Lab 4

Cratering and the Martian Surface

4.1 Introduction

Human space travel enthusiasts hope that our manned missions to the Moon will serve as stepping stones for an eventual trip to Mars. Our "visit" to the Moon in our previous lunar cratering laboratory exercise has prepared us similarly to visit Mars today. We have already learned that cratering is a key process in shaping the appearance of terrestrial planetary surfaces, and that counting craters can help determine the ages of surface features. We studied techniques used to decide which geological event occurred first, or which surface is younger (relative dating techniques), and also learned how to determine absolute ages based on radioactive dating of physical samples.

Lunar and Martian surfaces are similar in many ways (both types are heavily cratered in some places and covered with smooth ancient lava flows in others), but they exhibit several important differences. First, volcanic features on Mars are much more prominent than those on the Moon. Mars has the largest volcanoes in the entire solar system, and some of them have clearly become inactive only recently. (Some planetary scientists suspect that the largest Martian volcano of all, Olympus Mons, may still be active today.) Second, unlike the bone-dry Moon, Mars was once a very wet planet. Its surface contains channel and river delta-like features that were undeniably formed by flowing water in the past.

These differences lead us to two important questions. When did the last volcanic eruptions occur on Mars, and when did water last flow freely there? In this lab, you'll use crater counting techniques to help reconstruct a Martian surface chronology and investigate these questions.

These questions are important because they relate to how, and why, internal heat-driven volcanic processes differ on Mars and on Earth, and help us to form a coherent history of the

Martian climate. The evidence of widespread flows of surface water implies that Mars was once warmer and had a more substantial atmosphere. The current Martian atmosphere is so thin that it traps very little solar radiation, and provides less than 1% of the atmospheric pressure found at sea level on Earth. The resulting frigid temperatures make it impossible for liquid water to exist for very long at the surface, but it could be present in large quantities underground (along with ice deposits). These reservoirs could provide an important resource for astronauts, if people ever set foot on Mars.

4.1.1 Goals

The primary goals of this laboratory exercise are to explore the appearance of the Martian surface, qualitatively and quantitatively, to understand its geological and climate history, and then to use these data to contrast Mars with Earth and better understand similar evolutionary processes on the surface of our own planet.

4.1.2 Materials

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

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

You will also need a computer with an internet connection, and a calculator (or calculator app). Your primary activity for this exercise will be to analyze images of the Martian surface, so you do not necessarily need to print out any materials. (You can view this document, and the images, online, and enter your results directly into your online report template.)

4.1.3 Primary Tasks

This lab is built around three activities: 1) dating volcanic activity, 2) dating water-carved surface features, and 3) dating water floods caused by volcanic activity. You will analyze images of regions on Mars which have been captured by spacecraft.

4.1.4 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 within each section. The 19 questions in the body and the 6 final questions at the end of the laboratory exercise are each worth 3 points. Note that Section 4.9 (§4.9) contains 5 extra credit points.

Activity	Volcanic Activity	Water Features	Floods	Questions	Summary
Section	§4.4.2	$\S4.5.1$	§4.6.1	§4.7	§4.8
Page	12	19	23	25	31
Points	$10 \times 3 = 30$	$6 \times 3 = 18$	$3 \times 3 = 9$	$6 \times 3 = 18$	25

Table 4.1: Breakdown of Points

4.1.5 Timeline

Week 1: Read §4.1–§4.5, complete activities in §4.4.2 and §4.5.1, and begin final (Post-Lab) questions in §4.7. 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: Read §4.6, complete activities in §4.6.1, finish final (Post-Lab) questions in §4.7, write lab summary, and submit completed lab report.

4.2 Terrestrial Craters, Volcanoes, and Channels

Our solar system used to be a very violent place, marked by frequent collisions between careening proto-planetoids and randomly-moving space debris. This was especially true between 4.5 and 3.7 billion years ago, as the tumultuous level of activity within the solar system led to the formation of the objects that we know today as our planets, satellites, asteroids, comets, and other debris, moving along fairly regular orbits in a single orbital plane. We can identify heavily cratered surfaces on both the Moon and on Mars which date back to this time period, but we find no analogs here on Earth. Why is this so?

The Moon and Mars are both far less geologically active than the Earth. The Moon is considered to be inert, lacking internal heat-driven geological processes which could alter its surface. Mars is quite a bit more interesting in this regard. With a diameter more than twice that of the Moon, Mars has retained much more internal heat from the epoch of formation. However, internal heat-driven volcanic processes have apparently not periodically resurfaced the Martian surface as plate tectonic processes have done on Earth.

The Earth's surface is broken up into several large plates. Some carry continents and others oceanic crust, but they all float on hotter, partially molten rock found below. Plate interactions at the boundaries cause earthquakes and build mountains and volcanoes, and also form new crust while destroying the old. The entire Earth is thus continually being resurfaced, in a cyclic process with a period of 500 million years. Given such significant resurfacing, virtually all terrestrial craters which formed during the planetary formation era (a time period characterized by intense planetary bombardment) have long since been obliterated.

