Lab 3

Cratering and the Lunar Surface

3.1 Introduction

Even a child can look up at the Moon and distinguish between light and dark regions (which are often used to construct the face of a "Man in the Moon"). We refer to the light-colored areas as lunar highlands, and the dark-colored areas as lunar seas, or maria. Telescope images (see Figure 3.1) illustrate the dramatic contrast between the brighter, rugged, heavily cratered lunar highland terrain and the smooth, darker, flatter lunar maria, which are actually ancient lava flows. While we refer to the lava flows as ancient, we think that the mare (the singular form of maria) are generally younger than the highlands.

Figure 3.1: Telescope and space craft images of (a) the cratered surface of Moon, (b) the craggy lunar highlands, and (c) the smooth lunar mare.

How can we date surface features on the Moon? This exercise will acquaint you with that process, building on geological studies of the Earth. It will also help you to better understand cratering, an important process which shapes the appearance of many planetary surfaces.

We can study the Moon to learn more about the history of both the Moon and the Earth. Geological forces continually shape and reshape the surface of the active Earth. The Moon, lacking internal heat and thus geologically dead, has changed very little over the last three billion years. Its current appearance was formed in the early days of the solar system, a violent era in which the inner regions were littered with huge chunks of rocky planetesimals. This was material left over from the accretion process which drove the formation of the planets some 4.5 billion years ago. Impact craters resulting from frequent collisions with abundant space debris have mostly been obliterated on Earth, by plate tectonic-related activity and erosive forces. On the Moon, however, they have been preserved. By chronicling impacts, and accurately dating craters across the lunar surface, we can construct a record of the changing patterns of rocky debris in the inner part of the solar system. This is of interest for many reasons, and is an important step in estimating the probability that life could occur in various locations throughout the solar system.

The surface of the young Earth was kept in a hot, molten or semi-molten state, as space debris bombarded it over the first half billion years of its existence. The kinetic energy (energy of motion) of each rocky collision was transformed into thermal energy (heat). As the rate of collisions slowed, the planetary surface cooled and solidified, and conditions capable of supporting life slowly came into being. We think this happened around four billion years ago (four thousand million years). The earliest signs of terrestrial life date from 3.8 billion years ago, suggesting that life formed quickly once it became possible.

Sixty-five million years ago, a rare collision between the Earth and a huge rock ended the reign of the dinosaurs. The 180 kilometer (110 mile) diameter Chicxulub Crater in the Yucatan peninsula of Mexico is the "smoking gun" for this apocalyptic event. What size projectile (a huge rock, a larger meteoroid, a small asteroid, or even a comet) produced this crater? After experimenting with creating craters in this lab and using a program to simulate the effects of Earth impacts, you will better understand how such size estimates are made.

Could the Earth suffer a future collision, with catastrophic consequences for our species? We can help answer this question by observing the lunar surface, and establishing the current cratering rate. As reported in 2010 in Nature magazine, researchers studying NASA's Lunar Reconnaissance Orbiter images have established that at least five new lunar craters have appeared in the past 40 years.

3.1.1 Goals

The primary goals of this laboratory exercise are to analyze the appearance of the lunar surface and recognize how studying cratering can increase our understanding of the Earth's impact history. We will examine the key factors affecting the appearance of impact craters and ejecta, investigate the relationship between the velocity of a projectile and the crater it forms, and identify factors that determine the environmental consequences of impacts here on Earth.

3.1.2 Materials

All online lab exercise components can be reached from the GEAS project lab URL, listed here.

http://astronomy.nmsu.edu/geas/labs/html/home.shtml

You will need the following items to perform your experiment:

- a cooking pan, paint tray, or box (a container at least $10'' \times 12''$ across, and $2''$ deep)
- two quarts of clean, dry, loose sand (lunar base surface material)
- two cups of salt, sugar, or colored sand (lunar topping material)
- several dense round projectiles (such as $\frac{3}{8}''$ ball bearings or marbles)
- a cup or large spoon, small brush, and sieve to help in dressing your lunar surface
- a magnet (useful but not essential), to use in extracting your projectiles from the sand
- a small plastic container (not essential), to use to toss projectiles up to an assistant
- a page or two of newspaper, to keep your work area clean
- a $3''$-$8''$ ruler
- an 8-foot or longer tape measure

You will also need a computer with an internet connection, to analyze the data you collect from your cratering experiment. An assistant would be helpful for conducting the experiment in Section 3.3.1, but you can also work alone.

3.1.3 Primary Tasks

This lab is built around three activities: 1) studying the lunar surface and age-dating features, 2) creating your own craters (through experimentation), and 3) determining a crater size, projectile velocity relationship

3.1.4 Grading Scheme

There are 100 points available for completing the exercise and submitting the lab report perfectly. They are allotted as shown below, with set numbers of points being awarded for individual questions and tasks within each section. Note that Section 3.7 (§3.7) contains 5 extra credit points.

Table 3.1: Breakdown of Points

Activity	Crater Ages	Crater Experiment	Crater Sizes	Questions	Summary
Section	§3.2.1	§3.3.1	§3.4.1	§3.5	§3.6
Page	6	11	18	20	23
Points	19	16	15	15	35

3.1.5 Timeline

Week 1: Read §3.1–§3.4, complete activities in §3.2.1 and §3.3.1, and begin final (Post-Lab) questions 1–7 in §3.5. Identify any issues that are not clear to you, so that you can receive feedback and assistance from your instructors before Week 2. Enter your preliminary results into your lab report template, and make sure that your instructors have been given access to it so that they can read and comment on it.

Week 2: Complete activity in §3.4.1, finish final (Post-Lab) questions in §3.5, write lab summary, and submit completed lab report.

