIVE

The objective of this lab was to observe the craters and maria on the Moon from which I determined impact rates on the Moon and the Earth. By observing the surfaces of planets and moons we can understand how they relate in order to learn about the history of our Solar System.

INTRODUCTION

If you look up to the Moon, you will notice that it is always facing the same side. The Moon is in a state which astronomers call tidal lock. This is due to the Earth having 20x the gravitational effect on the Moon than the Moon has on Earth. Evidence shows that the Moon used to be closer to the Earth, which made the Moon rotate faster. Because the Moon lags slightly behind Earth's tides, it is creating friction and slowing down Earth's rotation. This slow process is what caused the Moon to slowly drift away in orbit which caused the Moon to slow its rotation, and eventually reach the tidal lock.

On the near side of the Moon, you can notice it has dark regions of basaltic rock that was formed from volcanic eruptions. These darker regions of the Moon are called maria. From samples brought back to Earth on the Apollo missions, we know that the maria formed approximately 3.5 billion years ago. They were named after seas in Latin because early astronomers originally thought that they were actually bodies of water. Today, we know that there is no such water on the Moon. The Moon was formed 4.5 billion years ago. As it lacks an atmosphere, water, and tectonic activity, the surface of the moon has remained unchanged. The Moon is covered by craters ranging from millimeters to hundreds of kilometers.

The Moon has taught us a lot about the history of our Solar System, specifically asteroid impacts. The maria only covers 16% of the Moon's surface. It contains a significantly smaller number of craters than the highlands. The highlands, also called Terrae, are the lighter regions of the Moon that are made of less dense rock, called anorthosites. The highlands solidified when the Moon cooled down and are much older than the maria They contain records of craters that date back to the early history of the Solar System. By knowing the age of the maria, we can calculate the rate of impact of collisions after its formation. The distribution of the craters on the Moon's surface is evidence that the impact rate of asteroids on the Moon has significantly decreased since the maria were formed. My assumptions involving density and depth of the ocean may have had uncertainties, but they did not have a big affect on my results. My crater counts may have been too high, due to repeated count of the same craters and unreliable measure of the craters when counting them.

PROCEDURE

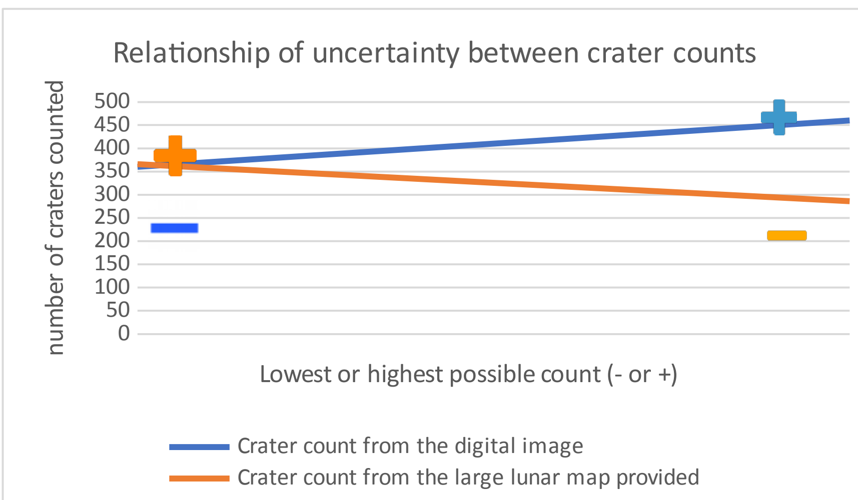
The first step was to download GIMP software. I opened the pdf format of the high-resolution lunar image in GIMP. Then, I scanned the Moon for three prominent craters. I labeled these and circled them on the image. I did the same for three maria and three spacecraft landing sites. I colour coded these groups and made a legend at the top of the image to distinguish between the groups. On a new window on GIMP, I opened another pdf format of the lunar image. I found overlapping craters and labeled them as I did in the first image. I also labeled a crater that was created before the mare and one that was created after. I found and labeled three craters that were lighter and had streaks. Then, I determined the scale of the digital image by dividing the actual size of the moon in kilometers by the diameter of the Moon in pixels. Using my scale, I calculated the actual diameter in km of one small crater (Kepler) and one large crater (Ptolemaeus). By using the rule of thumb stating that craters are 10 to 50 times the size of the asteroid that created them, I then calculator the possible size of these asteroids. Next, I found and labeled three craters of similar size as the ones in Table 1 in the lab manual. Using Impact Earth, I calculated the size of craters that would be created if 99942 Apophis and Swift-Tuttle were to collide on Earth. I observed the impact of these craters, including tsunamis, through the simulated collision calculator provided by Impact Earth. Using the website, I also found the crater size that would be created by 1-kilometer asteroids. At this period in the procedure, I noticed that the jpg digital image had better resolution (more pixels). So, I recalculated my kilometer to pixel scale. Using the diameter of crater size, I counted the number of craters of that size or bigger on the maria of the Moon from the digital image. I may have counted too many craters because I did not zoom in enough to accurately measure the size of the craters and therefore ended up counting craters that were formed by asteroids less than 1km in diameter. My estimation of uncertainty for my count was ±50. I then counted the number of craters on the maria from the lunar maps provided in class. Since the quality of my picture was poor and the reflection may have reduced my ability to count the craters, the estimation of uncertainty for my count was ±40. Based on the number of craters I counted, I calculated the total number of craters on the Moon created since the maria were formed. By dividing the age of the maria by my crater count, I found the number of asteroids more or equal to 1 kilometer in diameter that have hit the Moon since the maria was formed. I also found the number of asteroids that have hit the Moon each year since the maria were formed using the age of the maria and the crater count. Lastly, I compared the impact rate on the moon to Earth's surface area to find the chance of an asteroid colliding with Earth in a year.