The Martian and lunar surfaces are thus covered with ancient craters, unlike that of the

Earth. But before you assume that the surfaces of these two worlds are very similar, we need to discuss an important difference. A significant number of Martian craters formed through volcanic activity, but most lunar craters were caused by impact events. Mars and the Earth are similar in this regard, as both have significant numbers of volcanic craters and impact craters. However, on Earth only the youngest craters (those which formed within the last few million years) have been preserved.

Figure 4.1 contains an example of a terrestrial volcanic crater, Oregon's Crater Lake. Like most calderas, it formed in the collapse of land following a volcanic eruption – in this case, after the eruption of Mt. Mazama some 8,000 years ago. Unlike most calderas, it is filled with water. As the surface of Mars is currently too cold to support liquid water, we are unlikely to find any Martian counterparts to Crater Lake. At best, we can point to the summit of pictured Martian volcano Ceraunius Tholus, with a caldera that we think once brimmed with water. The prominent deep channel that flows from the caldera's rim down to its base may have been carved by water (though lava flows or land collapse are also possible causes).

The Moon carries no such ambiguity – none of the channels were carved by water on this bone dry surface. The winding channel pictured below resembles a sinuous stream, but is actually the remains of a path where lava once flowed through a tube that later collapsed. At its center one finds a small lunar caldera, Hyginus, one of the few lunar craters which formed without an impact event. Note the telling absence of a raised outer rim (a common characteristic of impact craters).



Figure 4.1: Volcanic features on the Earth, Mars, and the Moon. The first panel showcases Crater Lake, Oregon, the second Ceraunius Tholus, Mars, the third Hyginus, Luna, and the fourth Mauna Kea, Hawaii. Note the wide variation in appearance between craters in different environments.

The largest Martian volcanoes are mountainous structures, with large, extended bases but relatively low profiles. They resemble warriors' shields in shape, and so are commonly called *shield volcanoes*. The image of Ceraunius Tholus in Figure 4.1 illustrates their typical appearance when viewed from above. These volcanoes form as lava flows associated with repeated, though not especially explosive eruptions, slowly build up layers and layers of material. Our Hawaiian Islands are the tips of a chain of such volcanoes. Mauna Kea, the largest member of the chain, is truly the tallest peak on Earth (as well as the home of some of the finest astronomical observatories in the world). If you factor in the submerged portion of its base, it is slightly taller than Mt. Everest. In comparison, Olympus Mons towers some seventeen miles above the Martian "sea level," three times the height of Mt. Everest. Why are Martian volcanoes so much taller than those of Earth? In part, it is easier to support and stabilize tall structures in a lower surface gravity environment. Recall, as well, that Mars lacks tectonic plate movement, so its volcanoes can nestle over sources of internal heat for billions of years without displacement, giving them plenty of time to accrete material. On Earth, the movement of crustal plates carries volcanoes away from such hot spots in just a few million years.

4.3 The Geological History of Mars

On stable terrestrial bodies like the Moon, Mars, and Mercury, impact craters are typically well-preserved, and ages for surface features from different regions can be obtained by comparing the number density of local impact craters. The longer a surface has been exposed to meteoric bombardment, the more impact craters it should display. Older surfaces should thus exhibit more impact craters than younger ones, as shown in Figure 4.2.



Figure 4.2: The Cratered Highlands (Noachian period, left panel), Lunae Planum (Hesperian period, middle panel), and Northeast Tharsis (Amazonian period, right panel) illustrate ancient, intermediate, and young epochs in Martian surface history. Each image is 300 by 500 kilometers in size. Note the correlation between age and the surface density, and size, of observed craters.

We can divide the geological history of the Earth into the Paleozoic (oldest), Mesozoic (intermediate), and Cenozoic (youngest) eras. Figure 4.2 illustrates three similarly broad periods in the geological history of Mars. It links their relative ages to crater density. Surfaces dating to the Noachian period (left panel) are the most heavily cratered, and older than those dating to the Hesperian period (middle panel), which themselves are older and

more cratered than the youngest, and most sparsely cratered, Amazonian surfaces (right panel). These three epochs were named after regions containing large-scale surface features that formed at these times, such as large craters, wide-spread lava flows, and extensive water-carved topography.

We briefly summarize Martian geological history below, characterizing these three time periods and attaching dates to each one. These dates are estimates of the number of years that have elapsed since each type of surface solidified from a molten state (lava). They are approximations, and could be improved substantially if we could travel to Mars and back to obtain physical samples (rocks) from the Martian surface and date radioactive isotopes within them.

Noachian Period

The Noachian Period (ranging from the planetary formation epoch 4.5 billion years ago to 3.5 billion years ago) was named for Noachis Terra, a vast highland in the southern hemisphere. Heavy bombardment left many craters, but widespread evidence of water erosion – most notably valley networks cut by slow-moving rivers – suggests that the surface was both warm and wet.

Hesperian Period

The Hesperian Period began as the intense Noachian bombardment eased, and lasted until roughly 1.8 billion years ago (the lower boundary age is uncertain, lying between 3.0 billion and 1.5 billion years ago). Named for Hesperia Planum, a high plain in the southern hemisphere, the Hesperian was marked by intense volcanic activity which covered many craters from the formation epoch. Olympus Mons dates back to this period, as do catastrophic releases of water, which carved channels in areas like the Chryse Planitia basin (where the Viking craft landed in 1976), and short-lived seas and lakes.