3.2 Relative Ages on the Moon

When it first formed, the Moon's interior was so hot that the upper mantle was molten (in a liquid state). Frequent impacts cracked the lunar crust repeatedly, and so this molten rock (or lava) flowed freely onto the surface. As the Moon cooled over hundreds of millions of years, however, large projectiles impacting the surface triggered flows less and less often. We think that the era of impact-triggered, widespread lunar lava flows that produced the lunar mare ended around three billion years ago. How was this age determined?

There are two primary techniques used for dating rock samples. Radioactive dating (measuring the amounts of various elemental isotopes which decay at different rates) can produce solid, absolute ages. This technique has been used on lunar rocks collected from a few select regions by Apollo astronauts, and provides the foundation for estimating the duration and placement of many events in the Moon's evolutionary history. As most of the lunar surface remains unvisited and unsampled by humans, this chronology has been filled in using relative dating methods. These techniques can establish which of two rock samples is older, or determine which of two events happened first, but they cannot generate absolute times for events unless combined with sufficiently detailed, independent, absolute measurements for similar samples.

Large impacts are key events in lunar history. Consider how an impacting meteoroid creates a crater. The force of the high-speed impact obliterates the projectile and displaces part of the Moon's surface, pushing the edges of the resulting crater high above the surrounding rock. At the same time, displaced material shoots outward from the crater, creating rays of ejecta (seen as radial bright streaks centered on the crater). The most recent such event occurred some 110 million year ago, and produced the 85 kilometer (53 mile) wide crater Tycho, easily seen near the bottom of Figure 3.1a. Note the bright rays emanating outward from it in all directions, some extending over 1500 kilometers in length. Close-up views of the crater show a prominent central peak, produced when molten excavated material from the blast flowed back towards the center of the excavation and formed a mountain peak.

The Law of Cross Cutting Relations is the key principle behind relative dating of craters. It states that any geological feature (such as a rock structure or a fault) that cuts across another geological feature must be younger. A crater in a lunar mare region must thus be younger than the mare – because the mare had to be present before a meteoroid could hit it, producing a crater that cut through it. If we see a crater sitting atop the rim of another, partially obliterating it, the superimposed crater must be younger.

Example 3.1

In the image at the right (Figure 3.2), smaller crater Thebit A appears in the upper left-hand corner, on top of and interrupting the rim of larger crater Thebit. Common sense tells us that Thebit must have formed before the rock that created Thebit A could crash into and destroy part of its rim.

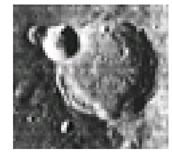

Figure 3.2: Crater Thebit

Relative ages for features over an entire planetary surface can be obtained by comparing the number of impact craters in different areas. The longer a surface has been exposed to meteoric bombardment, the more impact craters it should have acquired. Older surfaces thus have accumulated more impact craters than younger ones.

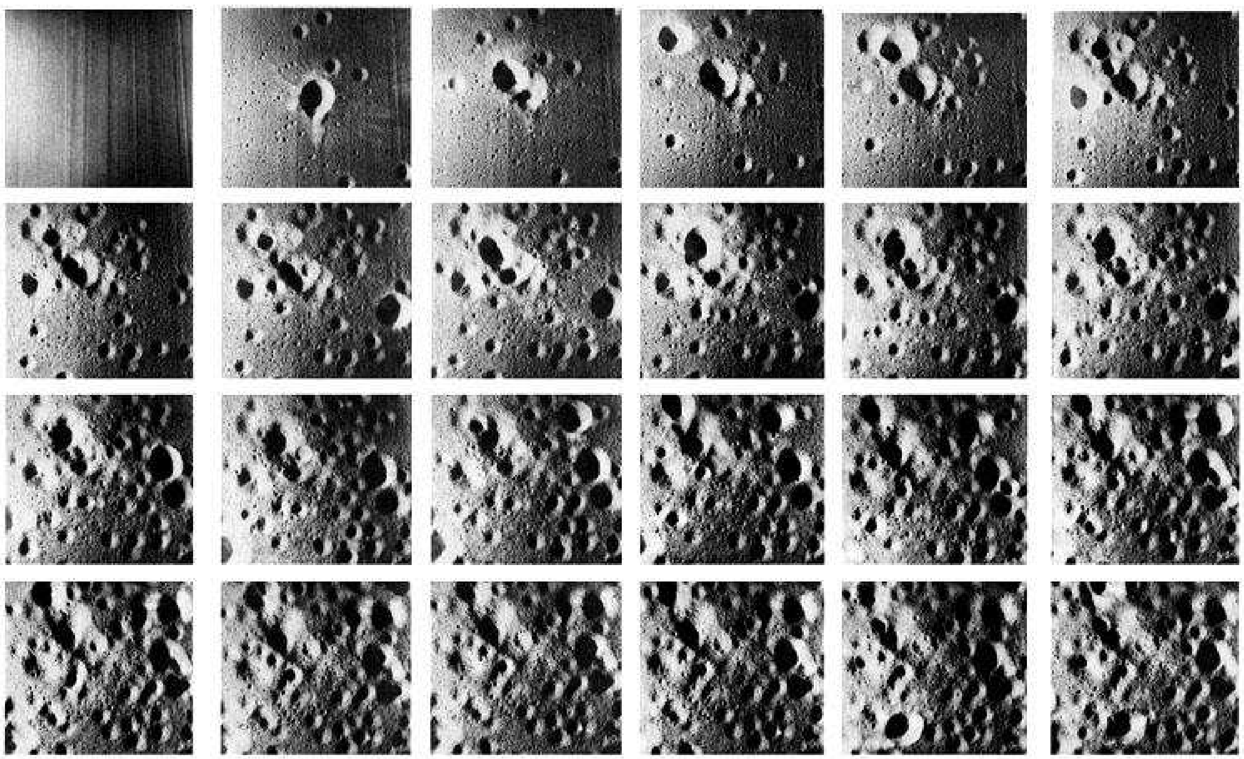

Figure 3.3: A series of time step images, starting in the upper left-hand corner and proceeding across each of four rows, in turn, models the changes in appearance for a smooth surface exposed to a steady rain of small particles of varied sizes.