OBSERVATIONS, TABLES, GRAPHS

Table 1: Crater count from part 4 and their estimations of uncertainty.

Crater count from the digital image	Crater count from the large lunar map provided
410 ± 50	326 ± 40

Graph 1: The relationship between the estimations of uncertainty of the different crater counts.



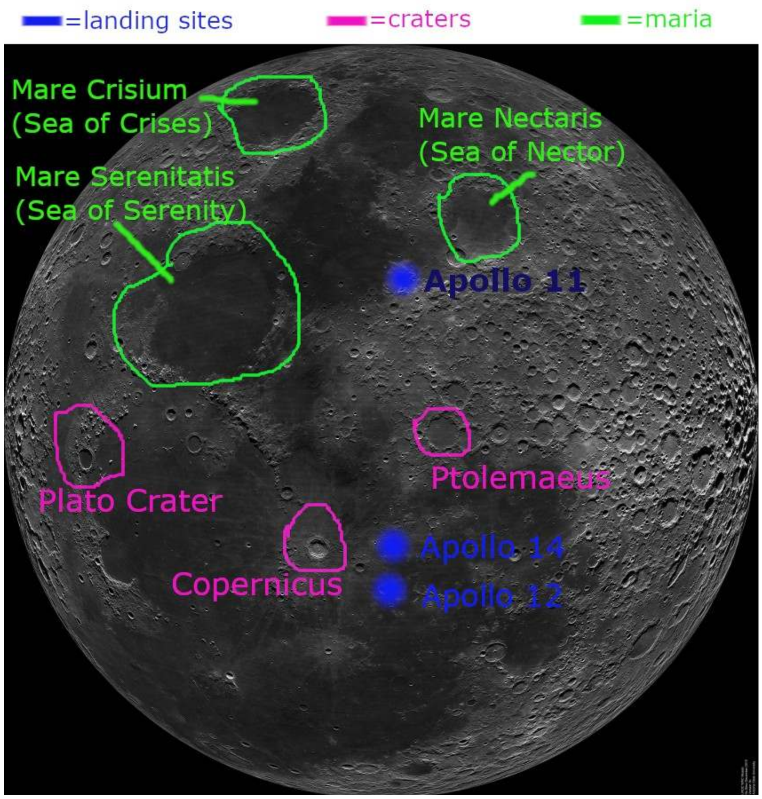
To show the relationship between the two counts, I inputted the highest count possible of the lunar map so that it corresponds with the lowest count from the digital image. As you can see, the lowest estimate of uncertainty of my count from the digital image is close to the highest possible count considering my estimation of uncertainty of the large lunar map.