Amazonian Period

The Amazonian Period (from the end of the Hesperian to the present) was named for Amazonis Planitia, a low plain in the northern hemisphere. Amazonian regions have relatively few impact craters, but are otherwise quite varied in morphology. Lava flows, glacial activity, and minor releases of liquid water continued during this period, although it's likely that most of the Amazonian region was too cold to allow liquid water to exist at the surface.



Figure 4.3: This image is a Mercator projection of the entire Martian surface, with the north and south poles stretched out on the top and bottom, and east pointing to the right. Light blue circles indicate the locations of craters with diameters of 100 kilometers or more, and the red markings divide the surface broadly into four regions from the Noachian, Hesperian, and Amazonian periods, based on the density and size of identified craters. The location of Hadriaca Patera, in the Circum Hellas Volcanic Province, is marked with the initials "HP," as is Elysium Mons ("EM") in the Elysium Planitia and the Chryse Planitia ("CP"), and you'll thank us for pointing them out later. The Amazonian region extends over much of the northern hemisphere, while the southern hemisphere is divided into the Hesperian region and two prominent Noachian highlands (encircled).

4.4 Volcanic History of Mars

The southern hemisphere of Mars is dominated by highland regions, older and more heavily cratered than the low-elevation, sparsely cratered, and younger lands to the north. The vast lowland region has been smoothed by lava flows, though water may have also played a significant role in shaping and filling the surface.

Martian volcanoes range in age from the Noachian to late Amazonian. While they cover a significant portion of the entire surface, the most notable volcanoes occur in three regions, Circum Hellas Volcanic Province, Elysium Planitia, and Tharsis Montes. Circum Hellas has the least conspicuous volcanoes, but also contains the red planet's six oldest central vent volcanoes (including the Hadriaca Patera). These structures formed after the creation of the huge Hellas impact basin, some 4.0 billion to 3.6 billion years ago. Elysium Planitia is a heavily cratered, ancient, uplifted volcanic plain which features several large volcanoes that were active some 1.5 billion years ago. It also contains several long trenches (including Cerberus Fossae). There is no question that Tharsis contains the largest, most recently active, and most visibly stunning volcanoes, pictured in Figure 4.4.

Large volcanic shields form over hundreds of millions of years, encompassing generations of lava flows. Surface ages derived from crater surface densities thus indicate the elapsed time since the *latest* eruption, the one which erased any existing impact craters and "reset the clock" for the surface.

4.4.1 Geology and Crater Density Timescales

As we discussed in §4.3, we can estimate the ages over which various Martian surfaces have remained undisturbed by lava or water flows, or any other obliterative processes, by counting how many impact craters have accumulated over time. The age of a particular surface is proportional to the surface density of craters (the number per square area) it has collected. Because larger impact craters are created by larger impactors (meteoroids), which are more rare, we also expect to find lots of smaller craters, and fewer larger ones.

In this exercise, we will identify and count craters of various sizes on a variety of Martian surface terrains, and then derive age estimates accordingly. Planetary scientists use this technique to study the geological history of Mars, commonly examining impact craters which range in size from 16 kilometers (large, but very rare) down to a mere 16 meters in diameter. You might wonder how we could possibly identify 16-meter-wide craters on Mars, when it lies so far away from us. Give thanks to NASA's Mars Global Surveyor spacecraft, which scanned the surface in 1997, resolving exquisite structures as small as half a meter in size.

Figure 4.5 is based upon these fantastic data. This plot tells us how many craters larger than a certain limit we expect to observe per square area on the surface of Mars, for surface ages ranging back as far as the planetary formation epoch.

Let's work through an example together.



Figure 4.4: This 3,000-kilometer-wide image showcases just a quarter of the largest volcanic region on Mars, Tharsis, containing 12 large volcanoes which extend up to 10 kilometers in height. Find its distinctive line of three large volcanoes (like the three stars on Orion's Belt) on the left side of Figure 4.3. White colors indicate the highest elevations, descending down through reddish and then green layers. These gigantic structures are up to 100 times larger (in volume) than the largest volcanoes found here on Earth. The four largest, all shield volcanoes of similar height, are identified by name. Arsia Mons is shorter and less broad than Olympus Mons, but exhibits the largest caldera on Mars, with a diameter of 120 kilometers.

Example 4.1

Figure 4.6 is an image of the Martian surface, showing a light-colored background layer of rock which has been partially covered up with a darker, younger lava flow. If the lava flow is indeed younger than the background layer, it should be covered by fewer craters per unit area. Examine both surfaces now, and take a quick guess as to whether or not the darker region shows a lower surface density of craters. Now that you have done so, let's make a more detailed estimate.

