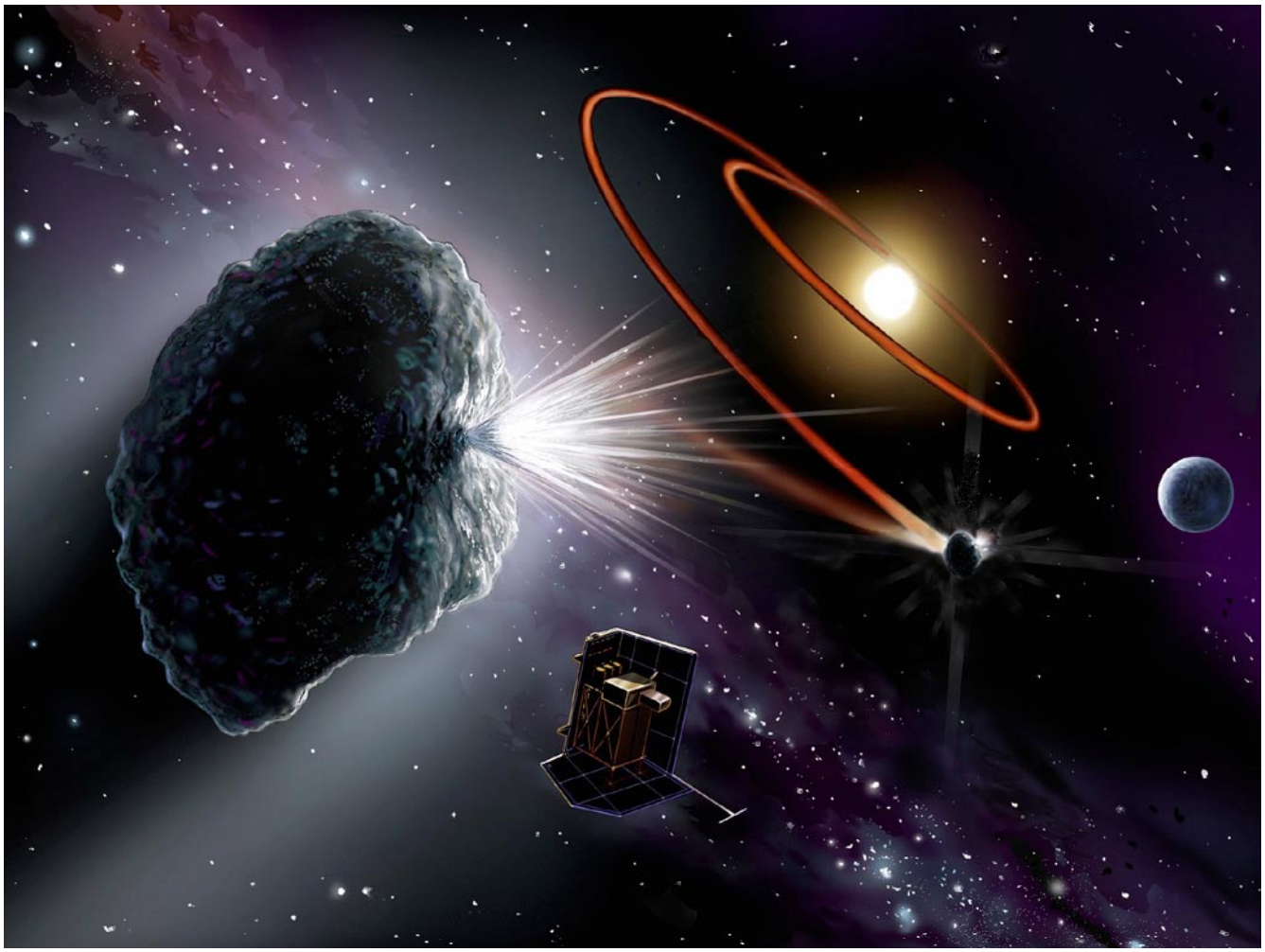
Educational Product	
Educators & Students	Grades 8-10

Excavating Cratering

A Deep Impact Educators' Guide



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Gretchen Walker

Module at a Glance

Overview: *Excavating Cratering* is a two to three week student inquiry into the question "How do you make a 7 story, football field sized crater in a comet?" The lessons are designed to provide students with experience in conducting scientific inquiries, gain a greater understanding of scientific modeling and get the students involved with the excitement of a NASA mission in development.

Table of Contents

Notes on Format

Each of the activity instructions follow the same basic format
Overview: few sentence summary of the activity
Standards: the specific standards addressed in the activity
Estimated Time Requirement: Estimated time needed to complete activity
Materials: List of materials needed for the lesson
Background: Brief applicable scientific background information
Teacher Procedures: Step by step instructions for carrying out the lesson.
Student Anticipations: Some hints as to what you might expect from your students in this activity, things to watch for, beware of, and encourage.
Student Handouts, Teacher Overheads, Rubrics: Most handouts and other support material needed for the lesson can be found

Basic Cratering Experiment Supplies

- trays (tin foil baking pans or other such containers, the deeper the better)
- sugar or sand
- meter sticks
- balances
- collection of objects to use as projectiles - ball bearings, styrofoam balls, superballs, clay, etc

Introduction

Excavating Cratering is a two to three week student inquiry into the question "How do you make a 7 story, football field sized crater in a comet?" The lessons are designed to provide students with experience in conducting scientific inquiries, gain a greater understanding of scientific modeling and get the students involved with the excitement of a NASA mission in development.

What's different about this module?

Cratering is a favorite topic for space science teaching. Many interesting activities have been developed for other NASA missions and other curriculums. So why do another cratering module? The Deep Impact team believes that the most important thing that a NASA mission has to offer the classroom is a look into the process of scientific inquiry in action. This module is designed to give students and teachers a structure for investigating one of the questions facing Deep Impact's mission design team, "How do you make a crater on a comet?" This module is designed to use some aspects of the familiar "drop the ball bearing in the flour" cratering activities as a launching pad for an exploration of the nature of ongoing science investigations and the development of students' inquiry skills. This module also takes these explorations a step further by doing some mathematical modeling with the results, and discussing the limitations of low energy classroom impacts as models of high energy solar system impacts.

Overview of module

The activities are designed to model one path that a scientific inquiry might take. The students will begin by brainstorming what factors might influence crater size and doing some initial experimentation and exploration. They will evaluate their suggestions and describe their initial ideas about cratering phenomena. Next, they will design their own experiments, testing one of the possible factors. Emphasis will be placed on experiment design, limiting the test to one variable, and quantifying the experiment.

After analyzing the data for patterns that might be used to predict crater size from initial variables, the students will test those predictions, use the results to refine their methods of prediction, and try again. The students will discuss the advantages and limits of scientific modeling as they compare their own low energy simulations, the work of Deep Impact Science Team cratering experts, and cratering on a solar system scale.

Finally, the students will use current information about comets, and the patterns they derived from their own investigations to give their best answer to the initial question. These answers will be submitted to the Deep Impact Education and Outreach team.

Why this approach?

The National Science Standards place a high value on inquiry in the science classroom. The first content standard for all levels, K-12, is "All students should develop abilities necessary to do scientific inquiry and understandings about scientific inquiry." The first science teaching standard begins with "teachers of science plan an inquiry-based science program for their students". Inquiry is often discussed in teacher preparation programs as one of the preferred methods of instruction. Yet, inquiry does not exist in equal prevalence in the classroom. Most science teachers can list reasons for the discrepancy immediately. Inquiry takes more classroom time. Inquiry is difficult to assess. Inquiry creates a heavy planning burden. It is difficult to operate in an inquiry mode and have a classroom that "looks like" what teachers and administrators often expect a classroom to "look like". This unit has been designed as an example of one example of what inquiry in the classroom might look like.

Cratering is a phenomenon that students have lots of ideas about. Most have experience with throwing things against each other and the results of those collisions. This module allows students to explore their own ideas about how cratering might work. They design experiments and look for patterns in the data, not trying to match a set outcome from the text book, but to try to reconcile their understanding of what they think will happen with what they see. *It is important to note that the designers of this curriculum believed that the primary goal of this module is to teach students methods of science inquiry, rather than develop a full modern understanding of cratering.* The students explore and refine their own ideas, rather than "discover" the "correct" answers.

Standards Addressed

National Science Education Standards	From the content standards for Grades 5-8
All students should develop the abilities necessary to do scientific inquiry	• Identify questions that can be answered through scientific investigations • Design and conduct a scientific investigation • Communicate scientific procedures • Develop descriptions, explanations, predictions, and models using evidence • Formulate and Revise scientific explanations and models using logic and evidence
All students should develop understandings about scientific inquiry	• Scientists usually inquire about how physical, living, or designed systems function • Scientists rely on technology to enhance data • Results of scientific inquiry emerge from different types of investigations and communications between scientists.
All students should develop an understanding of transfer of energy	• Energy is a property of many substances and is associated with heat, light, electricity, mechanical motion, sound, nuclei, and the nature of a chemical. • Energy is transferred in many ways
All students should develop an understanding of the Earth in the solar system	• The earth exists in a system that includes smaller bodies such as comets and asteroids
Principals and Standards for School Mathematics	From the algebra and data analysis standards for Grades 6-8
All students should be able to develop inferences and predictions that are based on data	• Make conjectures about possible relationships between two characteristics of a sample on the basis of scatter plots of the data and approximate lines of fit; • Use conjectures to formulate new questions and plan new studies to answer them.
All students should be able to understand patterns, relations, and functions	• Represent, analyze, and generalize a variety of patterns with tables, graphs, words, and, when possible, symbolic rules;
All students should be able to analyze change	• Use graphs to analyze the nature of changes in quantities in linear relationships.
All students should be able to use mathematical models to represent and understand quantitative relationships	• Model and solve contextualized problems using various representations, such as graphs, tables, and equations.

Acknowledgements

This module was made possible by the efforts of a team of educators, scientists, and students. Thank you to the teachers and students who gave their time and energy to initial pilot tests of this material: Stacy Satkofsky and the students of Lackey High School; Daniel Levin and the students of Walter Johnson High School; Tom Stickles and the students of Northwestern High School. Without your time, effort, patience, ideas, and reports, this module could not have been completed. Dr. H. J. Melosh and Dr. Peter Schultz of the Deep Impact Science Team have my gratitude for invaluable contributions to the content and editing suggestions. Thank you to Dr. David Hammer, my advisor in the College of Education, for input at all stages of development and many hours of discussion both in class and out about inquiry, teaching, and education in general. Finally, I would like to extend my gratitude and thanks to Dr. Lucy McFadden, Deep Impact's Education and Public Outreach Manager, for providing me with support and allowing me opportunity and the freedom to develop this module. Thank you!

Gretchen Walker
University of Maryland
College Park, MD
June 19, 2001

Thinking About Cratering

Overview:

This is the students' introduction to the Deep Impact Mission and the project on which they are embarking. This will provide a connection between the real scientists on the mission and the students in the classroom. This activity also includes some initial free-form investigation of factors involved in determining crater size.