Example 3.2

The preceding image (Figure 3.3) shows the results of cratering experiments conducted in a laboratory here on Earth. The first frame (upper left-hand corner) shows an initially smooth surface, one which is then exposed to a steady bombardment of small particles of various sizes. The time-lapse sequence of images, with time increasing from left to right and then top to bottom, illustrates the sequential degradation of the surface. Note how as the surface gets "older" it presents a steadily increasing number of craters. The "age" associated with each image could be estimated by counting the number of superimposed craters atop the surface.

Crater counts can be used to establish relative ages for surfaces. If an average cratering rate (the number of new craters created per unit area per year) is known, counts can be used to estimate ages for surface features. The basic idea is that older surfaces are more heavily cratered, so age is proportional to the surface density of craters. Complicating factors include an inability to correct for numerous secondary craters produced by secondary projectiles thrown up by a primary projectile, and lava (or water) flows that can obliterate craters. Given the Moon's minimal surface activity of late, it is safe to assume that once widespread lunar lava flows ended, few or no craters were erased from the record.

3.2.1 Activity: The Lunar Surface, Craters, and Relative Dating

Our introduction to the lunar surface continues with an examination of the regions visited by the crews of the Apollo 12 and Apollo 16 manned missions. We will examine two Lunar Orbiter survey photos, shown at low-resolution in Figure 3.4.

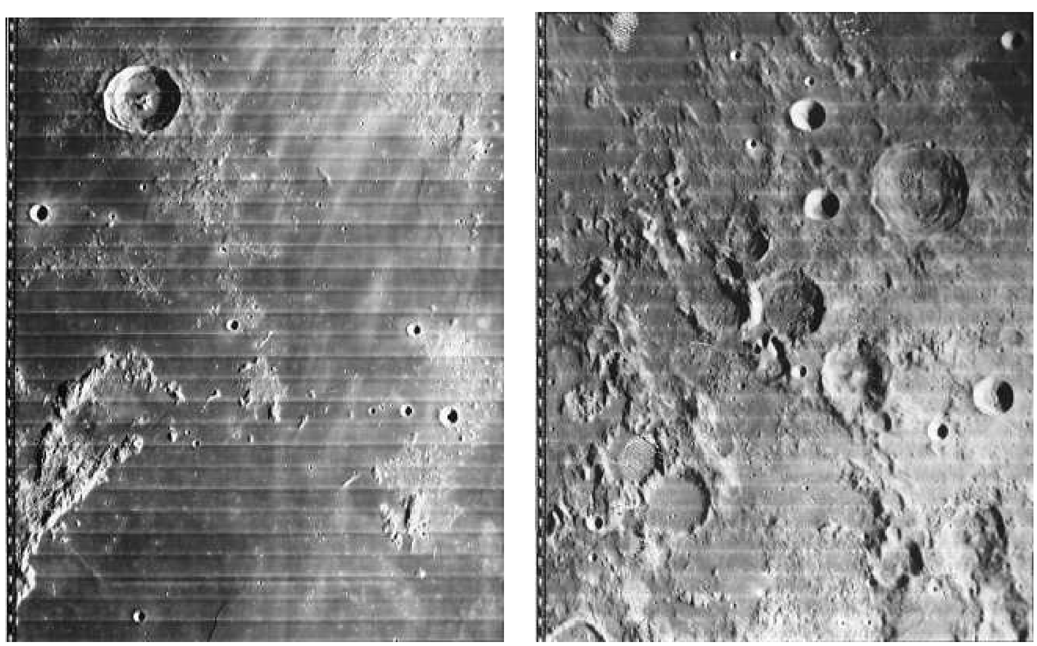

Figure 3.4: Low-resolution Lunar Observer images of the landings sites for the Apollo 12 (left) and the Apollo 16 (right) missions, taken from a space craft orbiting the Moon.

1. It is important that you view higher-resolution versions of the two images from the GEAS project lab exercise web page (see the URL on page 3 in §3.1.2). Click on the labeled and unlabeled versions of the images on the website to bring up higher-resolution images, zooming in to study detailed features. Do not use the lower-resolution images shown in the

manual, as you would lose too much detail.

Complete the following nine questions by circling the appropriate answer. (9 points total)

(a) Which landing site better represents the lunar mare region? (Apollo 12 / Apollo 16)

(b) Which landing site better represents the lunar highlands region? (Apollo 12 / Apollo 16)

(c) Which of the following craters lacks a central peak? (Lansberg / Eppinger / Taylor)

(d) Which of the following names on the Apollo 12 site image denotes a mountain chain?

(Mare Insularum / Montes Riphaeus / Luna 5)

(e) Which of the following craters on the Apollo 16 site image no longer has an intact, well-defined circular rim?

(Alfragenus / Theon Senior / Theon Junior / Zollner)

(f) Which lunar mission landed in an area crossed by a prominent lunar ray?

(Apollo 12 / Apollo 16)

(g) Which landing site appears to have a greater density of craters? (Apollo 12 / Apollo 16)

(h) If Crater Eppinger (at the bottom of the Apollo 12 landing site image) has a diameter of six kilometers, what is the diameter of the smallest crater shown in this image?