The image is 3.325 kilometers wide and 2.260 kilometers high, so it extends over an area of 3.325×2.260 , or 7.514, square kilometers. We estimate that the lava flow covers 65% of the image, leaving 35% of the background layer, extending over surface areas of 4.884 and 2.630 square kilometers. We now count up the number of craters which are 63 meters or more in diameter, using the red circle in the upper-right hand corner of the image as a 63-meter standard. (You could fit fifty 63-meter craters across the width of the entire image; a single one is just larger than the outer rim of the letter "o".) We find nine 63+ craters in the dark region, and 15 in the background layer.



Figure 4.5: This figure shows the expected surface density of impact craters, in units of craters per million square kilometers, for Martian surfaces of various ages. The six lines represent densities for craters larger than 16 meters (black solid line), 31 meters (green dashed line), 63 meters (dark blue solid line), 125 meters (light blue dashed solid line), 250 meters (red solid line), and 500 meters (magenta dashed line). This is a logarithmic plot, so the ages and densities change by a factor of ten at each labeled point on the axis, extending from four billion years in the past up to a mere 10,000 years ago. Note that at any age we always expect to find more small craters than large ones, and that the younger a surface is the fewer craters it has had time to accumulate.

The dark region has a crater density of 9 craters per 4.884 square kilometers, or 1.84 craters per square kilometer, or 1.84 million craters per million square kilometers. Examining Figure 4.5, we find that a density of 1.84×10^6 puts us a small amount above the labeled point for one million (10⁶) on the *y*-axis, and we then trace across the plot until we intersect the dark blue line which indicates the expected density for craters equal to or larger than 63 meters in diameter at this same height. The point on the *x*-axis below this point lies at 2×10^8 years, indicating an age of roughly two hundred million years.

How do we read coordinates on a logarithmic axis? If you are reading Figure 4.5 on a computer screen, increase the document magnification to 300% to make it easier to read. Note that you can bring up a stand-alone image of this figure by loading the GEAS lab page into a web browser (see the URL on page 2 in §4.1.2), and clicking on the link labeled "Figure #5 (Surface density of craters versus age)." This will allow you to keep reading through the



Figure 4.6: In this 3.325 by 2.260 kilometer image, a young, dark lava flow (lower-left corner, image center) lies on top of a lighter, older surface (upper-left corner and right edge of image). The small red circle in the upper-right corner indicates the size of a 63-meter crater. There are significantly fewer impact craters on top of the young lava flow than on the background layer, as expected.

manual without jumping back to this key figure every time you need to reference it.

Each interval between labeled points on the y-axis corresponds to a factor of ten change in value. The points corresponding to y-values of 10^6 and 10^7 are labeled, and lines extend from each one to the right across the entire plot. If you look carefully, you will be able to count eight small tick marks between them. These correspond to the values 2×10^6 , 3×10^6 , and so on, up to 9×10^6 . Note that these tick marks are not equally spaced, so the distance between 10^6 and 2×10^6 is larger then the next space, between 2×10^6 and 3×10^6 .

The light region has a higher crater density – 15 craters per 2.630 square kilometers, or 5.70 million craters per million square kilometers. A density of 5.70×10^6 puts us a large amount (almost six out of eight tick marks) above the labeled point for one million (10^6) on the *y*-axis, and we then again trace across the plot and intersect the dark blue line for craters equal to or larger than 63 meters in diameter at this same height. The point on the *x*-axis below this point lies between six and seven hundred million years ago.

We thus find the background layer to have been in place for six or seven hundred million years, while the lava flow is a mere two hundred million years old. You will now utilize this same technique to date various Martian surfaces, starting with four linked to volcanoes.

4.4.2 Dating Volcanic Activity

Load the GEAS project lab exercise web page into a web browser (see the URL on page 2 in §4.1.2), and click on the link labeled "Web application #1 (Martian craters)." This will cause a new browser tab to appear, containing a web application that we will use to examine images of the surface of Mars. You will be using this tool to identify the density, and locations and sizes, of craters in different regions on Mars.

Look over the entire screen carefully first, and make sure that you understand the options available to you. General options are shown in a row across the top of the screen: these allow you to make a printout (a paper copy) of your images, or to save copies as JPG- or PNG-format image files on your computer disk. By clicking on the button labeled "Help" you will get a quick run-down on the tool options and purpose, and "Credits" will tell you a bit about the creator.

You should always click on the "Help" button when you examine a new web application, as your initial questions may be answered there. Please do so now. In addition to these instructions, you may find it useful to note that when you are in the process of shifting the location or size of a given crater, many of the general options will be grayed out (unavailable). To access them, just click on the "save feature" button on the left in the Update Features Panel, or type the letter "s".

Be aware that if you type the letter "b" and then shift the location or size of a feature using the keyboard, the effect will be ten times larger than normal. (Just as in the stories, your strength will be the strength of ten because your heart is pure – and because you typed "b"!) This is particularly useful when the default feature size is much smaller than a given crater and you want to increase the size of your feature to match the crater with as few actions as possible. A well-marked crater should have a circle superimposed as closely as possible on its outer rim.

After loading an image by selecting it from the pull-down menu at the top of the screen and to the right, you'll find and identify all of the craters larger than a certain size within it. You may choose to increase the size of your circular features to overlap the crater rims, but this is not necessary, as we are simply interested in the *number* of craters equal to or larger than a given size. Note that the tool will not allow you to draw circles smaller than the limiting size of the field.