Standards:

Students will develop understandings about scientific inquiry (National Science Education standards 5-12)

- Scientists usually inquire about how physical, living, or designed systems function
- Scientists rely on technology to enhance data
- Results of scientific inquiry emerge from different types of investigations and communications between scientists.

Students will develop abilities necessary to do scientific inquiry (National Science Education Standards 5-12)

- Identify questions that can be answered through scientific investigation

Estimated Time Requirement:

Two 50 minute periods

Materials:

- Letter from the Deep Impact Science Team
- Images of Cratering in Solar System - found in Appendix #1
- Student Handouts: Exploring Cratering, Comet Research
- Student Journal Assignments #1 and #2
- Cratering experiment materials - see list at beginning of module

Background

This lesson introduces both the mission and the concept of cratering to your students. For more information about the mission visit the web site at http://deepimpact.jpl.nasa.gov. You can find a brief summary of our modern understanding of cratering in Appendix 2.

Teacher Procedures:

Day 1

1) Hand out the Deep Impact invitation letter to the students and read through it together as a class.
2) Present any additional information from the Deep Impact Fact Sheet you judge to be interesting and relevant.
3) Explain that, as stated in the letter, the students will be focusing on the problem of creating a crater on a comet.
4) Talk about cratering as a regular phenomenon in the Solar System. Show evidence of cratering on various planets, moons, and the Earth itself. (See Cratering Images) Discuss the idea that there are different types of craters (created by volcanoes, etc) but that the focus of this unit will be on those caused by impacts.
5) Explain to the students that in order to make predictions about crater size, the class first needs to determine what factors influence cratering and how. Set up ground rules for brainstorming. Some suggested ground rules are:
    - All ideas will be written on the board
    - Ideas are not evaluated during brainstorming session. (Setting this rule means that students are more likely to give ideas than if they are evaluated and discussed either by the teacher or the other students during the listing process)
    - Anything that you (the students) think could be a factor should be mentioned.

    You may want to record the student ideas on an overhead so that each class' ideas can be saved and displayed again the next day. *See the "Student Anticipations" section of the next activity for expected student responses and factors to add to the list if not generated by the class.*
6) When the brainstorming session winds down, assign "Comet Research", the long term homework assignment for the unit. This assignment has the students collect information about what comets are and what we know about what comets are made of. Set the due date for approximately when you think you will reach Activity #5 - Cratering on the Comet.
7) Talk about the Student Journal Assignments (see teacher directions with journal in appendix). Assign journal assignment #1 as homework.

Day 2

8) Review the list of possible factors influencing cratering generated in class yesterday. Inform the students that today they will be exploring their ideas. Hand out "Exploring Cratering" student handout and give any group structure, clean up and work area instructions you would like to give.
9) Students work on "Exploring Cratering"
10) Stop the class for clean up with enough time to allow you a 10 minute discussion at the end of class.
11) Review the list of factors that might influence crater size with the class. Now that the students have done some initial exploring, which factors seem like they would be the most important? Are there ways to categorize these ideas? Which ones are feasible for testing in the classroom? Do some factors need to be broken into more specific parts? ("how big" to mass, density, diameter, etc) *See the "Student Anticipations" section for more information about what answers to expect from your students and suggestions on how to select factors for investigation.*
12) Assign Journal Assignment # 2

Student Anticipations

Brainstorming Factors Influencing Crater Size

Interestingly enough, in initial interviews with students, all of the factors listed by students actually do contribute to determination of final crater size and shape to varying degrees. Most of the ideas from your students will fall into three basic categories; (1) how "big" the impactor is, (2) how "hard" it hits the surface, and (3) what the surface is like. Here are example comments that illustrate each category.

"Little impactors would make little holes"

"If it hits with a big impact, big smash, it will make a bigger crater"

"….the dust is so soft, it would make a smaller hole because the dust is going to cushion the fall"

During the original brainstorming session, your role as facilitator is to record all student ideas without evaluating them and to encourage students to contribute any ideas they might have. In the next activity, when your students think about designing formal experiments, it will be your job to encourage them to break down factors like how "big" the impactor is into more precise and measurable quantities like mass, density, diameter, etc.

Exploring Cratering

This activity was added as a result of the pilot tests. We found that the students had a difficult time sticking to their own formal experiment design in the second activity if they had not first been given the opportunity to explore different ideas in a more free-form fashion. Consider this section preliminary tests that will help your students form ideas about what sorts of tests can be conducted and what the results might be before they design a formal experiment limited to just one factor.

From these initial explorations, your students will see that dropping from greater heights produces deeper and larger craters, compacting the surface makes for smaller craters, and the heavier an object is, the deeper the crater will be. Some students in the pilot test also noticed that impactor mass was more important that impactor diameter when it comes to determining crater depth, but that crater diameter was driven by impactor diameter for the most part. This is an important observation that will become significant when we look at the differences between the low speed impacts we create in the classroom and the high speed impacts that take place on a solar system scale in Activity 4.

Refining the List

In the discussion at the end of class on the second day, your role as facilitator shifts from encouraging any and all ideas to encouraging the students to break down factors such as "the size of the impactor" into more specific and measurable quantities such as mass, diameter, or density. **It is very important to keep in mind that what your students mean by a term can sometimes be very different than what you mean by a term.** When drawing out student ideas, take care to have them thoroughly explain what *they* mean by hard, or big, or the other terms listed. If you simply jump to the terms used on the chart, you and your students may be using the same words to mean different things. Remember that you are interested in helping your students test their own ideas about cratering.

For example, one group during the pilot testing used the term "impact". Their idea was that the larger the "impact" the larger the crater. When the students were asked how they intended to create larger and smaller "impacts", they replied "We'll just drop one (ball), and then we'll throw the others at different speeds". This group was actually interested in looking at the impact speed. Meanwhile, another group using the term "force" wanted to change both the velocity of impact and the mass of the object. See the chart on the next page for possible student ideas, suggestions for refinements, and some experimental design ideas for the next activity.

Possible Student Responses	Possible Scientific or More Specific Terms	Possible Experiments
size of impactor (how "big" is it)	*mass	objects of different masses but same diameter and shape are dropped.
	diameter	objects of same mass but different diameter drop - could be done with a mass of clay that is reshaped to give different impacting diameters.
	density	same sized object, different mass
how "hard" it hits impact momentum+ force+ of impact	mass	see above
	*velocity	dropping the ball from different heights gives you an impact velocity that can be calculated from the formula $v^2=2gd$ with d=height in meters above ground from which ball dropped and $g=9.8$ m/s^2
	acceleration	avoid this one - difficult to vary acceleration in easily measurable way and doesn't give you much useful information. Velocity is the key in this section.
how hard or soft the surface is	*density	adding more flour and compacting to the same level in the pan or using different materials
	connectivity of surface materials (tightly bound like metal or loosely packed like sand)	using a variety of different surface materials in the pan (dirt, mud, cake, jello,) or try a variety of surfaces outside - mud, sand, concrete, etc.
	compressibility	see above
does the surface "bounce back"	elasticity	see above
state of matter of surface	is target solid, liquid, or gas	see above
how "hard" or "soft" the impactor is	compressibility elasticity	Use objects that maintain rigid shape and objects that can easily deform. Soft impactors will deform and produce a different crater than a rigid impactor.
Shape of impacting body		use impacting bodies of different shape. Using a particular mass of clay and reshaping may be best way to test mainly for shape
Angle of impact		roll impactor down a ramp at different angles
Temperature of target or impactor		non-flammable materials for surface or impactor either on hot plate of micro-waved
Presence or absence of atmosphere on target body		Dropping objects into the sand at the base of a filled fish tank.

+ It is easier, for experiment design purposes, to break the terms "force" and "momentum" into their components mass, velocity, and acceleration.

Dear Students:

Welcome to the Deep Impact Mission Team! We are hoping to make a hole in a comet and we need your help! We would like to make a crater, the size of a football field and seven stories deep in Comet Tempel 1 when it swings past the sun in July of 2005. In metric measurements, this comes out to around 100 meters across and 20 meters deep. The question is - how do we make a crater of these dimensions? We would like to find out what you think about how we should solve this problem.

We can see examples of cratering all over the Solar System. We can examine craters in other places and craters on the Earth and in laboratory tests and understand many things about how cratering works. However, there are a lot of things about cratering that we are just discovering. Over the next few weeks, you and your classmates will be examining what factors influence crater size, developing a model to help you determine how to make a crater of a particular size, and preparing a report passing on your findings and recommendations to us.

Why do we want to make a crater in a comet? Comets can tell us more about the formation of the Solar System. Comets are small chunks of ice and dust from the solar nebula, the cloud of gas and dust from which our Solar System formed. Objects like the Earth, the other planets, and their moons also formed from the solar nebula, however, their atmospheres, internal heat, and other forces have caused the composition and appearance of these larger objects to change over time. Comets, however, are frozen bits of that original material that have been sitting at the edges of the Solar System like time capsules since the Solar System began. Looking at comets can tell us what the early solar nebula was made of and help us develop a better picture of how the Solar System formed.

We have some idea of what comets are made of because we are able to study the sunlight reflected from the comet from observatories on Earth and with space telescopes. However, comets heat up as they get closer to the sun and cool as they move back out to the edges of the Solar System. Some of the material streams away as part of the comet's tail. This means that the outer layers of the comets may have changed over time. What Deep Impact will do is allow us to see inside the comet, to the layers that have not been effected by the comet's travel.

We only get a look inside our time capsule if we can successfully make a large enough crater in the comet. Our team members at the University of Maryland, Ball Areospace in Colorado, NASA Jet Propulsion Laboratory in California and other institutions around the country will be focusing on how to make this happen as we prepare for the launch of the mission in January 2004. We are interested to see what you and your classmates think about how we can make this crater. Thank you for lending your energy and your minds to this effort!

Sincerely,

The Deep Impact Science Team

Exploring Cratering

Group Instruction Sheet

In this activity, you will be exploring how the factors your class listed influence crater size.
1) Collect the materials that you need:

- Pan of surface material
- Collection of different objects to act as impactors
- Ruler & string to help you make measurements.

2) Come up with your own ways to test out the different factors listed by the class as possible influences on crater size. Experiment as much as you like.

Possible things to try:
Drop from different heights
Drop objects of different weights
Drop objects of different sizes
Drop objects of different shapes
Compact the surface material (pack down the flour or sand)

Things to measure and notice:
Crater depth
Crater diameter
Shape of the crater

Things to write down:
Keep notes on what tests you tried and the measurements and shapes of the craters that resulted.

Comet Research

Eventually, you are going to apply what you learn about craters in general to the specific case of cratering on a comet. Over the course of the next two weeks, collect any information and resources about comets that you can find. You should be looking for any information of the following items in particular

- the composition of comets (what are they made of?)
- the size of comets
- the shape of comets
- any other information you think would be useful in determined how to best make a hole in the comet

Due: _____

What Factors Influence Crater Size?