(0.1 kilometers / 1 kilometer / 2 kilometers / 3 kilometers)

(i) The largest crater identified by name on the Apollo 16 image has a diameter of:

(30 kilometers / 40 kilometers / 50 kilometers / 100 kilometers)

2. Next consider a region at the lunar highland–mare interface, shown in Figure 3.5. Note that parts of the rims of craters Fracastorius and Beaumont appear to have been destroyed by lava flows associated with the Sea of Nectar (Mare Nectaris). There is a bright streak (a lunar ray) to the lower-left of crater Rosse, illuminated when observed at full moon with the Sun overhead (as shown in the lower-left corner of Figure 3.5).

Consider four events:

(a) the lava flow associated with the impact that created the Mare Nectaris

(b) the impact event that created crater Rosse, sitting in the Mare Nectaris

(c) lunar highland crater production (of which Fracastorius and Beaumont are examples)

(d) a lunar ray (associated with crater Tycho, not shown), which is observed to pass over and rest on Rosse.

Order these four events in time, from earliest to latest: ________________________________

Explain why you ordered them as you did. (4 points)

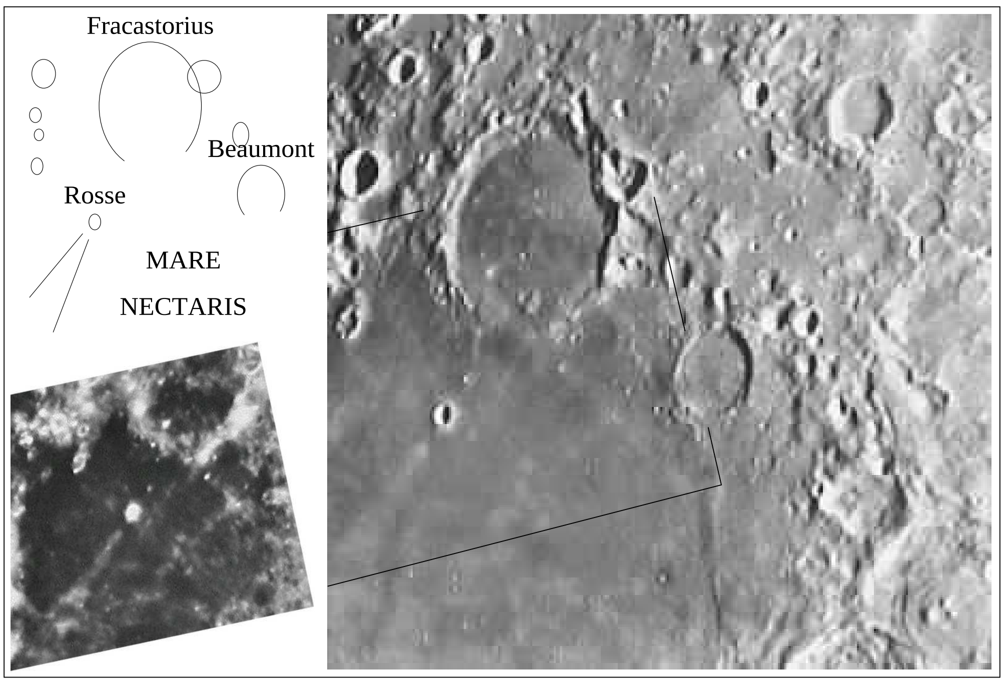

Figure 3.5: The region surrounding the large craters Fracastorius and Beaumont (right), identified by name (upper-left), and a second image with the Sun directly overhead, (lower-left) centered around crater Rosse in the heart of the Mare Nectaris (marked at right).

3. Now build two plots, showing the density of new craters found superimposed atop large craters which formed at various times in the distant past. Access the first plotting tool listed for this lab exercise from the GEAS project lab exercise web page (see the URL on page 3 in §3.1.2).

(a) In your first plot, track the large crater age versus the surface density of later, superimposed craters for the first four of the large craters listed in Table 3.2 (those less than 150 million years old). Be sure to give your plot a title – something like "Crater Properties" is fine. Label the x-axis "Surface Density (per 10^6 km^2)", and label the y-axis "Age (Myr)" to indicate units of millions of years. Select "yes" for both "show linear fit to data" and "force fit through origin," to add a line predicting the age of a crater covered by new craters to a certain density, and to force the line to go through the origin. (This is equivalent to saying that a brand-new crater should have no craters superimposed on top of it when it first forms, just like a freshly-washed counter-top should show no fingerprints.)

Table 3.2: Crater Properties

Entry	Crater Name	Density ($\#/10^6$ km^2)	Age (Myr)
1	Cone (Apollo 14)	20	26
2	North Ray (Apollo 16)	50	50
3	Necho	67	80
4	Tycho	90	109
5	Aristarchus	270	450
6	Copernicus	1,200	850

(b) Use the best-fit line on the plot to estimate the age of the crater Giordano Bruno, a young, virtually unblemished crater which lies slightly on the far side of the Moon. Recent studies have reported a surface density of 3.2 craters per million square kilometers on the continuous ejecta surrounding the rim of the Bruno crater. Use the relation between age and density derived for the four objects in your plot to estimate how long ago this crater formed, given the observed surface density of additional craters.

To do this, use the relation

$$\text{Age} = m \times \text{ Surface Density}$$

where the slope m of the relation is taken from the fit to the data in your plot. (For example, if the slope of your plot was 2, then the derived age would be $2 \times 3.2 = 6.4$ million years.)

Derived age: ______________________________ (Myr). (1 point)

To check your answer, add a new data point to the input data for your plot, with the crater density and the age for the Bruno crater. When you recreate the plot, the slope should not change appreciably, and the new point (the one closest to the origin, with an x-coordinate of 3.2) should appear right on top of the fitted line.

(c) In the 1970s, astronomer Jack Hartung proposed that the Bruno crater formed quite recently, on June 18, 1178. He hypothesized that five monks from Canterbury observed the impact, based on a written account of their testimony.

