Lab 3

Cratering and the Lunar Surface

3.1 Overview

This exercise begins a two-exercise module exploring evolutionary processes on terrestrial surfaces. It contains a hands-on cratering activity, an analysis component in which students fit multiple models to their data and determine which physical model best reproduces the observed trend between projectile velocity and crater size, and a cratering simulation which enables them to predict the effects of various solar system projectiles impacting here on Earth (duck!).

Students begin by studying the lunar cratering record through surface images obtained through the National Aeronautics and Space Administration (NASA) Lunar Observer and other missions. They then create a series of craters by dropping ball bearings onto sand from varying heights. Seven craters are measured for each drop height, allowing us to reinforce the lessons from the first two laboratory exercises about averaging multiple trials in order to improve statistics. Drop heights range from one to thirteen feet, but safety is emphasized very strongly. Students are told to work at the highest heights only if they have access to a staircase with a solid banister, and otherwise to limit their activities to the lower range. This message is driven home in the project chapter, and also proactively modeled by student actors in the supporting video tutorial.

After converting drop heights to impact velocities, students plot velocity against crater diameter in a specialized plotting tool. Note that the interfaces for our general and our specialized plotting tools are as similar as possible, so that once students have been exposed to one of these tools they can recognize the common elements in the others. This tool performs a fit to the data for three models: projectile diameter proportional to projectile velocity, diameter proportional to velocity squared, and velocity proportional to diameter squared.

All three models are discussed and motivated in the chapter text, leaving the students to choose a best-fitting model by examining their data and the model curves. We expect them to evaluate the fits via two different methods. They are provided with RMS deviations for each model, and based on the ideas introduced in exercise one and reinforced in exercise two they are expected to associate the lowest RMS value with the best-fitting model. More fundamentally, however, we want students to be able to look at the plot and decide which line runs the closest to the centers of the points by eye. This skill is very under-developed in our students, many of who appear to have never read a plot in this fashion before. Though this is not a difficult task, it is not an intuitive action for them. We thus encourage them to assess the fits directly for themselves, and then to use the RMS deviations to confirm their model choices.

3.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Appreciate that cratering has been an important process in shaping the appearance of the Moon's surface, and in shaping planetary surfaces in general.
- Distinguish between the heavily cratered, older lunar highlands and the younger, smoother and darker lunar maria.
- Understand both relative and absolute dating techniques, and describe the types of data needed to apply either method to lunar features.
- Realize that the Moon's surface, unlike that of the Earth, has changed little in the last three billion years, and that the once-high cratering rate has decreased markedly.
- Describe first-hand the experience of creating impact craters, and using the resulting data to define a relationship between impact velocity and crater diameter.
- Recognize that studying cratering processes and lunar craters can increase our understanding of the Earth's impact history, and the likelihood of future impacts.
- Identify key factors that determine the environmental consequences of impacts here on Earth.
- Realize that a catastrophic impact due to a six-mile meteoroid 65 million years ago produced a large crater and quite probably led to the extinction of the dinosaurs.
- Connect the act of plotting two variables against each other to the process of studying their intrinsic relationship.

- Understand the relationship between a mathematical model and its representation as a curve or set of points on a plot of relevant variables.

3.3 Teaching Toffees

Teaching toffees are practical tips based on the hard-won experience of fellow instructors.

For all GEAS lab exercises:

Please have students access the list of components for the lab exercise (lab chapter, video tutorial, web applications, report template) directly from the GEAS website so that they use the current version of all tools.

By having them save and share the lab report template, they will have their work backed up automatically and instructors will be able to observe their progress 24/7. This allows instructors to check for appropriate progress towards intermediate goals over a two-week period, and for students and instructors to interact asynchronously through threaded comments placed in the report margins at exactly the point where a question occurs. Note that the Lab #1 video tutorial describes how to work with Google resources, and there is a two-page handout on the lab website as well.

Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

For Lab #3 in particular:

The three labs #1 (Fundamentals of Measurement and Error Analysis), #3 (Cratering and the Lunar Surface), and #4 (Cratering and the Martian Surface) can form a cohesive six-week sequence, particularly for classes which emphasize the solar system or geology.