Overview:

Having done some initial exploration into cratering in the previous lesson, here students focus their ideas about the factors influencing crater diameter and depth. Students design experiments to test specific factors, evaluate each other's experimental designs, conduct the experiment, and present their data to the rest of the class.

Standards:

All students should develop abilities necessary to do scientific inquiry. (National Science Education Standards, 5-12). This standard incorporates many different skills. This activity will focus on the following aspects of inquiry, also from the NSE Standards.

- **Design and conduct a scientific investigation** - emphasis on identifying and controlling variables
- **Communicating scientific procedures** - emphasis on telling other students about investigations and explanations

Estimated Time Requirement:

5-6 days, based on 50 minute class periods.

Materials:

Since your students will be designing their own experiments in this activity, they should be encouraged not to limit themselves to materials provided and to bring in other everyday materials that might be useful as needed. However, having the basic supplies used in the last activity and listed in the "Module at a Glance" section can save time and serve as inspiration.

Background:

In this activity, your students will be exploring their ideas about what factors influence cratering. Your main task is to guide them as they design a formal test of a particular factor and look for patterns in their results. Your focus should be on the results that your students are getting rather than on "right" answers that you expect them to get. Appendix 2: "Current Scientific Thinking About Cratering" will give you a summary of what we understand about cratering today and the differences between high energy cratering events, like those that take place on a solar system scale, and low energy cratering events like those your students are creating in the classroom. This information can be useful to you as you are interpreting your students' results for yourself and asking students questions, but should not be seen as the collection of answers where you intend your students to arrive after completing their experiment. Remember that the main goal here is for students to work on experimental design skills and explore their own thinking about cratering.

Teacher Procedures:

Day 1

1. Distribute the "Guidelines for Good Experiments" handouts and discuss with your students. Explain that their group will be meeting with another group later in the period to compare ideas and check those ideas against the guidelines.
2. Break the class into groups and assign cratering factors.
3. Give the students a limited time frame for experimental design that will allow you 20 minutes at the end of class for peer review groups to meet. Most groups will be able to finish within 20 minutes or less.
4. As groups finish, pair the groups together and give each group a "Peer Review" handout. Instruct students to turn in Peer Review sheets when finished.
5. Assign "Journal Assignment #3" for homework.

Day 2

6. Let the students know that each person in the group will need to have a copy of the group's data for tonight's homework.
7. Students conduct experiments.
8. Assign "Graphing Your Data" as homework.

Day 3

9. Ask the students to share what they see in their graphs so far. Talk about reasons why the students might want to conduct more trials today, such as getting more data points for the chart, reducing error by repeating the experiment through multiple trials and averaging the results, exploring surprises in the data , etc.
10. Students return to their experiments.

11. If groups finish early, distribute "Poster Presentation Guidelines"
12. Assign "Journal Assignment #4".

Day 4

13. Meet with class to discuss reporting experiment results. Go over "Poster Presentation Guidelines". **Note:** You also need to instruct the students that their data & graphs need to also be turned in to you in a form that will be easy to photocopy and distribute for the next activity. Suggest they use the same format as "Graphing Your Data", but be sure that they add any new data collected on the second day of experiments.
14. Students work on presentation of data and results.

Day 5

15. Groups present their posters to the class.
16. Students fill out "Factors that Influence Cratering Summary Sheet" during presentations.
17. Have a summary discussion with your students about what factors seemed to have an effect.
18. Assign "Journal Assignment #5"

Student Anticipations

In this activity, the students design experiments to specifically test the effect of one factor on crater depth, diameter, and shape. If possible, every student group should work on a different factor. The factors marked with * are the ones to be sure you include. You should also include one or two more from the general "What is the surface like?" category. The chart in the previous activity also includes some ways in which these factors might be tested, although these are by no means the only ways.

Experiment Design

Your key role will be to encourage your students to devise ways of quantifying their results and of keeping all of the variables the same except the one being tested. Most groups will realize the need to quantify the crater diameter and depth. Some discussion of how they are choosing to measure those values might prove interesting. Your students will probably measure the crater from rim to rim for diameter and from rim to base for depth. Scientists actually measure in reference to the original surface of the planet instead. It is **not** necessary to have your students change how they are making their measurements, but having them articulate what they mean by "diameter" and "depth" could be useful.

More groups may need to be encouraged to quantify the variable they are changing in their experiments. For example, in the pilot testing, a group varying the mass of the impactor recorded the diameter and depth of the crater, but recorded only a label for each impactor (softball, golf ball, whiffle ball, etc). This seemed acceptable to the group at the time, but when asked to make predictions about masses they had not specifically measured, they found that their data did not allow them to easily interpolate for other masses. This group went back and measured the mass of their objects when it was time to make predictions.

Varying the speed of impact can create some quantification difficulties as well. The easiest way to vary speed of impact is to drop the object from different heights. However, making the connection between different heights and different impact velocities due to gravitational acceleration is difficult for students to make in detail. Instinctively, many of the students in the pilot recognized that dropping from different heights would produce different impact velocity. They measured and recorded the height. As they got further from the actual experiment, they moved away from their understanding that it was the impact velocity they were varying and began to think of it solely as the distance from the impacting surface. Several students who were asked "Why did you choose to vary the height?" and responded "To change the speed of impact - a higher drop gives you a greater velocity" later asked "Well, how far away are you sending the impactor from?" and focused on the distance as the important factor rather than the velocity of impact. Continually asking your students to explain the connection between height and velocity throughout the process may help alleviate some of these difficulties.

Experiments that involve the nature of the target surface will be both harder to quantify and harder to keep to just one variable. However, these experiments are also the ones that allow for more creative thinking by your students. Several groups testing different materials in pilot testing simply recorded the diameter and depth of the crater and a description of the target material (rocks, sand, rock and sand mix, etc). These groups ran into the same difficulties in the next activity as the group that recorded only a descriptor for the impactor. One of the groups that used different target materials went back and calculated the density of the surface material by massing a specific volume. Another estimated the average particle size. Yet another group varied the surface by adding different quantities of water to sand. They kept track of the volume of water added.

Another difficulty that arose in quantification was measuring those factors that you are **not** varying as a reference point. For example, students varying the mass of the impactor very carefully dropped the impactors from the same height every time, but did not record that height. That was not crucial to their own data the first day, but both repeating the experiment the next day and comparing results to the results of others in the class was more difficult with out that information.

While you may need to push your students to work on methods to quantify their experiments, you do want the experiments to be their own design as much as possible. Moving between the groups while they are working on the design process and listening to their ideas can help you strike this balance.

Graphing your data

The students are asked to graph their data on the first night of testing as homework. The format of the graph is left up to the students. Having students graph as homework is done in order to give them (and you!) a quick check as to whether or not they have done enough trials in their experiment to truly see a pattern yet and to begin to think about anomalous data. . It forces the students to think about what information they are recording and how to display that information. Interesting things seen in the graph in the first night can be further explored in the second day of experimentation.. It also gives you as a teacher a look at what further direction they may need about displaying and recording their data. How much support and additional direction your students need in order to graph their data can vary widely depending upon how much graphing they have done either in your class or in other classes. Some students in the pilot testing groups struggled with labeling the numbers of the graph with even spacing. Others created graphs that showed depth and diameter numbers for craters, but simply labeled the varying factor. Still other groups easily created a variety of graphs and charts using spreadsheet software.

End results

The basic trends you should expect to see in student data are

1) Greater masses make deeper craters. Crater diameter is a little more questionable - at these low speeds, the diameter of the crater is more a reflection of the diameter of the object. **NOTE:** *This is only true at low speeds, not in solar system scale cratering. This will be discussed in activity #4.*

2) Greater velocity will give you greater depth and diameter. Once again, the diameter is somewhat dependant on what you drop. You should get increasing diameter if you used something like a ball, because an increasingly large cross-section will sink into the surface.

3) The smaller the angle of impact, the shallower the crater. However, the diameter will tend to increase in one direction, making an elliptical crater. ***NOTE:*** *This is again an effect of low speeds. This will be discussed in activity #4.*

4) The more a surface is compacted, the smaller and shallower the crater will get.

Guidelines for a Good Experiment

Student Handout

Your Experimental Design is complete if.....

1. You have clearly stated which factor you are testing.
2. In your experiment, you change only the factor that you are testing. All other factors remain constant.
3. You have a plan for measuring and recording the factor you are testing.
4. You have a plan for measuring and recording the diameter and depth of the crater and for describing and recording the shape of the crater.
5. You have a plan for measuring and recording the factors that should remain constant, so that you or someone else could recreate the same conditions.
6. Your experiment is safe to conduct within the classroom.

DIRECTIONS: On a piece of paper, write down your group's experiment plan. Make sure that you cover the six guidelines above.

Peer Review

As you listen to the other group describe their experiment, check off each characteristic of a good experiment that you think they have covered in their experimental design. When they have finished their presentation, give them any suggestions you have verbally, and make a quick note of your suggestions on this page as well.

You have clearly stated which factor you are testing.	
In your experiment, you change only the factor that you are testing. All other factors remain constant.	
You have a plan for measuring the factor you are testing.	
You have a plan for measuring and recording the diameter and depth of the crater and for describing and recording the shape of the crater.	
You have a plan for measuring and recording the factors that should remain constant, so that you or someone else could recreate the same conditions.	
Your experiment is safe to conduct within the classroom.	

Suggestions for Improving Experiment:

Graphing Your Data

In the next activity, we will be looking for patterns in the data that you have collected.
For your homework tonight, you need to create a graph of your data. You want to show how the depth and diameter of the crater changed as you changed the factor you are investigating. Use whatever format you think is most effective to display your data. Create your graphs, and then answer the following questions.

Questions:

1) Do you have enough data to see a trend yet? Explain your answer.
2) Is there anything unexpected in the data? Explain your answer.

Poster Presentation of Experiment and Results
Student Handout

Scientists studying the same subject often meet at conferences or symposiums. The purpose of these meetings is to share your research results and learn about what research others have done to increase your understanding of your field. There are several ways in which scientists present their information at these conferences. One way is to put together a "poster". This is a display similar to what you've probably done or seen done for school science fairs. These posters are all displayed together, and scientists wander from poster to poster to get a feel for the research. Sometimes the scientist who authored the poster will give a very short talk right next to the poster and answer questions other scientists may have.

Directions: We are going to hold our own "Deep Impact Cratering Symposium" here in class. Each group is responsible for creating a poster that displays information about your experiment, your results, and your conclusion. Below are the Symposium standards for poster submission.