ANSWERS

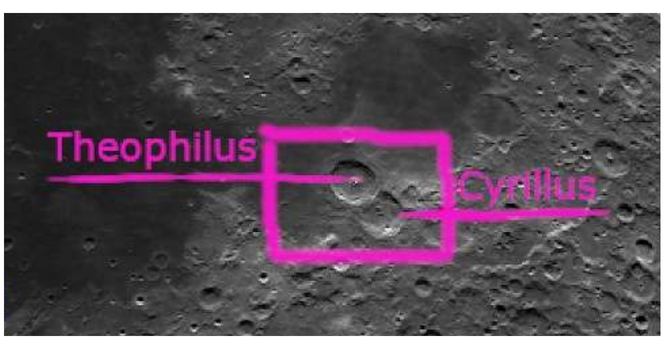
1) Labelled in Lunar image 1:

- The three prominent craters are circled and labeled in pink.
- Three maria are labeled and circled in green
- The three spacecraft landing sites are labeled and circled in blue

Lunar Image I:

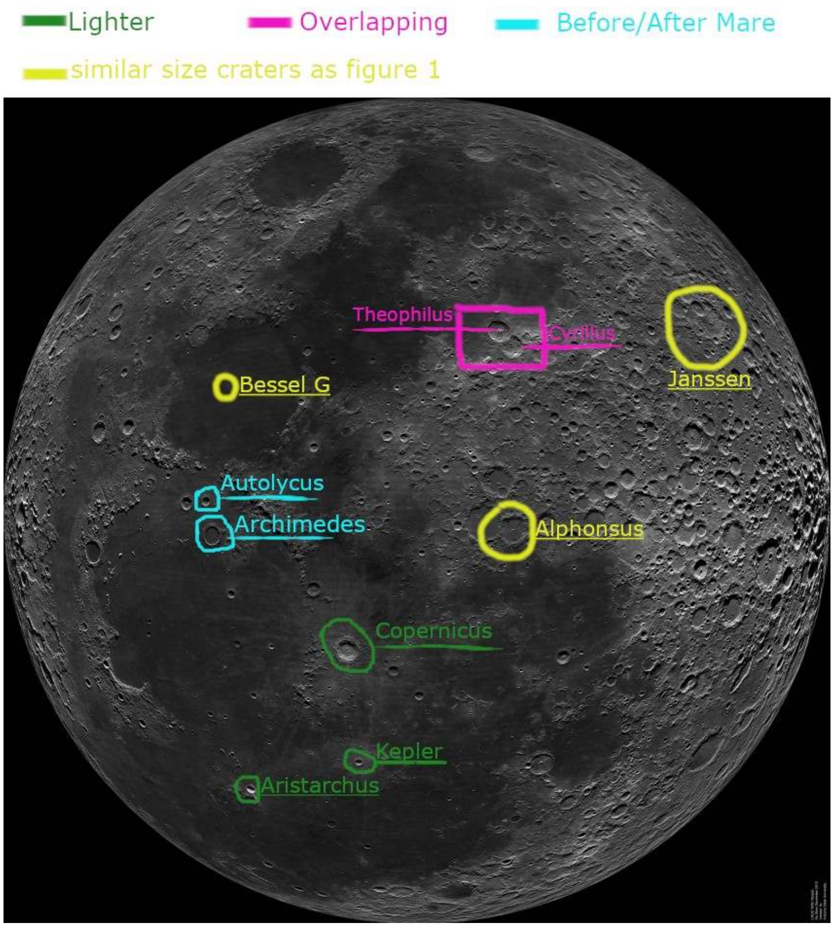


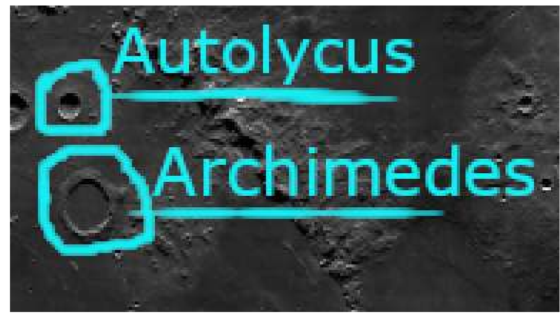
2) Cyrillus was formed before Theophylis. By looking at the craters in the Lunar image 2, we can see that Theophylis's edge overlaps over the edge of Cyrillus. The edge we can see at the overlapping site is the crater that came after, which is how we know that Theophylis was created after Cyrillus.



3) In the Lunar image 2, the two craters before and after the mare are labeled and circled in light blue. Archimedes was created before the mare. It was flooded by the mare and now appears to be cut in half. The inside of this crater has a smooth and even surface, which is more evidence that suggests it was created before the mare.

<u>Lunar image 2:</u>





4) The lighter-coloured craters are labeled and circlesd in green in the Lunar image 2. Copernicus, Kepler, Aristarchus are all lighter coloured craters. Although they all have streaks and/or patches of lighter coloured material, the streaks around Copernicus are more noticeable. They extend up to 510km away from the Copernicus crater. In comparison, the crater has a diameter of 81km.

5) I determined the scale of digital image in km per pixels by dividing the size in km by the size in pixels of the digital image:

3476km850pix = 4.0894127km/pix

6) I used my scale calculated in question 5 to find the diameter of the craters in km.

- Ptolemaeus (large crater) diameter=

$$34\text{pix} \times 4.089412\text{km/pix} = 139.04\text{km}$$

- Kepler (small crater) diameter=

$$8\text{pix} \times 4.089412\text{km/pix} = 32.72\text{km}$$

7) Ptolemaeus is the large crater I measured. Using the rule of thumb, this 139km crater could be the result of a meteorite of a diameter ranging from 2.78km to 13.9km. Kepler is the small crater I measured with a diameter of 32.7km. According to the rule of thumb given in our lab manual, the meteorite that created this crater should have had a diameter ranging from 654m to 3.27km.