The video for this exercise shows a group of three students working together to conduct the cratering experiment. They describe the use for each piece of equipment, review how to carefully measure a crater diameter along a ruler, and discuss the need to make a series of craters at each height to improve measurement accuracy.

Safety is prioritized, with the students placing their ball bearing within a small plastic canister (such as a pill bottle) before tossing it back and forth and also being careful to carry the projectile to increasing heights by ascending a stable, well-lit staircase with a solid handrail in a public area. All students must be informed that they may skip conducting the experiment from any heights (in particular for the final two positions at 10 and 13.3 feet) where they feel unsafe, and that they should not use a step ladder or anything else other than a stable staircase for this purpose.

The video also reviews how to enter data into the online plotting tool, and explains how to read the resultant plot with the data points presented on top of three possible model lines.

It then takes students through the process of using the Earth Impact Effects program to model the effect of crater impacts on our home planet. Note that this program is an external resource; we link to a workhouse version which operates through an HTML form, and a snazzier version which utilizes Flash. Both versions produce identical results for identical inputs.

This lab requires a roughly one foot diameter container filled with sand and a top layer of salt (or similar substances), and a ball bearing or marble. If students will work remotely, it is most helpful to let them know about these requirements at the beginning of the course so that they can plan ahead to secure appropriate materials. For students working remotely within driving distance of campus, it is beneficial if instructors are able to offer loaner kits of these items. The sand and salt can often be scooped out and reused over and over, as long as the salt is kept fairly clean and uniform in consistency. It is fine if a bit of salt gets mixed into the sandy lower layer over time.

When conducting this experiment in person with large groups of students, keep in mind that people can work through the first five heights (up to five feet) while simply standing next to their bucket (though having drop heights marked along a wall is helpful if possible). If instructors can set up stations along a staircase at the final three heights (6.7, 10, and 13.3 feet), students can then shift their buckets through those stations in turn fairly efficiently. One can gain an additional factor of two by having half of the group work with the Earth Impact Effects program before conducting the experiment and half do so afterward, if space and sand buckets are limited.

As a rule students do remarkably well conducting this experiment, and their data generally point fairly clearly to the expected model. If a student produces unexpected measurements (with huge scatter or matching one of the other models), the cause is most likely to be the use of a hard-packed material rather than something which is dry, loose, and granular as a surface. If a data set shows no trend with projectile height and the crater diameter is similar to the projectile diameter, the projectile has probably shot straight through the surface layer without interacting at all. If this happens with a steel ball bearing, then switching to a glass marble projectile can often solve the issue. Instructors may find requesting a photograph of a crater, or even a short video of an impact, to be helpful in diagnosing these issues.

The most common conceptual error made by students is to argue that their chosen model is correct because crater diameter increases with projectile velocity/height. It is helpful to emphasize that this trend occurs for all three models, and so does not serve to discriminate between them.

3.4 Keywords

Absolute dating – Absolute dating refers to the process of assigning absolute ages to physical samples (such as rocks) or to geologic events. These ages are usually based on radioactive decay rates.

Central peak – A central mountain peak is produced when molten excavated material from an impact blast flows back towards the center of the excavation and creates an uplift. This typically occurs at the center of large craters, those which are 40 kilometers or more in diameter.

Crater – A crater is a generally circular surface depression, caused by an impact or an explosion, a volcano, or a geyser.

Crystalline rock – Crystalline, or igneous, rock forms as molten rock cools and crystallizes. It is generally harder and denser than sedimentary rock. Granite is an example of crystalline rock.

Density – The density of a three-dimensional object is equal to its mass divided by its volume (or the mass per unit volume), and is typically measured in units of grams per cubic centimeter, or kilograms per cubic meter. The density of water is one g cm^{-3}, while rock is roughly three times more dense, and steel has a density of eight g cm^{-3}. to the surface density of features found on a planetary surface, for example, with units of counts (the number of features) per unit area.

Ejecta – Ejecta refers to a blanket of material surrounding a crater that was excavated during an impact event. The ejecta will become thinner at increasing distances from a crater.

Impact crater – An impact crater is one produced by the collision of an object with a planetary body's surface.