Introduction & Experiment		
Which factor is being tested for is clear		
Experiment procedures are described		
What quantified measurements were being made and how are discussed		
Data		
Results of experiment clearly presented		
Data displayed in graphs - where possible, graph of factor tested vs. crater diameter and factor tested vs crater depth		
Any anomalous or bad data explained		
Conclusions		
States whether factor does or does not effect crater size or if results were inconclusive		
Explains how data supports above conclusion		
Describes any patterns in effect on crater size (how?)		
Visual Presentation		
Neat and easy to read		
Sections clearly labeled		
Layout makes it easy to follow what happened and what the results were		

Poster Presentation of Experiment and Results
Teacher Version

Scoring Suggestion: Rank each answer between 0-3. Average the scores by adding them all up and dividing by 12.
>2.5 = A 2.0-2.5 = B 1.5 –1.9 = B 1.0-1.4 = D

Introduction & Experiment	
Which factor is being tested for is clear	
Experiment procedures are described	
What quantified measurements were being made and how are discussed	
Data	
Results of experiment clearly presented	
Data displayed in graphs - where possible, graph of factor tested vs. crater diameter and factor tested vs crater depth	
Any anomalous or bad data explained	
Conclusions	
States whether factor does or does not effect crater size or if results were inconclusive	
Explains how data supports above conclusion	
Describes any patterns in effect on crater size (how?)	
Visual Presentation	
Neat and easy to read	
Sections clearly labeled	
Layout makes it easy to follow what happened and what the results were	
Total	
Average	

Class Results: Factors that Influence Cratering

Student Handout

Welcome to the Deep Impact Symposium on Cratering! Your task is to examine the results of your classmates to get an overall picture of what factors influence crater size.

Factor Investigated: **Did Factor Affect Crater Size?:** **What Effect Did It Have?:**	**Factor Investigated:** **Did Factor Affect Crater Size?:** **What Effect Did It Have?:**
Factor Investigated: **Did Factor Affect Crater Size?:** **What Effect Did It Have?:**	**Factor Investigated:** **Did Factor Affect Crater Size?:** **What Effect Did It Have?:**

Predicting Crater Size

Overview:

In this activity, students will be looking for patterns in their experimental results, using those patterns to make predictions, and testing those predictions by revisiting the initial cratering experiments.

Standards:

All students should develop abilities necessary to do scientific inquiry. (National Science Education Standards, 5-12). This standard incorporates many different skills. This activity will focus on the following aspect of inquiry, also from the NSE Standards.

- **Develop descriptions, explanations, predictions and models using evidence** - emphasis on providing causes for effects and establishing relationships based on evidence and logical argument

Instructional programs should enable all students to (National Council of Teachers of Mathematics Standards for 6-12). See "Standards Addressed" Chart in the introductory material for more specific information.

- **Develop and evaluate inferences and predictions that are based on data**
- **Understand patterns, relations, and functions**
- **Analyze change in various contexts**
- **Use mathematical models to represent and understand quantitative relationship.**

Time Requirement:

2 Days (based on 50 minute class periods)

Materials:

- Materials used for the initial cratering experiments
- Student data graphs from Activity 2, both copied on to overheads and copied for distribution to groups.
- Student Handouts "Looking for Patterns and Making Predictions Part 1 & 2"
- Teacher Overheads "Best Fit Lines", "Finding a Formula for a Line", and "Common Patterns"

Background:

One of the biggest differences between science in the classroom and science in the lab is what happens *after* an experiment has been conducted. In the classroom, a report is usually written that ends with a conclusion, discussing whether or not the data showed what was expected and what factors might have contributed to inaccuracies in the data. After that, the students move on to the next topic.

In the scientific world, one experiment can lead to more questions or to a reevaluation of the scientist's thinking about a phenomenon. Experiments are refined and repeated or new ones are designed. This activity attempts to bring this kind of thinking into the classroom, encouraging the students to really look at what they came up with, how that information might be used, and what further testing might be needed. More specifically, your students will be practicing looking for patterns in data and trying to use those patterns to make predictions.

It is important to note that we are not expecting students to derive a "correct" formula for final crater size in this activity. Scientists do have a good understanding of the general dependencies, however the proportionality constants depend upon the specific materials involved in the impact. (*See Appendix 2 for more information about cratering*) For classroom scale cratering events, crater diameter should be proportional to the sixth to fourth root of the impactor's kinetic energy - a difficult relationship to uncover in classroom data. There should, however, be some recognizable patterns that can be used to make predictions over a limited range of variables. *See the Student Anticipations section for more information about what you can expect from your students.*

Teacher Procedures:

Day 1

1. Remind the students that what we really want to be able to do is to make predictions about crater size. This will allow us to design the mission's impactor in such a way that it will create a crater of the appropriate size on the comet.
2. Put up a graph of student generated data on an overhead. Ask the students if they see any patterns in the data. Ask them what they mean by "pattern".

3. Put up the "Common Patterns" overhead. Briefly discuss each of the patterns. As you are discussing these patterns, ask your students to think about what that pattern would physically mean. Suggested talking points:
   - Linear- The best fit line is straight. The value on the y axis goes up in a regular pattern with changes in the value on the x axis. A linear pattern in your data would mean that as you change the value of the factor (mass, angle, etc), the resulting crater size changes in a similar way.
   - Exponential - Best fit line is a curve with an increasing slope. One possibility is that the value on the y axis is the square of the value on the x axis. In your data, this would mean that as you increase the factor you changed, the resulting crater size increased faster and faster.
   - Cyclical Pattern -Some patterns repeat themselves in a regular way. The example pictured here is a cosine function – a pattern that you will learn more about in later math classes. This would mean that as you changed the factor, certain values of the factor would produce the same results - like something "resetting" the system every so often.
   - Changing Patterns - Patterns like this can be described in different sections. Patterns like this indicate that maybe different things are important at different points in the process. For instance, really low speeds of impact may have a different effect on the target body than really high speeds of impact.

4. Ask the students if data can still be considered to show a pattern even if the data doesn't fall exactly on a line or a curve. Put up the "Best-Fit" overhead and discuss the concept of best-fit lines. Explain that best fit lines can be determined mathematically, but that today the students will visually estimate a best fit line.
5. Distribute photocopies of student data charts. You may make these specific to the class or use representative examples that are particularly good with all your classes. You want to be sure the students have mass, velocity, angle of impact, and hopefully some variety of surface data.
6. Have students work in partners to determine what patterns they think fit each data set and sketch in the best fit line on the data.
7. Bring the class back together. Ask your students what patterns they found. Ask your students if there are any data points that don't seem to fit. Discuss those points with your class and talk about why you might exclude particular data points when looking for a pattern.
8. Go back to the "Common Patterns" overhead. Ask your students how patterns could be used to predict results for values outside of those that have been tested. Discuss how predictions might be made. Focus on using the line itself to make predictions, rather than on making mathematical predictions at this point.
9. Handout "Making Predictions Part 1". In this assignment, the students will use the graphs to make a few predictions and then test those predictions using the same lab equipment used to make the original tests.
10. Assign "Journal Assignment #6" as homework

Day 2

11. Ask students to share how their prediction testing experience went yesterday. Discuss ways in which they might be able to improve the accuracy of their predictions, such as collecting more data, mathematically calculating a best fit line or curve, etc.
12. Talk about looking for patterns in the numbers. Look at the linear example in particular. Display and discuss the overhead "Finding a formula to describe a line"
13. Assign "Searching for Patterns and Making Predictions, Part 2"
14. Students work through Searching for Patterns Part 2.
15. Assign "Journal Assignment #7" as homework.

Student Anticipations

This activity relies on the use of graphical representation of data to find trends useful for making predictions. Classroom data is not going to fall on to a simple line or curve in most cases, nor are your students going to derive an accurate formula for the prediction of crater size that could be applied in all cases. However, this activity gives them experience in looking for patterns in data, analyzing data points for accuracy and inclusion, and making the connection between the slope of the line and rates of change.

Tests of velocity changes on the classroom scale tend to show an almost linear relationship between crater diameter and velocity, despite the

mathematical reality of the relationship. Changes in mass will also be a roughly linear relationship. Other experiments may or may not show easy patterns. If a collection of data is not showing a clear pattern, have the students think of possible explanations. Does the factor actually have an effect on crater size? Could this factor actually be more than one factor? Is there something about the way the experiment was conducted that might be giving a false impression of the effects of one of the variables?

Students may need help with the concept of best-fit lines. Some groups will tend to connect data in a dot to dot manner and then get bogged down in trying to predict complicated point to point trends. Focus the students on eyeballing a best-fit line or curve.

There will be a strong temptation among students to fudge data so that their predictions match actual events. Encourage them not to do this by pointing out that scientists make great discoveries when they find things they were not expecting in their data.

Students may need to be reminded when carrying out calculation in part two, that the formulas they have put together only work for a specific set of conditions. For example, they may have come up with a linear formula for the effect of mass on crater depth. However, the numbers in that formula will only work for masses with the impact velocity used in the experiment into the surface material used in the experiment. Question 4 on "Looking for Patterns and Making Predictions" part 2 is asked to get students to think about this issue, but some students may need a slight push in that direction. With more advanced students, you may want to continue beyond part 2 and discuss the kinetic energy formula at this point and have the students look for a quadratic relationship by graphing the square of the velocity against the crater size.

Looking for Patterns & Making Predictions

Student Handout Part 1

1. Use the patterns you find to make predictions for two of the factors. This means that you should pick several values of the factor being tested that were NOT done by the original group and see if you can guess from the data what the size of the new crater will be. Fill in the first two columns of Tables 1and 2.

Table # 1 Factor being tested_____

Value of factor	Crater Diameter Predict.	Crater Depth Predict.	Crater Diameter Results	Crater Depth Results

Table # 2 Factor being tested _____

Value of Factor	Crater Diameter Predict.	Crater Depth Predict.	Crater Diameter Results	Crater Depth Results

2. Now, go back to the experiment apparatus and test your predictions. Fill in the last two columns of Tables 1-2.

3. Did you get the results you predicted? Are there changes you can make to the pattern you saw in the original data that could explain your new data? Are there other reasons for the discrepancy (something in the way you carried out the experiment might have been different from the original group, etc)? How could you improve your predictions?

Looking for Patterns & Making Predictions

Student Handout Part 2

Directions: In this activity, you will be finding mathematical formulas to represent the lines on your graph and using those mathematical formulas to make predictions about what the resulting crater might be if you used values far outside the range of those we were able to test in class.

1) Choose three graphs you have with a straight-line pattern. One should be a graph of the effects of mass vs. either diameter or depth, one should be velocity vs. either diameter or depth, and the third is completely your choice. Find the $y = mx + b$ formula to represent that line. Show your work.

Graph 1Title:

Formula for Graph 1:

Graph 2:

Formula for Graph 2:

Graph 1:

Formula for Graph 3:

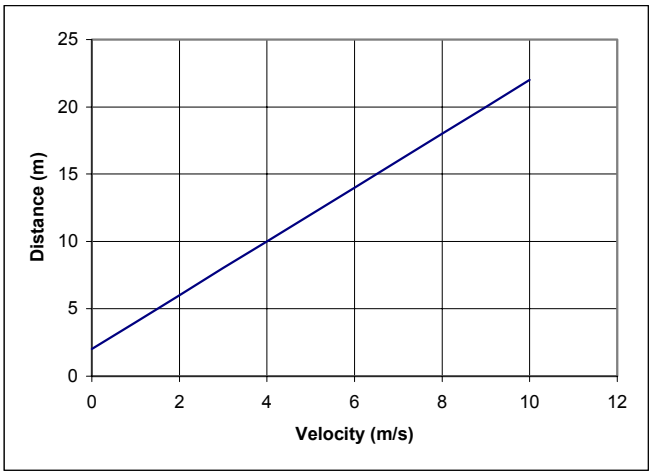
2) Now pick values for each of your three factors that are much greater than the largest number tested in class. Use the formulas you found above to calculate the crater depth or diameter.