"Now there was a bright new [thin crescent] moon, and as usual in that phase its horns were tilted toward the east and suddenly the upper horn split in two. From the midpoint of this

division a flaming torch sprang up, spewing out, over a considerable distance, fire, hot coals, and sparks. Meanwhile the body of the moon, which was below, writhed ... like a wounded snake."

Does your age estimate support or counter Hartung's hypothesis? (Support / Counter)

Explain your answer. (2 points)

(d) In your second plot, add in the two oldest craters (Aristarchus and Copernicus) listed in Table 3.2 to the data to be plotted. Once again, fit a line through the data points and through the origin. Compare the slope of the line in the first plot to that of the second plot.

Based on the distribution of all six data points, and the best-fit lines, has the lunar cratering rate changed significantly over the last 850 million years? Explain your answer. (3 points)

Be sure to include both plots in your lab report.

Congratulations, you have completed the first of this lab's three activities. You may want to answer Post-Lab questions 1 through 3 on page 20 at this time.

3.3 Cratering Experiments

Astronomers are rarely presented with opportunities to perform active experiments, being constrained to observe whatever the Universe happens to send our way. We can, however, better understand the process of planetary and lunar cratering through direct experimentation. By launching projectiles of various masses at various speeds, and angles of impact, towards a variety of hard and soft surfaces, we can simulate a wide range of potential impact events.

In this activity, you'll investigate how the velocity of a projectile is related to the size of the craters it creates. To control the projectile speed as much as possible, we will drop each one from a set height, calculating its speed at impact by computing the kinetic energy (energy of motion) it gains as it falls.

These velocities will be much smaller than the tens of kilometers per second (km s^{-1}) at which space debris typically crash into planets or satellites. Our craters will thus be smaller (whew!), as less energy will be released upon impact. Note that space debris typically travel fast enough to explode on impact, a phenomenon which tends to produce circular, symmetric craters, but we will not be able to reproduce this exciting behavior.

3.3.1 Activity: Forging Craters

Start by listing the factors you that think might define a crater's size and appearance (the shape, the presence or absence of central peaks, ejecta, rays, etc.). (1 point)

Experimental Procedure

1. Begin by spreading out a page of newspaper on the ground or floor, to collect any scattered materials. Choose a location that is sheltered (or indoors) if the weather is very hot or windy, or if it might rain, and make sure that you have at least seven feet (and ideally thirteen feet) of accessible space above the paper so that you can release projectiles from a variety of heights above it easily. Prepare a simulated "lunar test surface" by filling an appropriate container with your base material. Your could use a large cooking pan, a paint tray, a clean litter box, or a even a sturdy cardboard box, one with dimensions of at least 10 by 12 inches. Fill the bottom inch of the container with clean, dry, uncaked sand, or a similar substance. Smooth the surface carefully, tapping the sides of the container gently to help the material to settle evenly and form a flat, even surface.

2. Sprinkle a fine layer of appropriate lunar topping material on top of the base layer. The topping should differ distinctly in color and in appearance from the base. You might try

Table 3.3: Crater Diameter Measurements I

Drop from height of 25.4 cm (10 inches), for impact velocity of 223 cm s^{-1}.								
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	$\text{Avg}_5 \pm \sigma$
Diameter (cm)								
Notes								
Drop from height of 50.8 cm (20 inches), for impact velocity of 316 cm s^{-1}.								
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	$\text{Avg}_5 \pm \sigma$
Diameter (cm)								
Notes								
Drop from height of 76.2 cm (30 inches), for impact velocity of 386 cm s^{-1}.								
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	$\text{Avg}_5 \pm \sigma$
Diameter (cm)								
Notes								
Drop from height of 101.6 cm (40 inches), for impact velocity of 446 cm s^{-1}.								
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	$\text{Avg}_5 \pm \sigma$
Diameter (cm)								
Notes								

(6 points)

Table 3.4: Crater Diameter Measurements II

Drop from height of 152.4 cm (60 inches), for impact velocity of 547 cm s^{-1}.

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	$\text{Avg}_5 \pm \sigma$
Diameter (cm)								
Notes								

Drop from height of 203.2 cm (80 inches), for impact velocity of 631 cm s^{-1}.

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	$\text{Avg}_5 \pm \sigma$
Diameter (cm)								
Notes								

Drop from height of 304.8 cm (120 inches), for impact velocity of 773 cm s^{-1}, *or _____ cm for velocity of _____ cm* s^{-1}.

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	$\text{Avg}_5 \pm \sigma$
Diameter (cm)								
Notes								

Drop from height of 406.4 cm (160 inches), for impact velocity of 892 cm s^{-1}, *or _____ cm for velocity of _____ cm* s^{-1}.

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	$\text{Avg}_5 \pm \sigma$
Diameter (cm)								
Notes								

(6 points)

table salt, bath salts, colored sand, or any inexpensive powder with a similar consistency that is handy. Be sure to cover the base layer completely, and to a uniform depth, with the topping.

3. You will be dropping a projectile repeatedly into the container, measuring the resultant crater diameter, noting anything unusual (such as distinctly non-circular craters), and resurfacing the materials in the container between sets of trials. In order to obtain useful data, it is important that you consistently prepare the surface in the same manner, and measure crater diameters the same way. If a crater is non-circular, measure the longest dimension; if its rim is terraced, measure from the outer terrace on one side to the outer terrace on the other side. Use a small ruler to measure crater diameters to the nearest half of a millimeter or two-hundredths of an inch, and a longer tape measure to determine the height above the surface from which projectiles will be dropped.