8) The moon craters of similar size to the three craters in table 1 are circled and labelled in yellow in the Lunar image 2.
    - Bessel G (comparison to Barringer): 1.1km diameter
    - Alphonsus (comparison to Manicouagan): 120km diameter
    - Janssen (comparison to Chicxulub): 201km diameter

9) Using the Impact Earth calculator, I found that 99942 Apophis would create a final crater of 1.67km in diameter. Swift-Tuttle would create a 325km diameter crater.

10) According to all the websites and articles I read, the density of 99942 Apophis is between 2.6-2.8g/cm^3. So, I assumed a density of 2600kg/m^3. Swift-Tuttle is a porous rock made of ice, dust, rock, and dark organic material. So, I assumed the density as a porous rock which is 1500kg/m^3. I assumed an impact angle of 45°. Other articles studying impacts of meteorites have used 90°,45°, and 30°, but most sources assume 45° because it is the most probable impact angle. 66% of the exposed rock of the surface of the Earth is sedimentary rock. Therefore, it is more probable that the objects would land on sedimentary rock, if not in the ocean. This is why I assumed the object would land on sedimentary rock. I chose the city of impact randomly.

11) I assumed that the water depth would be 4,280m deep; the average depth of the North Pacific Ocean according to a paper by John Bardarch (J.E. Bardarch, 2021). If 99942 Apophis hit 300km away from Victoria, the tsunami would be less than 10cm and would arrive 13.3 hours after impact. Another interesting effect about this collision is the sound intensity caused by the airblast, which would be as loud as heavy traffic. So, we might not even notice the effects of the meteorite colliding if it were to hit the ocean. If Swift-Tuttle hit 300km away from us, also at a depth of 4,280 m, the tsunami wave would have an amplitude between 1.8 meters and 3.5 meters. The airblast would have an intense effect. Impact Earth states that wood-frame buildings woudl almost completely collapse, glass windows would shatter, 90% of trees would be blown down, and the rest of the trees would be stripped of branches and leaves.