3) Remembering that we want to make a crater with a depth of 10m and a diameter of 100m - how might you use these formulas to figure out what impactor mass or velocity is needed in order to make a crater of that size? Do the calculation for mass and velocity.

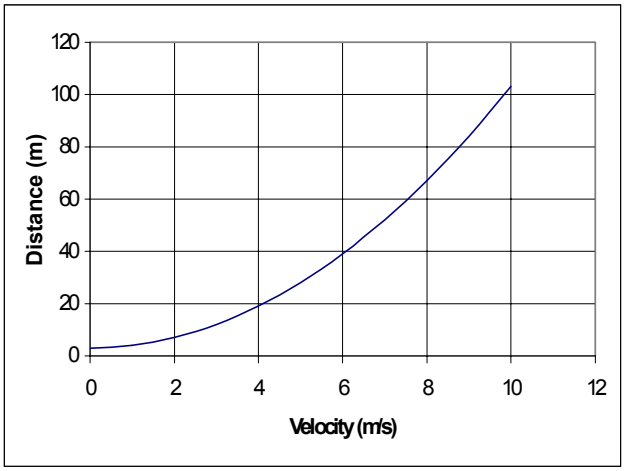
4) Is that our answer? Can we stop there? Why or why not?

Looking for Patterns in Data

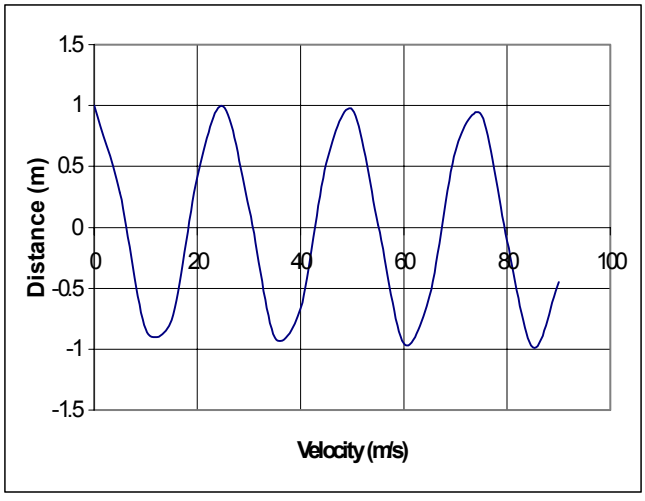
Overhead



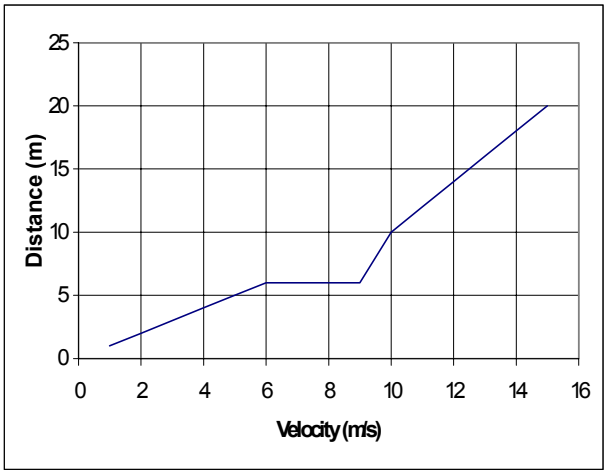
Linear Pattern



Exponential Pattern



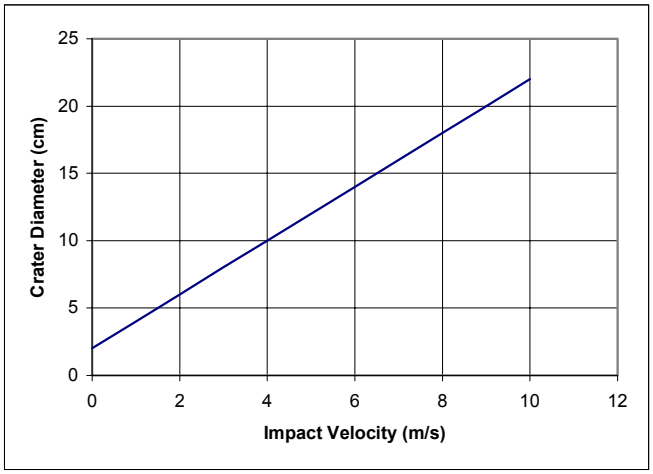
Cyclical Pattern



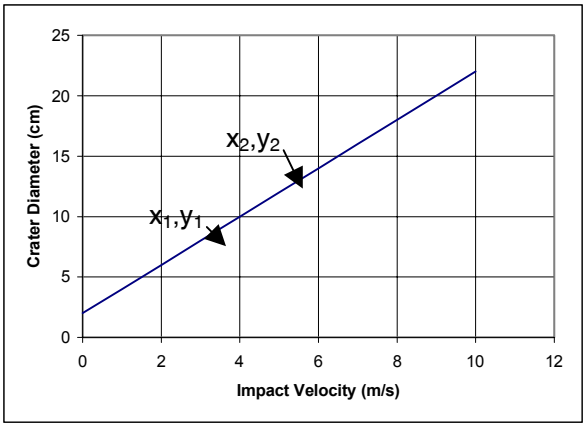
Changing Pattern

Finding a Formula for a Line

Lines can be represented by formulas

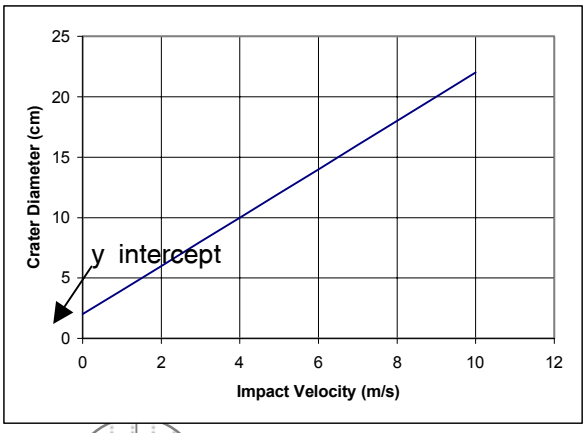


$$y = mx + b$$



m= slope of the line
Slope=rise/run
$=(y_2-y_1)/(x_2-x_1)$

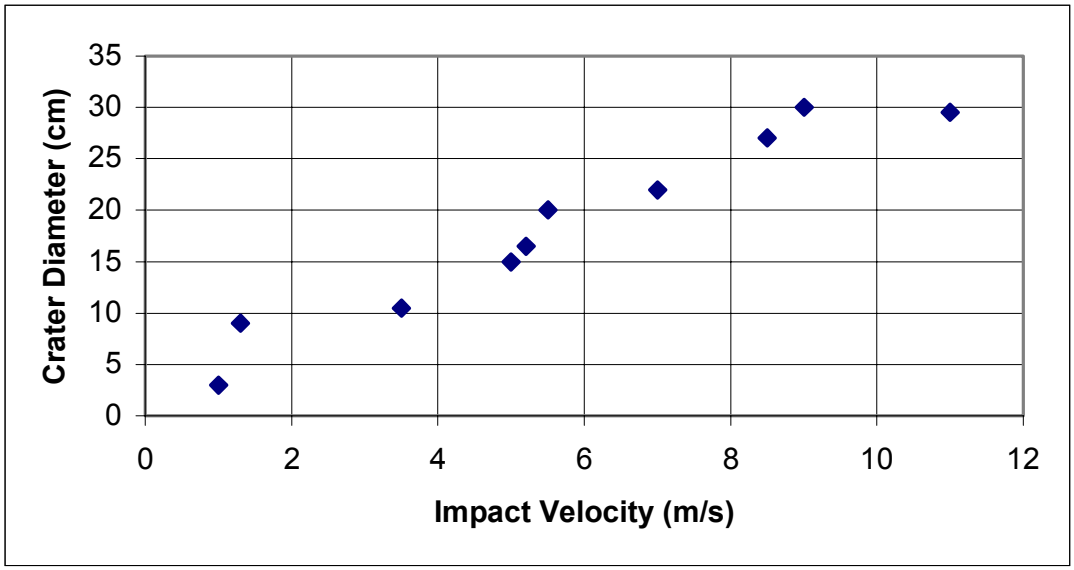
In this example:
m = (14-10)/(6-4)
= 4/2 = 2

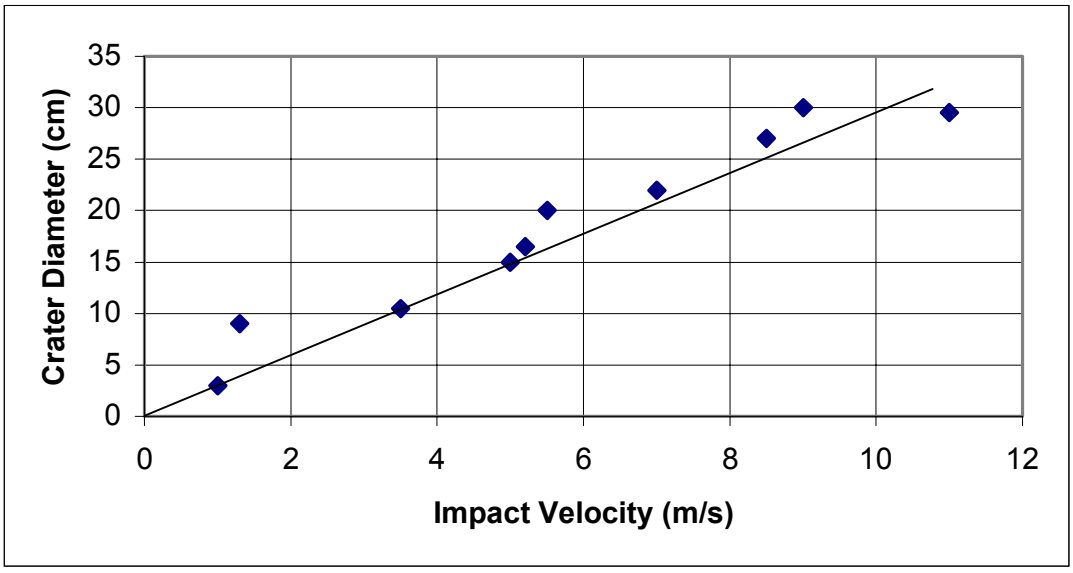


b = y intercept (place where the line crosses the y axis)

In this example b= 2
Our formula?
y = 2 x + 2

Best-Fit Lines
Overhead





Cratering in the Classroom, the Lab, and the Solar System

Overview:

In this activity, students will be looking at the similarities and differences between their classroom experiments, professional lab cratering experiments, and cratering on a solar system scale. The students will be asked to think about the limitations and advantages of small-scale simulations as a form of scientific modeling.