As you mark craters, a table to the right of the image will fill in with the locations and sizes (in meters) of your marks. Once you have identified all of the appropriate craters on a given image, you can divide the number of craters by the surface area of the displayed region, deriving a local surface density of craters. You should also save a copy of each annotated image and the list of craters to your local disk (with the "Save" command), to use in your lab report. Your instructor may ask you to include these figures for all ten fields, or for a subset of them.

We will examine four volcanic regions of interest with the web-app. As you work, keep in

mind that we are counting the number of impact craters, those with well-defined, raised rims, not all craters. Skip any craters which you think formed through volcanic activity (like Ceraunius Tholus, shown in Figure 4.1), or through the collapse of a valley or tunnel (like Hyginus crater, also shown in Figure 4.1). If a crater lies partially on an image, you may choose to include it if more than 50% of the outer rim appears.

Let's start with a few quick questions related to Figure 4.5, to help everyone to become comfortable with using it. You can give your answers to the nearest power of ten.

1. Over the last billion years, there have been ______ times fewer 500+ meter impact craters than 250+ meter ones, and ______ times more 63+ meter than 250+ meter ones.

2. A billion-year-old surface should have ______ times more 125+ meter impact craters than a million-year-old surface.

3. The density curves for the smallest size craters are flat between four and one billion years, because there were so many impact events at that time that you couldn't incur one without rubbing out a former crater. Is the same trend true for 250+ and 500+ meter craters, and if not, why not?

<u>Hadriaca Patera</u>

Reload the first image from the pull-down menu in the Martian craters web application, and examine the area around Hadriaca Patera. One of the oldest central vent volcanoes on Mars, this ancient shield volcano is located in the Circum-Hellas Volcanic Province. The volcano occupies most of the color image on the left of the web-app (labeled "view of the surrounding area"), and the black-and-white image on which we will mark craters is a magnified view of a portion of the floor of the volcanic caldera (shown as a small red square on the color image).

4. Mark all craters equal to or larger than 500 meters in diameter on the black-and-white image, and then use your measurement of the crater surface density and Figure 4.5 to derive an age for this surface.

Examine the surface features carefully as you work. Avoid the temptation to include craters which are "just a bit" smaller than the size limit, such as the 411-meter crater at (22.7%),

20.4%) in the lower-left corner, and the 445-meter crater at (60.4%, 93.3%) near to the top edge of the image. To find the craters at these coordinates easily, note that the image is 15.42 kilometers wide (running from 0 to 15420 meters from left to right), and also 15.42 kilometers high (running from 0 to 15420 meters from top to bottom).

There are also several structures on this image that are not impact craters. The extended, dark-floored feature in the upper-right corner at (94.4%, 97.1%) has a non-circular shape and an irregular "rim" which may be part of a mountain chain, while the dark floor could be an ancient lava flow. A smaller feature on the left edge at (5.3%, 48.4%) reveals the shadow of a mountain peak bounded by a couple of very small impact craters that together give the illusion of a larger, roughly circular, impact crater.

As you examine the entire series of images, keep an eye out for features like these which might contaminate your impact crater samples. On each image, as you complete the task of marking craters go back and re-examine the list you have assembled, to double-check that you are satisfied with each decision. If you are particularly uncertain about classifying a particular feature, make a note of your concerns (and the structure coordinates) in your lab report.

Justify your final answer, by showing your work for each stage of the problem and describing your intermediate results (as in the following example).

Example 4.2

The black-and-white image is 15.42 kilometers wide and 15.42 kilometers tall, as noted in its title, so it has an area of $15.42 \times 15.42 = 237.78$ square kilometers. If you had found ten craters with radii greater than or equal to 500 meters on this image, then you would derive a surface density of 10 craters per 237.78 square kilometers, or 10/237.78 = 0.042056 craters per square kilometer, or 42,056 craters per million square kilometers. From Figure 4.5, this density (y-value) suggests an age of 3.0 billion years (x-value) for this surface.

Large craters are easier to identify than small ones, so a large size limit means that the process of identifying craters is more straight-forward. However, large craters are rare, and so the derived crater densities can vary greatly if just one more, or one less, large crater happens to have formed within your sample region. To determine surface ages from the distribution of the largest craters, one needs to spend lots of time studying fields which are as large as possible, in order to build up solid statistics. For a young enough surface, there may not be any large craters yet to find!

Small craters are reliable measures of surface ages, because there are so many of them. If you have counted 1,000 craters in a single field, for example, then being off by one or two craters won't bias your results very much. However, it is difficult to identify small craters reliably, because at the smallest size scales small variations in terrain (gullies and small depressions) tend to resemble small impact craters.

5. Your age estimate for Hadriaca Patera is based on the density of craters equal to or larger than 500 meters in size. Why did we select that size limit for this image? We asked you to focus on 500+ meter craters because there are enough of them present in a field of this size and this age to give a statistically useful answer. How would your age estimate change if you studied craters down to a limit of 250 meters?

To save you some time, we will tell you that we found 80 craters 250 meters or larger in diameter in the Hadriaca Patera image. Calculate a second age estimate based on these craters, and compare it to your first value. Do they agree?