12) We would be safe from the tsunami wave created by 99942 Apophis if we were on Mount Doug. Other effects from this impact would not be fatal and as mentioned in question 11, and it is possible that we might not even notice the effects. Swift-Tuttle, on the other hand, has much more catastrophic impacts. The wave created by the collision

would be 1.8m-3.5m, which would not reach Mount Doug. The airblast effect on trees would be dangerous if we were on mount Doug. There would be an earthquake of 11.0 magnitude, which is larger than any earthquake ever recorded on Earth. We would be inside the fireball created by the collision. We would suffer 3rd-degree burns and most things would ignite, including our clothes. These effects would be fatal and many if not most people would die if we did not have shelter.

13) According to Impact Earth, with my assumptions (stated in Discussion), the final crater created by a 1km asteroid would be approximately 13.7km in diameter.

During this section, I realized that the JPG_LunarImage_HiRes file has more pixels than the PDF and has better resolution. To make it easier to count smaller craters and measure their size, I decided to use this image from this part on. So, I recalculated the scale of the digital image in km per pixel:

New digital image scale: 3476km10000pix = 0.3476km/pix

Size of crater created by 1km object: 3.7km 0.3476km/pix=10.64pix

14) By observing the moon's surface, I noticed there are much fewer craters on the maria than on the highlands. This indicates that more craters were formed early in the history of the Solar System. Early in our Solar System history, there was a period with an intense rate of cratering. This may have been because of the large debris traveling around the Solar System because of many planets and moons which had recently collided. Most of these old craters were created before the mare when the moon was very new and had just cooled down, approximately 4.5B years ago. Since then, the cratering has slowed down and become much more uniform.

15) I counted approximately 410 craters on the maria. I assumed that there are as many collisions of the far side of the moon as there are on the near side. That means, according to my calculations, that a total of 2 562 craters were formed after the maria on the surface of the moon.

Formula: $\frac{Area\ covered\ by\ the\ maria}{Area\ of\ moon} = \overset{Total}{\frac{\text{¿}Craters \in maria}{\text{¿}}}\ of\ craters\text{¿}$

Calculation: ↓↓↓

$\frac{16}{100} = \frac{410}{x}$ → x = 2 562craters on the surface of the moon

16) By dividing the age of the maria by the total number of asteroids I have the time it would take for an asteroid of this size to hit Earth.

Formula: $\frac{Age\ of\ the\ Maria(Gyrs)}{¿}\overset{Total}{of\ craters\,¿}$ = time between asteroid impacts (Gyrs)

Calculation: ↓↓↓

$$\frac{3.5\,Gyrs}{2562\,craters}=0.00136585\,Gyrs\ per\ strike \quad = \quad 1365850\ years\ per\ asteroid\ strike$$

17) By dividing the total number craters by the age of the maria, I found the number of asteroid impacts per year. I found that the average probability of an asteroid 1km striking the moon in a year is 32×10^{-7}

Formula: $¿\,of\ craters\,\frac{\overset{Total}{¿}}{Age\ of\ Maria(yrs)}$ = # of asteroid impacts per year

Calculation: ↓↓↓

2562 $\frac{craters}{3500000000\ years}=0.000000732\,asteroid\ strike/year$

18) By comparing the area of the Moon to the area of the Earth, I found the probability of an asteroid hitting the Earth. I also found how much more an asteroid would strike the Earth than the Moon.

Formula: $\frac{Area\ of\ the\ Earth}{Area\ of\ the\ Moon}=\frac{¿\,of\ asteroid\ strikes\ per\ year\ on\ Earth}{¿\,of\ asteroid\ strikes\ per\ year\ on\ the\ moon}$

$\frac{510\,000\,000\,km^2}{38\,000\,000\,km^2}=\frac{x}{0.000000732}$ → x = 0.00000982 asteroids strike the Earth /year

0.000000982 -0.000000732 = 0.00000025 asteroid strikes/year more on Earth than the Moon.