Standards:

All students should develop the abilities necessary to do scientific inquiry. (National Science Education Standards, 5-12) This standard incorporates many different skills. This activity focuses on the following aspect of inquiry, also from the NSE Standards

- **Formulate and revise scientific explanations and models using logic and evidence** - emphasis on examining models as models and for their limitations and strengths

All students should develop an understanding of transfer of energy. (National Science Education Standards, 5-12)

- Energy is a property of many substances and is associated with heat, light, electricity, mechanical motion, sound, etc.
- Energy is transferred in many ways

Time Requirement:

1 day, based on 50 minute class periods

Materials:

- Solar System cratering images from Appendix #1
- "Solar System Scale Cratering" Student Handout
- "Deep Impact Cratering Research: Scientific Modeling in Action" Student Handout
- "Thinking about Scientific Modeling" Student Handout

Background

Teaching using analogy and modeling is a common and effective approach to helping students understand complex or abstract ideas. However, research shows that students often transfer all attributes of the model to the phenomenon itself, not just those attributes that are appropriate. This can be reduced if we help students to think about models and analogies as representations or descriptions of the phenomenon, rather than the phenomenon itself. This lesson steps back from the modeling of cratering in the experiments just conducted in the classroom and encourages students to recognize that there are differences between what they did in the classroom and cratering events at Solar System scales. The lesson also shows that while scientists often have better equipment and more knowledge on which to base their lab experiments, those experiments have limitations as well. Finally, the students think about why we do such modeling in science if it is not an *exact* representation of what is going on.

Teacher Procedures:

1. Have the students look back at their notes about crater shape. Have them share anything they noticed about crater shape. What factors seemed to be an influence on crater shape?
2. Now display an image of craters on Mercury, the Moon, or any one of the images included with this module in Appendix 1 that shows a large number of very circular craters. Point out that craters in the solar system are mostly circular.
3. Ask students for initial ideas about what might explain this discrepancy.
4. Explain to the students that they have noticed a difference between craters on a solar system scale and craters they created in the classroom. Tell them that today they will be looking for more possible differences between what goes on in the larger scale solar system and what happened in their experiments.
5. Divide students into groups. Provide each group with Solar System Cratering images from Appendix 1 of this module and each student with the handout "Solar System Scale Cratering"
6. Students should work on handouts in groups and be ready to return to classroom discussion in roughly 20 minutes.
7. Bring students back together. Have students share ideas about the general differences they found. Have the students discuss their ideas about why there are differences between cratering in the classroom and cratering on a solar system scale. *See Student Anticipations*

section for suggestions on points to include in this discussion.

8. Ask students to share what they think is the same about their cratering experiments and cratering on the solar system scale. What did their experiments tell them that still applies?
9. Assign "Scientific Modeling - Reading & Questions". Students should read the article found in Appendix 3 and then answer these questions.

Student Anticipations

The important thing for students to understand in this lesson is that their experiments were modeling small and slow impacts, and that this can give them a feel for the importance of particular factors in cratering - namely the effect of mass and velocity on crater size. Cratering happens in three stages (See Appendix 2). Small scale modeling does a good job of modeling excavation and modification of the crater. There are also important differences between high and low energy cratering events, especially during the initial compression stages when the energy transfer to the target may involve energy losses due to heat or transformation. Differences between classroom and solar system experiments include changes in crater shape as the impact angle changes, and the importance of the diameter of the impactor in determining the size of the crater. Another difference between classroom experiments and cratering in the Solar System is the presence of an atmosphere in the classroom. *See "Appendix 2: Current Scientific Thinking About Cratering" for more information.*

Most student interviews conducted in the initial writing of this material indicated that students believed an impactor has some quantity - momentum, force, energy - that is somehow transferred or absorbed by the target body during impact. Encourage them to share their ideas about this in your discussion. This is your chance to talk with your students about cratering as an exchange of energy.

IMPORTANT NOTE: How far you go in terminology (from sticking with the student chosen and defined words at one end, all the way up to the formal kinetic energy equation on the other) is up to you and your goals for the unit. It is important, however, if you put the equation for kinetic energy on the board, that you emphasize that this equation alone cannot explain crater size. Little undermines an inquiry experience for a student more than the perception (and in this case it would be a false one!) that the entire process they just engaged in was unnecessary because they could have been given the right formula to begin with! Ideally, you would like your students to begin to understand that the energy of motion of the impact is transferred to the target body in the form of moving some of the target material, heating the surface, and changing the rocks themselves.

When you are looking at the "Thinking about Scientific Modeling" paragraphs, be looking for

- a recognition that there is a difference between experiments conducted in the classroom, in the lab, and actual phenomena in space
- a recognition that the difference is largely one of scale
- a recognition that smaller scale experiments are necessary to help you begin to understand what is going on in a larger scale world in which you can not control conditions as well.

Thinking about Scientific Modeling
Student Handout

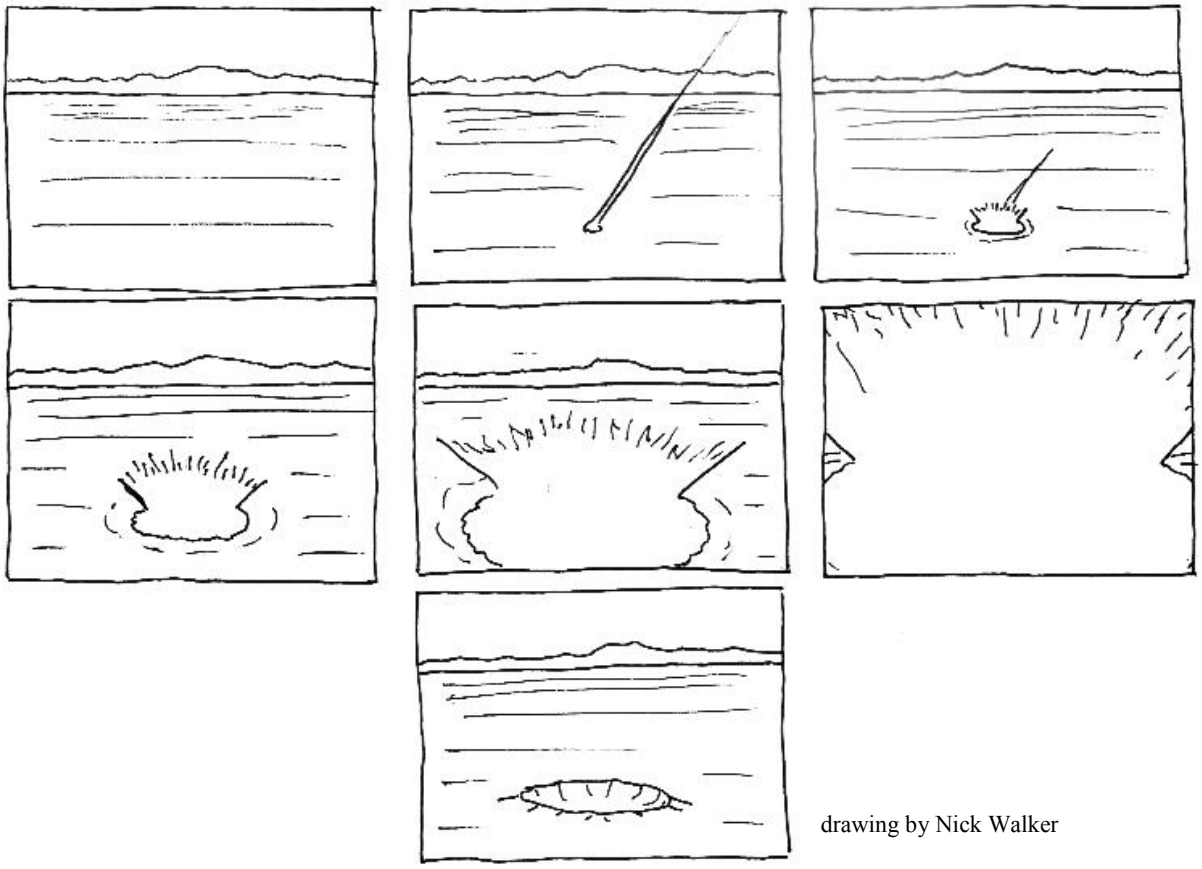
After reading "Deep Impact Cratering Research: Scientific Modeling in Action" write a paragraph that discusses

- how the impact event in your experiment was similar to the Deep Impact event
- how your experiment is different
- what your experiment can tell you that will apply to cratering on a comet
- what added benefits are there to the way the Deep Impact scientists conducted their experiments.
- why you think scientists rely on small scale modeling even though it is not an exact replication of events.

Cratering in the Solar System

Student Handout

Use the collection of images provided by your teacher and the drawing below to think about the answers to the following questions.



drawing by Nick Walker

1) Look at the collection of cratering images provided by your teacher. Compare them to the cratering experiments you conducted. What differences do you notice? How do you account for the differences?

2) Why do you think the craters in these pictures are mostly round, whereas the classroom craters came in different shapes?

3) In your classroom experiments, how was the diameter of the impactor related to the diameter of the crater? In the solar system, you get craters that are much greater diameter than the original body that created it. Why?

4) What similarities are there between the craters you created in the classroom and craters in the images?

Cratering on the Comet

Overview:

In this activity, the students will use their model to make their best suggestions for creating a seven-story deep football field on Comet Tempel 1. They will complete a two-part report to the Deep Impact team.

Standards:

All students should develop the abilities necessary to do scientific inquiry. (National Science Education Standards, 5-12) This standard incorporates many different skills. This activity focuses on the following aspects of inquiry, also from the NSE Standards

- Develop descriptions, explanations, predictions, and models using evidence - emphasis on making predictions using models.
- Communicate scientific procedures and explanations - emphasis on communicating their ideas and their reasoning to fellow students.

Estimated Time Requirement:

1-2 days, based on 50 minute periods

Materials:

- Student assignments and journal entries for the unit to date
- "Reporting to the Deep Impact Team", parts 1 & 2
- Comet information collected by the students

Background:

One of the reasons that cratering was chosen for the focus of this set of activities was that the problem of designing an impactor has proved to be truly fascinating (at least to the author!). Deep Impact needs a crater of a certain minimum size in order to be able to determine the composition of the interior of the comet. Yet, to accurately predict how large a crater we will get, we need to know the composition of the interior of the comet. Also, not everything about cratering is completely understood, so while having the exact conditions on the comet would certainly take us closer to being able to predict what will happen, it would not provide us with an exact script. Scientists must make estimates given what we know about comets already, what we know about cratering already, model events in the lab and come up with a plan for the mission. Both comet and cratering scientists hope to learn from the results. This is an important part of science for students to understand - that science is done by people like them, using what information they have to make some predictions, and learning what they can from how reality either matches or plays out differently from the predictions.