Pavonis Mons

One of the three large shield volcanoes of the Tharsis Montes, the volcano again occupies most of the color image, while the magnified black-and-white image covers a portion of the floor of the volcanic caldera.

^{6.} Mark all craters equal to or larger than 63 meters in diameter on the black-and-white

image, and then use your measurement of the crater surface density to derive an age for this surface. Show your work.

Arsia Mons

Another one of the three large shield volcanoes of the Tharsis Montes, the volcano again occupies most of the color image, while the magnified black-and-white image covers a portion of the floor of the volcanic caldera.

7. Mark all craters equal to or larger than 63 meters in diameter on the black-and-white image, and then use your measurement of the crater surface density to derive an age for this surface. Show your work.

Olympus Mons

Olympus Mons is possibly the largest volcano in the solar system. The western scarp of this huge shield volcano, with a diameter of 600 kilometers at the base, is shown in the web-app

view of the surrounding area. The magnified region in which you will mark craters covers the most recent lava flows in the area.

8. Mark all craters equal to or larger than 16 meters in diameter on the black-and-white image, and then use your measurement of the crater surface density to derive an age for this surface. Show your work.

9. Which crater field was the most difficult for you to mark, and which was the most straightforward? Is there a connection between the terrain of the surface being sampled and the accuracy with which craters are identified? Does it matter how small the minimum target crater size is, or how well-resolved the image is (the size of the smallest physical structure which can be observed on it)?

10. Consider the information given in the text, and Figures 4.3 and 4.4, and explore whether your age estimates for all four volcanic regions agree or disagree with the time line established for the three major epochs of Martian surface evolution.

4.5 Surface Water Flows on Mars

We can count craters to estimate time intervals since lava flowed on surfaces, and we can apply the same technique to dating features carved by flowing water. In addition to exploring how much time has passed since water was found in a liquid state on the surface, we would like to know how much water there was, and for how long it was present. Just as we contrasted Martian volcanic mountains to terrestrial ones, we will compare the behavior of Martian water to that of terrestrial oceans, rivers, and catastrophic floods.

Mars exhibits a wealth of water-carved topographic features, and so planetary scientists hypothesize that a major portion of the surface was once covered by a large ocean. The data suggest that 3.5 billion years ago, roughly one-third of the surface, centered in a flat, lowelevation region in the northern hemisphere, lay underneath a small ocean (with a volume one-tenth that of the Earth's oceans). The evidence includes delta-like regions where rivers may have emptied into the ocean, and relics of ancient shorelines. While we will not test this hypothesis directly, we will investigate two types of water-carved features, valley networks and outflow channels.

Earth contains many large rivers such as the Mississippi and the Colorado, which drain huge watersheds and create networks of valleys. Outflow channels are less common here, though found, for example, in the scablands region of eastern Washington. These channels were produced by repeated flooding at the end of the last ice age 14,000 years ago, as the glacial Lake Missoula drained abruptly. While the river topography associated with valley networks takes millions of years to develop, outflow channels can be created by floods on a time scale of mere days.

Martian valley networks were formed by slow-moving, relatively long-lasting Martian rivers,

associated with atmospheric water cycles of rain and snow. The most mature have highly developed, integrated branching patterns of tributaries. Some can be described as fretted channels, or long, relatively wide valleys with flat floors and associated tributaries, which gradually increase in size over large distances. Some of the most well-known include Nirgal Vallis, Echus and Melas Chasma (both in the Valles Marineris region), and Warrego Valles.

Outflow channels are formed by catastrophic floods involving huge amounts of water and occurring over brief periods of time. They feature streamlined teardrop islands, longitudinal grooves, terraced margins, inner channel cataracts, and generally chaotic terrain. They can be tens of kilometers wide and more than a kilometer deep, indicating significant erosion. Tiu Vallis is an excellent example of a typical outflow valley, as are Ares Valles and Maja Valles. Most such structures are found in the northern hemisphere near to the Chryse basin, almost three kilometers below the average surface level for the planet.

Which of these two types of water-carved features is older? The valley networks appear to date to the Noachian era, when the young Martian atmosphere was thicker and the climate both warmer and wetter. In this ancient era, rivers flowed freely into oceans and large lakes. As the thin Martian atmosphere slowly seeped away, however, the air dried and cooled, and the rain and snow that sustained these rivers ended.

As Mars shifted from the Noachian to the Hesperian Period, sustained water flow and rivers had ground to a halt, but significant amounts of water still remained, bound up in large lakes. Imagine such a reservoir, one lying at a slightly higher elevation than its surroundings. If a natural dam broke, the sudden release of water could easily carve out outflow channels. This is one likely hypothesis for their creation. We think that this is how the Hesperian Period topology formed in the Chryse Planitia basin region, for example.

These hypotheses suggest that Hesperian outflow channels should be younger than Noachian valley networks. In the next activity, you'll test this idea by estimating the ages of representative examples of both type of features.

4.5.1 Dating Valley Networks and Outflow Channels

Nirgal Vallis

Nirgal Vallis is one of the longest valley networks on Mars. It covers almost 500 kilometers, and tends to have short tributaries which end in steep-walled valleys.