According to my calculations, I would expect that 0.00000025 asteroids 1km in diameter would hit Earth more than the Moon per year. In other words, Earth has 0.00000025 more chance of being hit by an asteroid than the Moon. This means that an Asteroid could hit the Earth every few million years. I am assuming that the number of asteroid strikes on earth only depends on its size compared to the moon. I am not including other factors such as the moon protecting the earth from collisions or the possible changes in the orbit of an asteroid. I am also assuming that the Earth and the Moon have the same impact rate.

19) The cratering on the Moon tells us a lot about the history of our Solar System. Scientists use its craters to estimate the rate of collisions on Earth. Although it gives us a great estimate of the rate of the collision on Earth, there could be another aspect to consider. Although the Moon was not always in tidal lock, the far side of the moon seems to have much bigger craters. This could indicate a relationship in such a way that the Moon acted as a shield against bigger asteroids. But this would be a very small shield today considering the angular size difference, keeping in mind that Moon used to be closer to the Earth.

20) Civilization is only about 6,000 years old. If we consider the age of civilization and my calculations, there could be an asteroid in 994 000 years. According to my calculations, an asteroid with a diameter of 1km could hit the Earth and likely end human civilization in the year 996 021. By that time though, because of human impact on climate change, we would have to leave Earth before that.

21) Although we use the craters on the Moon to estimate the rate of collision on our planet, there are very few existing craters on Earth. This is due to erosion, volcanic activity, and tectonic activity that have erased the evidence of craters on the Earth. But, we still see traces of large craters because since they are bigger, it takes more work and time for change to occur. The Moon, on the other hand, has no atmosphere, no water, and no tectonic activity. Because it does not have these effects, the Moon has a surface that is unchanged. We can see craters on the Moon from when it was first formed. Since we can see traces of asteroid impacts dating from billions of years ago, we can calculate the impact rate of asteroids before it became more continuous and uniform as it is today. The unchanged surface of the Moon is like a fossil record of the Solar System.

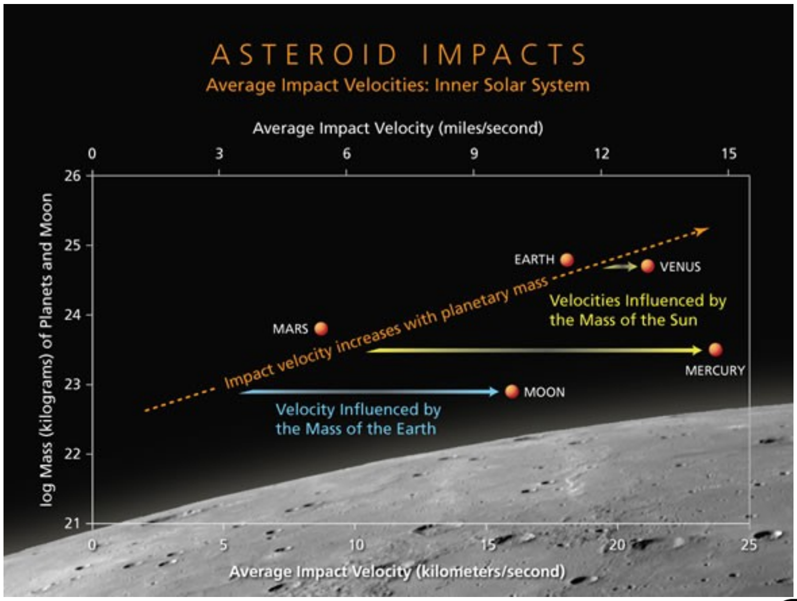
DISCUSSION

During this lab, I observed and examined different surface features of the Moon. By counting the number of craters on the maria I was able to find the impact rate on the Moon. There are regions of the Moon that have many more craters. From this, I was able to identify that early in the history of the Moon, it was bombarded much more frequently than it is today.