Teacher Procedures:

1. Have the students meet again with their groups, with the information they have researched about comets. Return any earlier assignments (and hold off collecting last night's) for them to use as they file their final reports.
2. Hand out "Reporting to Deep Impact Team, Part 1". The students will pull together all of the thinking they have done so far in this unit to think about how they might answer the goal question.
3. Assign "Reporting to the Deep Impact Team, Part 2". This is an individual assignment in which the student will explain what he or she has learned over the course of the module about cratering and about how science is done.
4. Collect reports. If you choose, submit reports to the Deep Impact team *See Appendix 4: Interacting with the Deep Impact Team*

Student Anticipations:

This activity is designed to serve as the assessment for the module. The first part of this activity was designed to be discussed in groups, so that the students can pool their information about comets and think through the application of what they have learned about cratering to the specific case of cratering on a comet together. You can, however, choose to have this part of the assignment done individually or allow the students to discuss their ideas in groups and then have them write up their answers individually.

The second part of the assignment, designed to be done individually, looks both at what the student learned about cratering throughout the module and at what they learned about how science is done. Students may need to be encouraged to write as complete an answer as possible.

Answers may very widely. Here are some example paragraphs from the pilot trials in five different ninth grade classes. These are student responses to the science process question. (Looking back over your work for this project, have your ideas about how NASA missions are planned or how science is done in general changed? If so, how?) These paragraphs are from 6 papers chosen at random by one of the pilot teachers.

Note: The wording of the question has been changed slightly since the pilot trials to encourage students to be more specific about their suggestions for conducting a science inquiry. It is now being asked as a separate question.

"Over the last three weeks my idea about NASA missions has changed a little. I knew they got to sit down and think stuff up but I didn't know they had so much fun experimenting. I think I've learned that science is more thinking recording data, and experimenting instead of studying and going by what happened in the past. If I had to outline for someone how to do a scientific inquiry, I would say remember to record and compare all data and try to imagine your experiments full scale."

"Yes it changed it big time! I used to think all they did was nothing. But now I see they have to work hard on what they do. I've learned that its very hard to put a lab together but it also can be lots of fun."

"This has changed my ideas about how NASA missions are planned and worked out. I did not know that NASA did lab to see what would happen before they went on their missions."

"No this hasn't changed what I though on NASA missions are planned because I have done something like this before which explained NASA's techniques to me. I have learned a scientific inquiry needs to be done slowly and you need to take time with it and try to be neat."

"What we did in class are like what scientists do because we talked with each other. They do the same thing. We talk with each other because we want to find out what the other people did to. "

"Yes, because now I know that science is not just read out of a book. I would tell the person (conducting a science inquiry) to give details and explain all your answers."

Name:
School:
Teacher:
Date:

Reporting to the Deep Impact Team

Student Form Section #1

Requirements & Limiting Factors:

Desired Crater Diameter: 100 m
Desired Crater Depth: 20 m
Upper Mass Limit on Impactor: 500 kg
Upper Limit on Impactor Volume: 1 m^3
Target: Comet Tempel 1

1) Look back at your answer to questions #3 and #4 on "Looking for Patterns and Making Predictions #2". What did you recommend for the mass and velocity of the impactor?

2) Looking through the information you have collected about comets, what do we know about the composition of comets? (What are they made of?)

3) In what ways do you think cratering on the comet will be different from the cratering experiments conducted in the classroom from which you made your recommendations in question 1?

4) What effect will those differences have on the necessary mass and velocity to create a crater of the desired depth and diameter?

5) What further tests would you suggest be carried out before final decisions about the impactor's design are made?

Name:
School:
Teacher:
Date:

Report to the Deep Impact Team

Student Form Section 2

Cratering Event:

In the space below, draw a *storyboard* (a series of drawings that illustrate a sequence of events, somewhat like a comic strip) of what you think will happen during the Deep Impact cratering event and its effects on Comet Tempel 1. Don't worry about the artistic quality of the drawing, just make it neat and label everything.

Write a paragraph outlining what factors are important in determining the final size of a crater and why those factors are important.

Science Process:

Looking back over your work for this project, have your ideas about how NASA missions are planned or how science is done in general changed? If so, how?

If you had to outline how to conduct a scientific inquiry for someone, what would you say? Be specific and mention all steps or other aspects that you think are important.

Scoring Suggestions: Reporting Your Findings, Part 1

for Teachers

Scoring Suggestion: Rank each answer between 0-5. Answers will vary, so use your own judgement, but the table below lists some characteristics of a good answer.

Question 1		
* Transfer of values from "Looking for Patterns"		
Score for Question 1:		
Question 2		
* Mentioned comets composed of ice		
* Included any other facts about comet related to their composition or structure		
Score for Question 2:		
Question 3		
* Mentions differences in surface (can include difference in materials in composition and/or difference in particle size - as in, classroom experiments conducted in loose flour, surface of comet may be "more solid")		
* Mentions any specific differences between the conditions of the predictions and the comet (predictions made for mass traveling at slower speeds, predictions made for a smaller mass, etc)		
Score for Question 3:		
Question 4		
* Mentions greater speed or mass may need to be used as result of differences in composition		
Score for Question 4:		
Question 5		
* Discussion of the need to test using materials more similar to those of the comet		
* Any other tests that would give more accurate information about what to expect		
Score for Question 5:		
Total Score		

Rubric: Reporting Your Findings, Part 2
for Teachers

Scoring Suggestion: Rank each answer between 0-5. Average the scores by adding them all up and dividing by 4.
>4.0 = A 3.0 – 3.9 = B 2.0 – 2.9 = C 1.0 – 1.9 = D

Cratering Event:

Storyboard covers entire process from start to finsh		
Clearly labeled & easy to tell what is going on		
Factors in determination of crater size mentioned include:		
Mass of impactor		
Velocity of impactor		
Mass of target body		
Material properties of target body (density, elasticity, etc)		
Explanation of cratering process logical and consistent with what was seen in class		

Science Process:

Since this section asks about changes in the student's perception, answers will vary widely. However, you can look for the following point in their description of how to conduct a scientific investigation. An answer that mentions at least five of these points would be a good answer.

Brainstorm initial ideas		
Evaluate ideas for likelihood, feasibility		
Design experiment to test ideas		
Analyze data		
Find patterns useful for making predictions		
Test predictions		
Revise ideas		
Model larger scale events with small scale		
Find mathematical descriptions of the patterns in your data		

Appendix 1:

Cratering in the Solar System: Images

The images on the pages that follow come from NASA's image databases. All of them are examples of cratering in the solar system that you can use to illustrate the phenomenon to your students. These images can be used in your initial discussion of cratering with your students in the first activity. They are specifically needed in Activity 4: Cratering in the Classroom, the Lab, and the Solar System.

1) Craters on the Far Side of the Moon
2) Craters on Mercury
3) Crater on Mars
4) Dickinson Crater on Venus
5) Crater on Mars
6) A Chain of Craters on Ganymede
7) The Manicouagan Crater in Northern Canada
8) Craters on the Far Side of the Moon
9) Pwyll Crater on Europa
10) Comet Shoemaker-Levy 9's Collision with Jupiter

Craters on the Far Side of the Moon

Largest crater in center of photo has a diameter of 77 km.

Photo Credit: NASA/JSC

Craters on Mercury

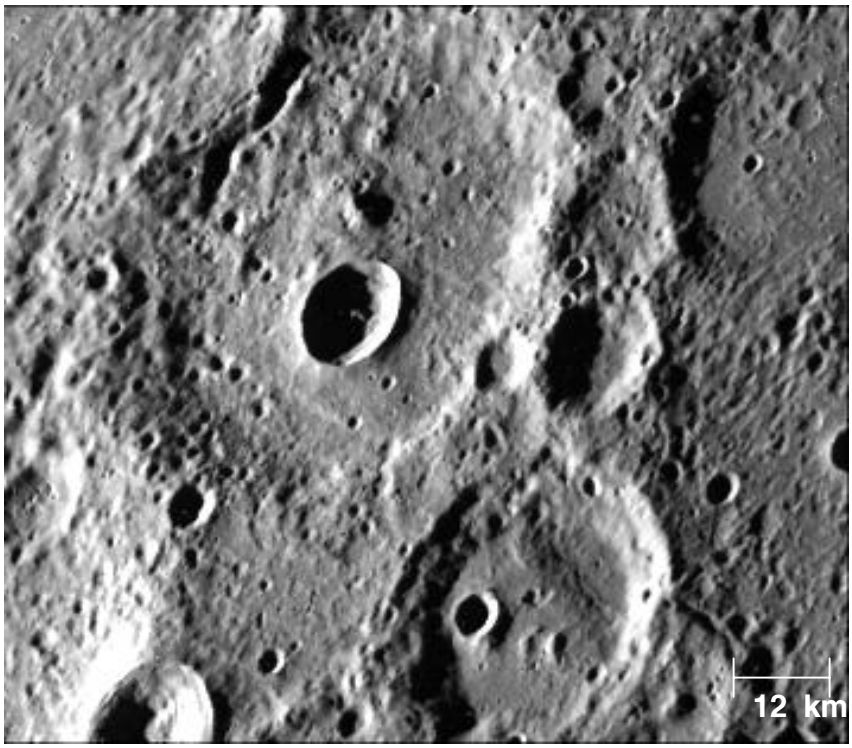


Photo Credit: NASA/JPL

Crater on Mars

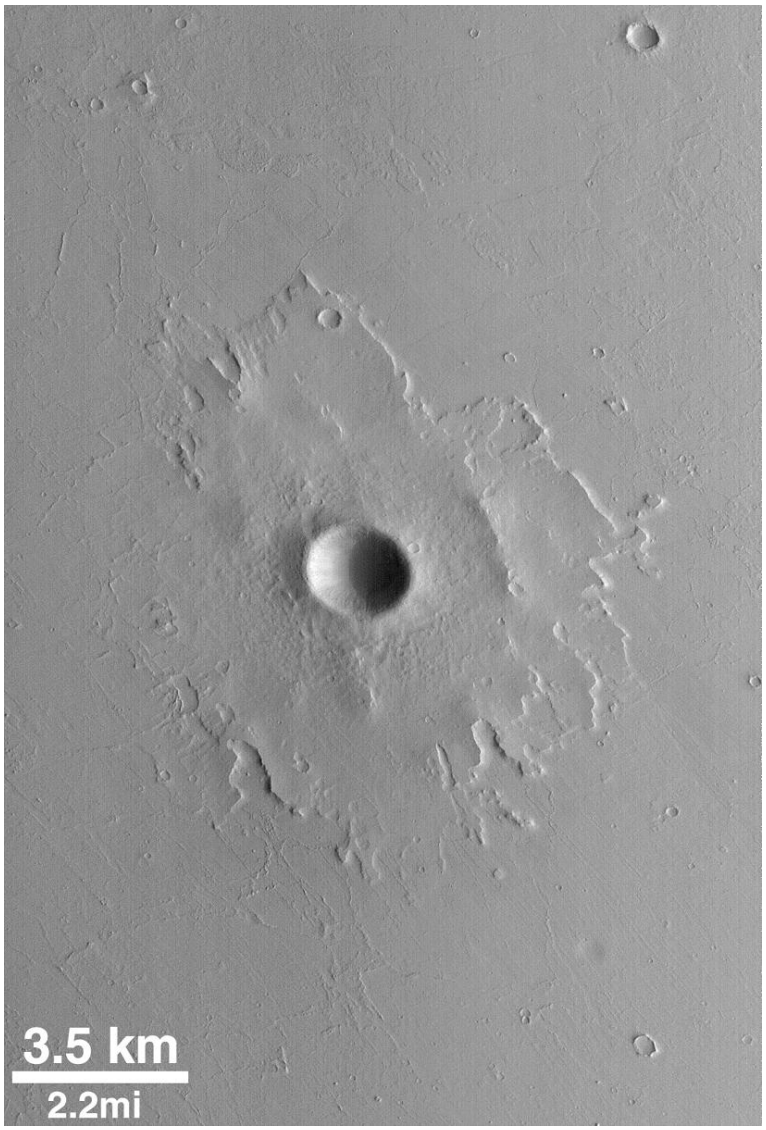


Photo Credit: NASA/JPL

Dickinson Crater on Venus

Dickinson Crater has a diameter of approximate 69 km.