4. Begin the data collection process by dropping the projectile from a height of 10″ (25.4 cm) onto the prepared surface. (If you measure the height from the ground level, or the bottom of your container, make sure to account for the roughly one-inch height of your lunar surface!) Examine the crater *before* removing the projectile from the sand, as its removal may damage the delicate crater pattern. Measure the diameter of the resulting crater and record it under "Trial 1" in Table 3.3, in units of centimeters. Measure the length to the nearest half of a millimeter (0.05 cm), so write "3.25 cm," for example, rather than just "3 cm." (If you do not have a metric ruler, one marked with centimeters and millimeters, recall that one inch is equal to 2.54 centimeters and translate your measurements from fractions of inches accordingly.) Take notes about crater appearance as appropriate (when you notice interesting or unusual patterns).

5. Perform seven trials from this height, recording diameters and notes in Table 3.3 each time. If your container is large enough, you may be able to fit in an entire set of seven trials in one go by dropping the projectile onto various areas. If your projectile ever forms a crater which overlaps with an existing structure, discard that trial and drop the projectile again. Whenever the surface fills up with craters, remove the top layer of material, smooth away any craters in the base, and re-apply a new, smooth top layer.

6. Examine the set of diameter measurements, and discard (set aside) the largest and the smallest of the seven values. (This is called removing the outliers, and eliminates the points most likely to have been affected by the wind or errors in procedure or measurement.) Then average the remaining five values and record an error estimate based on their spread in value, by creating a histogram of the values in the first plotting tool listed for this lab exercise on the GEAS project lab exercise web page (see the URL on page 3 in §3.1.2). Place these values in the final column of Table 3.3.

7. Next increase the height from which the projectile is dropped to 20″ (50.8 cm), and perform seven more trials, recording your observations in the next two lines of Table 3.3. When your measurements are completed, discard the largest and smallest values and average the remaining five together, estimating the spread, or scatter (σ), again as well.

8. Repeat this process at heights of 30″ (76.2 cm), 40″ (101.6 cm), 60″ (152.4 cm), and 80″ (203.2 cm), entering the data into Tables 3.3 and 3.4. Each completed data table is worth up to 6 points.

9. There are two remaining lines in Table 3.4. If you are working near a tall staircase and can **safely** drop a projectile from higher than seven feet, then go ahead; ideal heights are 120″ (10 feet) and 160″ (13 feet, 4″). However, if you do not have a safe, secure way to drop a projectile from a larger height then leave these two lines blank or work at lower heights. **Do not use a step ladder or climb anything but a stable staircase – your safety is much more important than these final two sets of data points.**

You may want to enlist a helper (and a few identical projectiles) for this part of the experiment, to save you time by dropping the projectiles while you measure the crater diameters below. If you do so, bring along a 35-mm film cannister or another small plastic container, so that you can easily toss the projectiles back up to your assistant after each cratering event. **Be careful that no projectiles are dropped on anyone's head!**

Discuss your findings in the space below. In particular, comment on observed ray patterns and lengths, any non-circular craters and central peaks seen, and anything else of interest. (3 points)

Congratulations, you have completed the second of this lab's three activities. You may want to answer Post-Lab questions 4 and 5 starting on page 20 at this time.

3.4 Predicting the Sizes of Impact Craters

It is quite difficult to study impact craters on the surface of the Earth, as our warm planet is geologically active and undergoing substantial amounts of surface evolution (e.g., lava and water flows, glaciation, erosion, continental drift). You may, however, already be familiar with one of the best-known impact craters in our vicinity, shown in Figure 3.6.

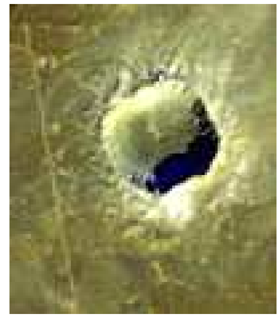

Figure 3.6: The Meteor Crater, in northern Arizona, is one of the best-preserved craters known on Earth. It formed some 50,000 years ago, when a 40-meter diameter chunk from an asteroid entered the atmosphere at a speed of 20 kilometers per second and struck the Earth at a 45° angle. The projectile massed around three-hundred-million kilograms, and contained a substantial amount of iron (with a density around eight grams per cubic centimeter, or 8,000 kilograms per cubic meter). The resulting crater spans more than a kilometer, and is more than 170 meters (550 feet) deep.

Consider the details of this event that are relevant to the cratering experiments that you have conducted. The most important properties of a projectile are its mass, m, and impact velocity, v. They determine how much energy of motion (kinetic energy) the moving projectile possesses. As you might expect, the kinetic energy of an object scales with its mass, and with its velocity.

We can write this mathematically as follows. The kinetic energy of a projectile, KE, is equal to one-half times the product of its mass m and the square of its velocity v:

$$\mathrm{KE} = \frac{1}{2} m v^2.$$

Because the kinetic energy increases linearly with the mass but goes as the square of the velocity, the velocity is the more "important" term in the equation. (A relatively small change in velocity can produce a large increase, or decrease, in kinetic energy.) If the mass of a projectile doubles, its kinetic energy goes up by only a factor of two. If the velocity doubles, however, its kinetic energy increases by a factor of 2^2, or four.

Example 3.3

Let's calculate the kinetic energy at impact of the projectile that caused Meteor Crater, with a velocity of 20 kilometers per second (20,000 m sec^{-1}).

$$\mathrm{KE} = \frac{1}{2} m v^2 = \frac{1}{2}\left(2.7 \times 10^8\,\mathrm{kg}\right)\left(20,000\,\frac{\mathrm{m}}{\mathrm{sec}}\right)^2 = 5.4\times10^{16}\,\text{joules, or 13 megatons of TNT.}$$

In §3.3.1, you worked with a projectile of fixed mass m, varied the impact velocity v by dropping the projectile from different heights, and measured the resulting crater diameters. How are the projectile velocity v and the crater diameter D related? We might hypothesize that they are simply related directly – the greater the velocity v, the greater the crater diameter D, so that if v doubles, then so does D. We can write this mathematically as

$$D \propto v, \quad \text{meaning } D \text{ is proportional to } v$$

and we will call this model #1.