1. Mark all craters equal to or larger than 500 meters in diameter on the black-and-white image, and then use your measurement of the crater surface density to derive an age for this surface. Show your work.

Look closely at the somewhat non-circular 811-meter feature at (9.8%, 14.4%) in the lowerleft corner of this image. The prominent upper-right flank (between the 11 o'clock and 3 o'clock positions) may indicate that the entire structure was first raised up and then later collapsed, suggesting that it was not created by an impact event, but is of volcanic origin. 2. A crater is observed to cut through the Nirgal Vallis in the view of the surrounding area, suggesting that this water-carved valley is (older / younger) than the crater.

<u>Tiu Vallis</u>

Tiu Valles is a typical outflow valley, and one of the major outflow channels leading to the Chryse Planitia basin.

3. Mark all craters equal to or larger than 250 meters in diameter on the black-and-white image, and then use your measurement of the crater surface density to derive an age for this surface. Show your work.

Warrego Vallis

Warrego Valles is an example of a mature valley network, and roughly resembles similar structures found here on Earth.

4. Mark all craters equal to or larger than 500 meters in diameter on the black-and-white image, and then use your measurement of the crater surface density to derive an age for this surface. Show your work.

Ares Vallis

Ares Valles is an example of an outflow channel; note the tremendous amount of smallscale structure shown in the area surrounding our crater-marking region. Like Tiu Vallis, it connects to the Chryse Planitia basin.

5. (a) Mark all craters equal to or larger than 250 meters in diameter on the black-and-white image, and then use your measurement of the crater surface density to derive an age for this surface. Show your work.



Figure 4.7: A 16.4-kilometer-wide image of the Ares Valley, showcasing a dramatic teardropshaped island and the evidence of ancient water flows which surrounds it. The impact responsible for the large crater in the lower-right corner may have also formed numerous smaller craters in the upper-right corner, as surface materials were ejected at the impact site.

(b) Figure 4.7 shows a slightly larger region in the Ares Vallis (you may recognize the lower-left quadrant of the image as the region in which you just marked craters). Note how the teardrop-shaped island which crosses the region presented a wide face to the oncoming flow of water, but was then thinned out (forming a long, protected tail) downstream. Water flowed into this region from the (lower / upper) - (right / left) corner, and exited via the (lower / upper) - (right / left) corner.

6. Based on your estimates of the ages for these four water-carved surfaces, (outflow channels / valley networks) are older. Explain your answer.

4.6 Fire and Ice on Mars

There is an alternate scenario which suggests that some Martian outflow channels may have formed in even more recent times. In the Amazonian Period, it become too cold for surface water to exist in liquid form. Suppose that a large body of ice was present, however, elevated slightly above the surrounding terrain and located near to a dormant volcano. Imagine the volcano rekindling, in an event worthy of a blockbuster summer disaster movie (lava flows threaten a home for orphaned puppies on Mars – who will come to their rescue?). Volcanic magma would heat and melt the ice reservoir, causing the newly liquefied water to burst through its boundaries. This sudden flood could then carve out a series of very young outflow channels.

You will next examine two regions that may have formed in this fashion. Dao Vallis lies near to the ancient volcano Hadriaca Patera. You estimated the age of one of its earliest lava flows earlier, and now will study an outflow channel which may have formed due to a much more recent eruption event. Cerberus Fossae is thought to be an even younger surface. Your age estimate will be of considerable interest, since evidence of both local volcanic activity and water flows suggest that both forms of activity may have occurred quite recently on Mars.

4.6.1 Dating Water Floods Caused by Volcanic Activity

Dao Vallis

Dao Vallis is a large outflow channel that starts on the southeast flank of the large ancient volcano Hadriaca Patera and runs for 1,000 kilometers into the Hellas impact basin.

1. Mark all craters equal to or larger than 250 meters in diameter on the black-and-white image, and then use your measurement of the crater surface density to derive an age for this surface. Show your work.

Cerberus Fossae

Fissures in the Cerberus Fossae region cut sparsely cratered plains. These cracks are thought to be volcanic in origin, where magma rose up from below.

2. Mark all craters equal to or larger than 16 meters in diameter on the black-and-white image, and then use your measurement of the crater surface density to derive an age for this surface. Show your work.

3. How do the ages of these two outflow channels compare to those studied in §4.5.1?

4.7 Final (Post-Lab) Questions

1. Astronomers can learn a lot about conditions on all sorts of terrestrial bodies (planets and satellites with solid surfaces) without visiting them, by examining their cratering records. Figure 4.8 contains images of four Jovian moons, all with thin atmospheres (too thin to protect them from meteoroids). Examine the images and then answer the following questions based on your observations.

(a) Sort the four surfaces from oldest to youngest. Why did you rank them in this order?

(b) Which moon(s) are most likely to be geologically active, and why?



Figure 4.8: Images of the surfaces of Jovian moons, heavily cratered Callisto (upper-left), icy Europa (upper-right), rocky, icy Ganymede (lower-left), and volcanic Io (lower-right). The surface terrains reflect a wide range of geological histories.