The final calculation, the impact rate of Earth, found that it could take approximately 1M years for a 1km asteroid to strike Earth. In the lab PowerPoint, we it addresses the impact rates of Earth and states that every few million years, the year could be hit by an asteroid of this size, which could end civilization. So, my results were close but a little lower than the actual impact rate on Earth. I may have been because I counted too many craters on the digital image since I did not zoom in enough to accurately measure the size of the craters and therefore ended up counting craters that were formed by asteroids less than 1km in diameter. Some asteroids have unknown densities, such as Swift-Tuttle. Because this asteroid contains ice and low-density carbon material, it may be considered a porous rock. I used a porous rock density of 1500kg/m^3. Since this asteroid also contains rock, the assumption I made that Swift-Tuttle is a porous rock may have decreased the impact that it would make on Earth. When calculating the affect of a tsunami, I assumed a depth of the ocean as 4,280m. Since 300km from the shore may be less deep than the average depth of all the North Pacific Ocean, the actual depth might have been less than my assumed depth of the ocean. The wavelength and period of tsunamis are determined by how much the ocean floor was disturbed. 99942 Apophis would hit the ocean floor in fragments but would disturb it to very small extent. By inputting the same value in the Impact calculator but with a shallower depth (3.7km), I found that this depth of the ocean would produce the same small impact and tsunami as the deeper depth, due to small disturbance of the ocean floor. Although water is great at absorbing shock, an object as large as Swift Tuttle with such high velocity would have impacted the sea floor. This object would create a huge crater. By inputting the same values with a shallower depth (3.7km), I found that the crater size and tsunami wave would not increase if the depth was 3.7km. So, my assumption of the ocean floor did not affect my results.

For question 13, I made the following assumptions. According to a study by Krasinsky, there are three classes of asteroids with densities of 1.38, 2.71, and 5.32g/cm^3 (G.A. Krasinsky et al, 2002). I used the average of these densities, which is 3.14g/cm^3, because I was calculating the average diameter of craters created by 1km asteroids. According to the Lunar and Planetary Institute, asteroids have an impact velocity of 18km/s. Although this is similar on the moon, the velocity distribution values are lower because of the moon's lower gravity. The higher mass of an object, the more the velocity will be increased. Figure 3 illustrates this well. If the impact velocity to Earth is 18km/s, it would be approximately 16km/s on the moon. So, I assumed a 16km/s impact velocity to input in the Impact calculator. Because 45° is the most probable angle of impact, I inputted this value into the Impact calculator. Crystalline rock on earth is more similar to the moon's surface than sedimentary rock, which is why I selected it.

Figure 3. From the Lunar and Planetary Institute



I counted 410 craters from the digital image. I think this count is high because I may have counted many craters that were under the length I calculated. I did not zoom in enough to accurately measure the length of the craters. I may have also counted the same craters twice. There were about 20 craters that I included in my count that I was unsure if I should include or not. My estimate for the uncertainty of this count was 410±50. I expect my count to be too high and therefore I think it should be about 360 craters.

My count from the large lunar map was very different than the count from the digital image. This may be due to poor visibility and reflection hiding some craters on the large lunar map. Since I did not have a ruler for the large lunar map, I used an estimate from a scale provided. This was not a reliable method. These limitations are what I expect caused the difference between my counts. My estimation of the uncertainty of this count was 326 ± 40. Since I think my count was too low, I would expect a count of about 360 craters from the lunar map. I also think that my estimation of crater count on the mare from the high-resolution image is more reliable than the count from the large lunar map.

My mistake in this lab was the count of craters. Although this took a long time, it may have been flawed. Nevertheless, I still got an accurate impact rate, which means that this mistake did not make a big change in my results.

CONCLUSION

The Moon is like a fossil record of the Solar System's history. I learned that the impact rate of the Moon, and therefore the Earth and many planets in our solar system, used to be a lot more frequent. In this lab, I learned and calculated impact rates on the Moon from different periods of our Solar System and found the possibility of a catastrophic asteroid collision on Earth.

I assumed the density of asteroids based on information from a paper by Krasinsky. (G.A. Krasinsky et al, 2002). I used Impact Earth to calculate asteroid impacts. I used the rule of thumb from the lab manual stating that craters are 10 to 50 times the size of the object that created them. I assumed the depth of the ocean at the point of impact from the average depth of the North Pacific Ocean according to a paper by John Bardach (J.E. Bardach, 2021).

I conclude that my assumptions involving crater count, density, and depth of the ocean were not perfect, but they did not affect my results in a drastic way.

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