We can improve this model by realizing that the kinetic energy of the projectile can do various things upon impact. It could be used to deform surface material, lifting it up and out while forming a crater, it could heat the surface, and it could also create seismic waves. If most of the energy goes into the first task, however, then we can argue that v and D should relate to each other in a different way.

Let's assume that material is scooped out of the ground in a vaguely spherical shape, like a scoop of earth. The volume of the material lifted will then be proportional to the cube of the radius of this sphere, as the volume of a sphere is $\frac{4\pi}{3}R^3$ for a sphere of radius R, or to the cube of its diameter (as the diameter is simply twice the radius). This sphere's diameter, and the crater diameter D and depth y, will all scale (or change) together in size. The amount of energy used to lift the material is equal to the weight of the material times the height y that it is lifted. As weight scales with volume, and as the crater height scales with its diameter (larger craters are also deeper), the energy used to lift the material will scale as $D^3 \times D$, or as D^4.

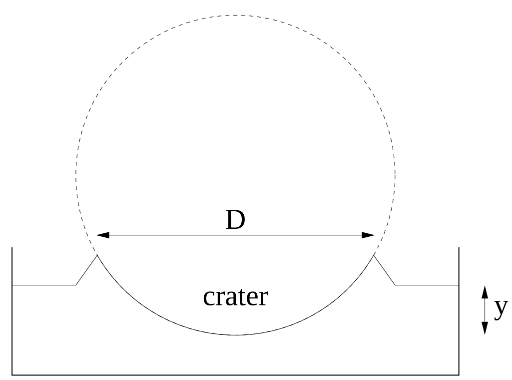

Figure 3.7: A simple model, illustrating the connection between the diameter of a sphere of material scooped out to form a crater, and the diameter D and depth y of the crater.

As we already know that the energy is proportional to the square of the projectile velocity, we can now say that $D^4 \propto v^2$, or $D^2 \propto v$. Let's write that again for emphasis:

$$D^2 \propto v, \quad \text{meaning } D \text{ squared is proportional to } v$$

and we will call this model #2.

We can take the square-root of each side of this equation if we wish, and we will then see that

$$D \propto v^{\frac{1}{2}}, \quad \text{meaning } D \text{ is proportional to the square-root of } v.$$

Let's also test a third model, where rather than D^2 varying with v, v^2 varies with D. In this case,

$$D \propto v^2, \quad \text{meaning } D \text{ is proportional to the square of } v \ (v \times v).$$

We now have three models for the behavior of D versus v, predicting the size of a crater produced by a projectile traveling at a certain velocity. The models make different predictions, so by studying the data we have collected regarding crater sizes for projectiles dropped from various heights, and thus impacting at different speeds, we can test the models against each other.

<u>Example 3.4</u>
Simulations tell us that if the projectile that created Meteor Crater fell straight down at 15.3 kilometers per second when it hit sedimentary (soft) rock, it would have created a crater 1.6 kilometers in diameter. At twice that speed (30.6 kilometers per second), it would have forged a 2.17 kilometer crater. The ratio of the two crater diameters is $\frac{2.17}{1.6}$, or 1.36. This lies closer to the prediction of model #2 (a factor of two change in projectile velocity should produce a factor of $\sqrt{2}$, or 1.414 in crater size), than that of model #1 (which predicts a change of a factor of two in size) or model #3 (which predicts a change of a factor of four in size).

If $D \propto v$, then $D_1/D_2 = v_1/v_2 = 2$.

If $D^2 \propto v$, then $D \propto v^{\frac{1}{2}}$, and $D_1/D_2 = \sqrt{v_1/v_2} = \sqrt{2} = 1.414$.

If $D \propto v^2$, then $D_1/D_2 = (v_1/v_2)^2 = 2^2 = 4$.

3.4.1 Activity: What Determines How Big an Impact Crater Is?

Before we test the crater diameter data recorded in Tables 3.3 and 3.4 against our suite of models, let's examine the relationship between the height from which we dropped our projectiles and their resulting speed at impact on the surface. The impact velocity of a projectile of a certain mass is a simple function of the height h from which it is dropped and the strength of the surface gravity g. The velocity v, derived from Isaac Newton's laws of motion, is

$$v = \sqrt{2gh}.$$

If you completed the last two lines of Table 3.4 by dropping your projectile from different heights than 120″ and 160″, make sure to update the height and velocity values listed in the table to reflect your changes. For a height h measured in units of centimeters, use a value of 980 centimeters per squared second for g, to calculate a velocity v in units of centimeters per second. (Check your calculations by first recalculating the velocities for the 120″ and 160″ cases and verifying that you reproduce the values listed in the table.)

1. Plot the crater diameters, including associated errors, against velocity for the data you entered into Tables 3.3 and 3.4, using the second plotting tool listed for this lab exercise from the GEAS project lab exercise web page (see the URL on page 3 in §3.1.2). This application will plot crater diameter as a function of impact velocity, and then attempt to fit each of the three models for the behavior of D versus v.