2. Figure 4.3 suggests that the two hemispheres (northern and southern) of Mars are made up of surfaces with significant differences in age (one hemisphere is much older than the other). Let's test this hypothesis, by creating histograms of all craters equal to or greater than 10 kilometers in size for each hemisphere. Load the GEAS project lab exercise web page into a web browser (see the URL on page 2 in §4.1.2), and click on the links labeled "List #1 (Southern hemisphere craters)" and "List #2 (Northern hemisphere craters)." Use these two lists to create two histograms, each one counting the total number of craters in a single hemisphere, with our plotting tool: "Web application #2 (plotting tool)."

Do the two histograms support, contradict, or in no way relate to the hypothesis? Explain your reasoning. Make sure to label the axes of both plots, and save the plots so that you can include them, with appropriate figure captions, in your lab report. 3. Could you distinguish between a billion-year-old surface and a 3.5-billion-year-old surface by counting the surface density of craters with diameters equal to or greater than 16 meters? If so, how? If not, why, and what simple change could you make to your approach to do so? What results (specific values for your measurements) would you expect for each surface?

4. Figure 4.9 shows a portion of the caldera at the summit of Ceraunius Tholus. The image contains many circular depressions, but it is difficult to ascertain whether they are impact craters, volcanic craters, or structures which formed otherwise, through the collapse of terrain. Many do not show the raised rims characteristic of impact craters, and the data are ambiguous. You could derive an age for the surface by assuming that all of the craters were caused by impactors. If you then realized that half of them were interlopers (volcanic or collapse features), how would your answer change – would your derived age increase or decrease, and by how much? Explain your answer. You should find Figure 4.5 to be helpful in answering this question.

5. Consider three possible sources of error that might affect your measurements of impact crater densities (and derivative ages) in this exercise: (1) a natural variation in the number and size of craters created in various locations across the planet, due to variations in the meteor distribution across the sky and with time, (2) measurement errors, in which you count ghost craters or miss real craters, or under- or over-estimate crater diameters, and (3) systematic errors.

(a) Recall that a systematic bias is one which acts to either increase, or to decrease all of your measurements together (like leaving people's shoes on when you measure their height). Describe a possible systematic bias which might affect the measurements of impact crater densities that you made in this laboratory exercise.



Figure 4.9: A 4.5-kilometer-wide image of part of the caldera at the summit of Ceraunius Tholus, showing ambiguous crater-like shapes that may be impact craters, volcanic craters, or depressions caused by other evolutionary processes. Perhaps it is Mars, and not the Moon, which is made of (Swiss) cheese!

(b) If you find four 63+ meter craters in a ten-square-kilometer field, what age would you derive for the area? If you found two in the adjacent ten square kilometers, what age would you derive from that field? What is the difference between your two estimates, in years?

If you then expanded your field size and found 4,000 63+ meter craters in a ten-thousand-square-kilometer field and 3,937 in a neighboring field of the same size, what ages would you now derive, and what would the difference be, in years?

What can you conclude about the importance of field size in determining surface ages? You may notice that the difference in crater counts between adjacent fields of the same size is roughly the square-root of the number of counts in this example. In the first case, $4 - \sqrt{4} = 4 - 2 = 2$ craters, and in the second case, $4,000 - \sqrt{4,000} = 4,000 - 63 = 3,937$ craters. Because the first set of fields are a thousand times smaller than the second set (10 versus 10,000 square kilometers), the crater counts are roughly a thousand times smaller as well - 4 versus 4,000 craters. As the surface density, and the surface age, is derived from the crater density per unit area, it need not change just because we change the size of our field. This is an example of a Poisson process, which is very common in nature, and in this case is driven by the natural variation, or randomness in the rate at which meteoroids impact the surface in various locations. The more impacts you examine, the smaller the variation in their distribution due to randomness becomes.

6. The geological history of Earth has been controlled by both gradual and short-lived, catastrophic processes. Some think that the landscape developed slowly over long periods of time, in response to a variety of slow geological processes, while others maintain that unusual, short-lived and energetic events have had a hugely significant effect on our history. Which of these two models best explains the formation of Martian valley networks, and which best explains the formation of Martian outflow channels?

4.8 Summary

After reviewing this lab's goals (see §4.1.1), summarize the most important concepts explored in this lab and discuss what you have learned. (25 points)

Be sure to cover the following points.

- Describe the appearance of the Martian surface, identify the primary drivers for its surface evolution, and explain the scientific basis for our conclusions regarding the ages of features.
- When did the last volcanic eruptions occur on Mars? Use your own age estimates for various regions to explain your answer.
- When did water last flow freely on Mars? Connect your answer to global changes in the planetary climate, and again use your own age estimates for various regions to explain your answer.
- Include the plots of Martian surfaces on which you marked craters, and the lists of the craters which you marked, for the fields requested by your instructor.
- How can studying geological process on Mars increase our understanding of the Earth's history, and its future?

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

4.9 Extra Credit

There are two notable craters in the Southwest, found near to Flagstaff, Arizona and named Barringer and Sunset. Research them, explain their respective origins, and compare their sizes and ages to those for craters of similar origins found on Mars. (5 points)