Kinetic energy – Kinetic energy is commonly referred to as energy of motion, and is equal to one-half of an object's mass times the square of its velocity.

Law of Cross-Cutting Relations – The law of cross-cutting relations states that any geological feature that cuts across another geological feature must be younger (must have formed later) than the feature it disturbed.

Maria – The lunar maria are the dark, smooth regions believed to represent ancient lava flows. They are generally younger than the heavily cratered highlands. They were immortalized in Bernstein and Sondheim's 1956 West Side Story.

Meteoroid – A meteoroid is a particle of rocky or metallic debris found in space. If a meteoroid enters the Earth's atmosphere it becomes a meteor, and upon landing any surviving remnant is called a meteorite.

Plate tectonics – Plate tectonics defines a theory of planetary surface dynamics in which a planet's outer skin (the lithosphere) is broken into plates. These plates are driven by internal heat, and shift and interact in various ways (including collisions).

Projectile – A projectile is an object that is launched or dropped into space, or into an atmosphere. It is sometimes called an impactor, once it has struck a surface.

Radioactive – An radioactive isotope of a particular element is unstable, and will decay into other elements and isotopes over time. We define the "half-life" of a radioactive sample as the amount of time in which half of its atoms will decay into another state. By comparing the relative amounts of various isotopes of key radioactive elements, we can often determine absolute ages for samples of various materials.

Rays – Rays are bright linear streaks extending radially outward from certain craters, most notably young ones like Tycho and Copernicus on the Moon. They indicate the presence of thin deposits of lighter material.

Relative dating – Relative dating refers to the process of placing an event along a time line relative to other events (before them or after them), without defining a specific time for any event.

Sedimentary rock – Sedimentary rock, such as limestone or sandstone, is rock that was originally laid down as horizontal sediment (deposited by water, air, or ice). Contrast it with igneous rock, which is formed by the cooling of molten rock.

Terraces – Terraces are stair-like levels in the sloped walls of craters.

Terrestrial – The term "terrestrial" means Earth-like or pertaining to the Earth's surface. Planets with rocky surfaces are sometimes called Terrestrial planets, in contrast to the Jovian gas giants.

Velocity – The velocity of an object is its speed in a particular direction. It has units of distance traveled per unit time, such as miles per hour, or centimeters per second.

3.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 12: The Terrestrial Planets. There are related materials in Chapter 6: The Origin of the Moon and Chapter 11: The Formation of the Planets.

3.6 References and Notes

1. The left-hand image in Figure 3.1 is a mosaic of lunar images collected by the Clementine spacecraft in 1994 [NASA/USGS/ASU]. All three images shown in Figure 3.1 are shown courtesy of NASA.

2. Figure 3.2 is a portion of a larger lunar orbiter image [NASA].

3. Figure 3.3 is an adaptation of a figure taken from D.E. Gault's 1970 article in Radio Science, volume 5, #2, page 277, with permission being given by Dr. Shane Bryne of the Lunar and Planetary Lab of the University of Arizona.

4. Figure 3.4 is composed of two lunar orbiter images of the Apollo mission landing sites (photo IV-125-H3 of Apollo 12, and photo IV-089-H3 of Apollo 16) [NASA].

5. The primary and secondary images in Figure 35 are #C223 and #N5818 from the Consolidated Lunar Atlas, of the Lunar & Planetary Institute [NASA].

6. The basis for the account of the Giordano Bruno crater study is

www.psrd.hawaii.edu/Feb10/GiordanoBrunoCrater.html

which is partially based on the following Plescia, Robinson, & Paige 2010 conference proceeding

www.lpi.usra.edu/meetings/lpsc2010/pdf/2038.pdf.

7. Figure 3.6 is a portion of a larger Landsat satellite image [NASA].

8. The Earth Impact Effects program is used courtesy of Robert Marcus, H. Jay Melosh, and Gareth Collins of Imperial College, London. Detailed information regarding the program can be found in Collins, Melosh & Marcus 2005 publication in Meteorics & Planetary Science, volume 40, #6, pages 817-840.

9. Certain physical measurements for the asteroid 99942 Apophis were taken from its Wikipedia entry.