Place v on the x-axis (the horizontal axis, running from left to right) and D on the y-axis (the vertical axis, running up and down), so when you enter your data under "Numbers to plot" on the form, place v first on each line, followed by D and then σ, the error (or spread) measured in each D value. Give your plot a title – something like "Crater Experiment Data" is fine. Label the x-axis "Impact Velocity (cm per second)", and label the y-axis "Crater Diameter (cm)." Trace the distribution of the points on the plot by eye, and select the model which best fits the data. Examine the rms deviations (σ_1) through (σ_3), as the best fit should have the lowest σ value. Be sure to save the plot as well, to include in your lab report. (4 points)

The best-fitting model is ____________. (1 point)

This means that the relation between D and v is __________________________. (1 point)

Is this the result you expected? Why, or why not? (2 points)

2. Use the Earth Impact Effects program found on the GEAS project lab exercise web page (see the URL on page 3 in §3.1.2) to answer the following questions.

(a) Consider two hypothetical impact events occurring in the uninhabited area between Deming and Columbus, in a sedimentary rock region some 50 miles from Las Cruces, NM.

Impact A: A 100-meter icy comet traveling at 50 km s^{-1} strikes at a 45° angle.

Impact B: A 40-meter iron-dominated rock traveling 20 km s^{-1} strikes at a 45° angle.

Answer each of the six question below by circling A or B. (1/2 point each, 3 points total)

Which impact would:

i) be caused by the object carrying the most kinetic energy? (A / B)

ii) produce the largest crater? (A / B)

iii) be the most unusual (the rarest)? (A / B)

iv) sound the loudest in Las Cruces? (A / B)

v) produce the largest earthquake in Las Cruces? (A / B)

vi) disturb the air most in Las Cruces (consider winds, and changes in pressure)? (A / B)

(b) Click on "impact examples," (just below "Enter Impact Parameters") and compare the size of the projectile that created Meteor Crater to the one that ended the reign of the dinosaurs and created Chicxulub Crater. (1 point)

(c) Chicxulub Crater has a diameter of 113 miles. What size would it be under the following three circumstances?

i) The projectile landed on sedimentary rock rather than in 100-meter deep water.

Diameter = ___________________ miles. (1 point)

ii) The projectile was made of iron rather than rock.

Diameter = ___________________ miles. (1 point)

iii) The projectile landed on sedimentary rock *and* was made of iron.

Diameter = ___________________ miles. (1 point)

3.5 Final (Post-Lab) Questions

1. A careful examination of the lunar surface reveals that most lunar craters (a) come in widely assorted shapes, (b) are very oval shaped (elongated), or (c) are circular.
(Circle one.) (1 point)

2. Is it easier to obtain relative or absolute ages for lunar surface features? Why? (Which can be estimated from images, and which require an analysis of actual rock samples?) (2 points)

3. Suppose current lunar cratering rates were found to be much higher than those averaged over the last 100 million years. Would this be a cause for concern? Why, or why not? (2 points)

4. How did the craters that you created differ from lunar craters? Were your initial guesses about which factors would determine the sizes and appearances of your craters confirmed, or denied? (3 points)

5. Nearly all lunar craters are circular because the projectiles that create them (a) travel almost straight down through the atmosphere, or (b) have high impact velocities, producing explosions on impact. (Circle one.) (1 point)

6. For a projectile of a given mass, what factors besides its impact velocity determine the resulting crater diameter? (3 points)

7. Suppose that the huge meteoroid that created the Chicxulub crater was ten million times more massive than the much smaller object that forged the Meteor Crater in Arizona, but they were both traveling at 20 km s^{-1} on impact.

(a) Compute the kinetic energy, in units of megatons of TNT, associated with the Chicxulub progenitor object just before the moment of impact, by using the information derived in Example 3.3 (on page 16). Kinetic energy is proportional to the projectile mass times the square of its velocity, so if this projectile traveled at the same speed as the Meteor Crater projectile and was ten million times more massive, then its kinetic energy is also ten million times larger. (2 points)

(b) Compare this amount of energy with the most powerful man-made explosive device ever detonated, a hydrogen bomb yielding 50 megatons of TNT.

The Chicxulub impact event was ________________ times more powerful. (1 point)

3.6 Summary

After reviewing this lab's goals (see §3.1.1), summarize the most important concepts explored in this lab and discuss what you have learned. Describe the set-up and implementation of your cratering experiment in detail, your analysis of the resultant data, and your overall scientific conclusions. (35 points)

Be sure to cover the following points.

- Describe the appearance of the lunar surface, identify the primary drivers for its surface evolution, and explain the scientific basis for our conclusions regarding the relative and absolute ages of features.

- What primary factors determine the size and appearance of impact craters?
- How can studying the cratering process on the Moon increase our understanding of the Earth's impact history, and help us to estimate the likelihood of future catastrophic events?
- Describe the set-up and execution of your cratering experiment. What types of materials did you use to form the base and surface layers? What type of projectile did you use, and of what size? What were the most challenging aspects of the experimental procedure? How might you change your procedure if you repeated the experiment now, knowing what you now know?
- Include the two plots of crater age versus feature density that you made as part of the activity in §3.2.1, and the plot of crater diameter versus projectile impact velocity for the data you collected in §3.3.1.
- Discuss which of the three proposed models for the behavior of crater diameter D versus impact velocity v was best supported by your experimental data.

Use complete, grammatically correct sentences, and be sure to proofread your summary. It should be 300 to 500 words long.

3.7 Extra Credit

An 350-meter asteroid named Apophis (after a serpent from Egyptian myth) has an orbit that crosses that of the Earth, and so it might collide with us at some time in the future. Orbital crossings will occur in 2029, 2036, and 2068, but the possibility of an actual impact event is computed to be a few percent at most.

If Apophis were to hit the Earth, how large a crater would be created? You may assume that it travels at a speed of 20 km s^{-1}, and lands in sedimentary rock at an angle of 45°. We think that it is composed of nickel and iron, with an overall density of 8000 kg m^{-3}. What would you expect the environmental consequences of such an event to be? (5 points)