Photo Credit: NASA/JPL

Crater on Mars

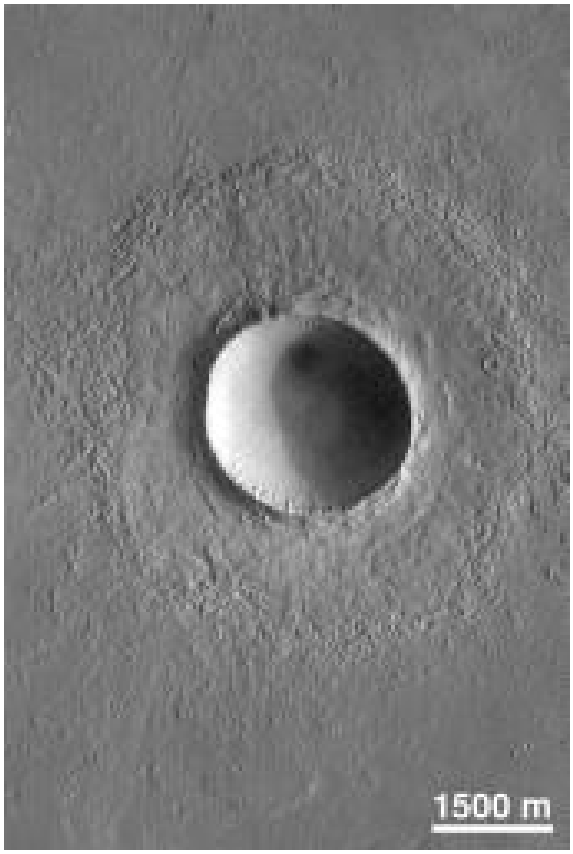


Photo Credit: NASA/JPL

A Chain of Craters on Ganymede

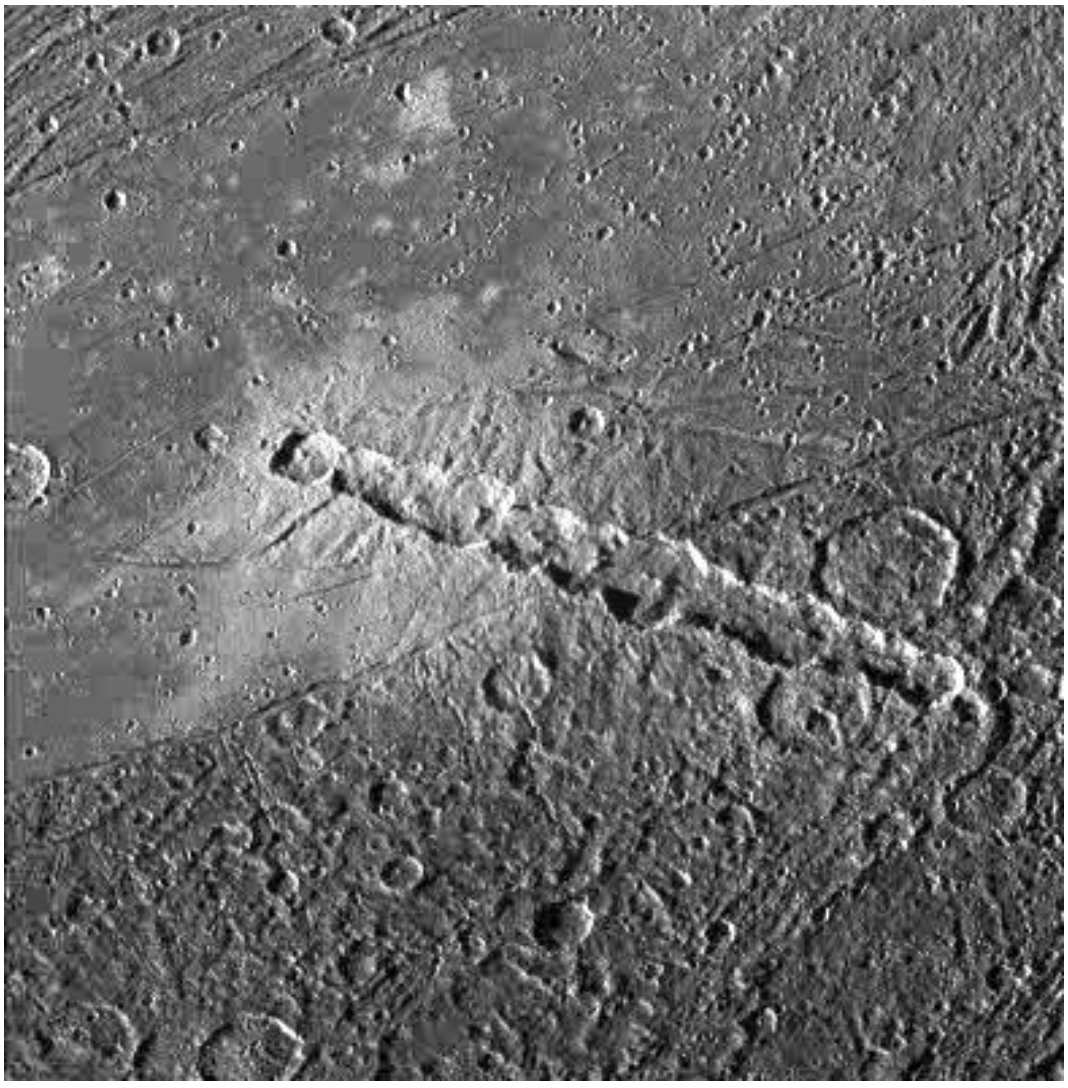


Photo Credit: NASA/Brown University

214 km

The Manicouagan Crater in Northern Canada

Photo Credit: NASA/JSC

Diameter of the Crater is approximately 70 km.

Craters on the Far Side of the Moon

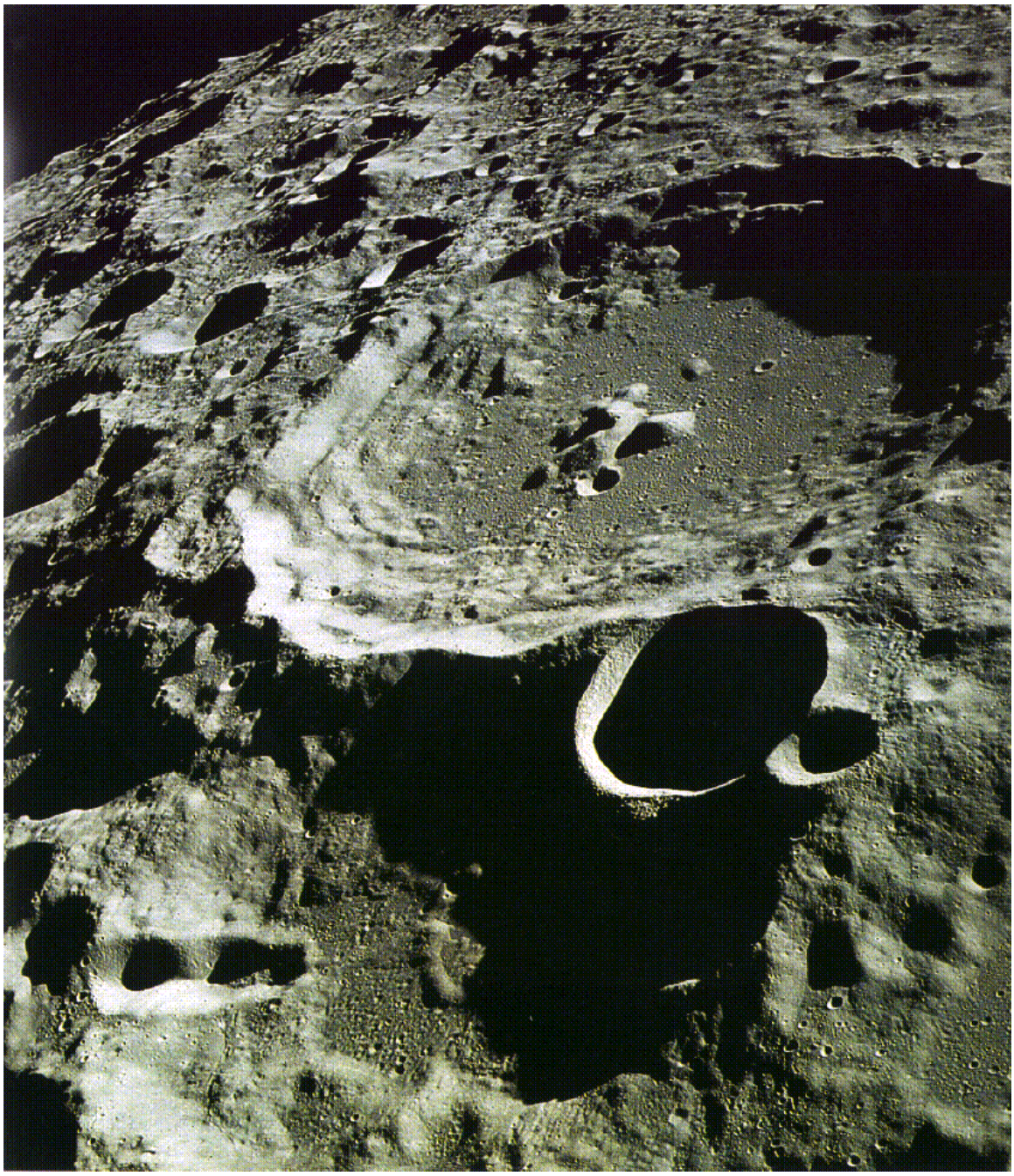


Photo Credit: NASA

Diameter of largest crater in picture above is approximately 80 km.

Pwyll Crater on Europa

1240 km

Comet Shoemaker-Levy 9's Collision with Jupiter

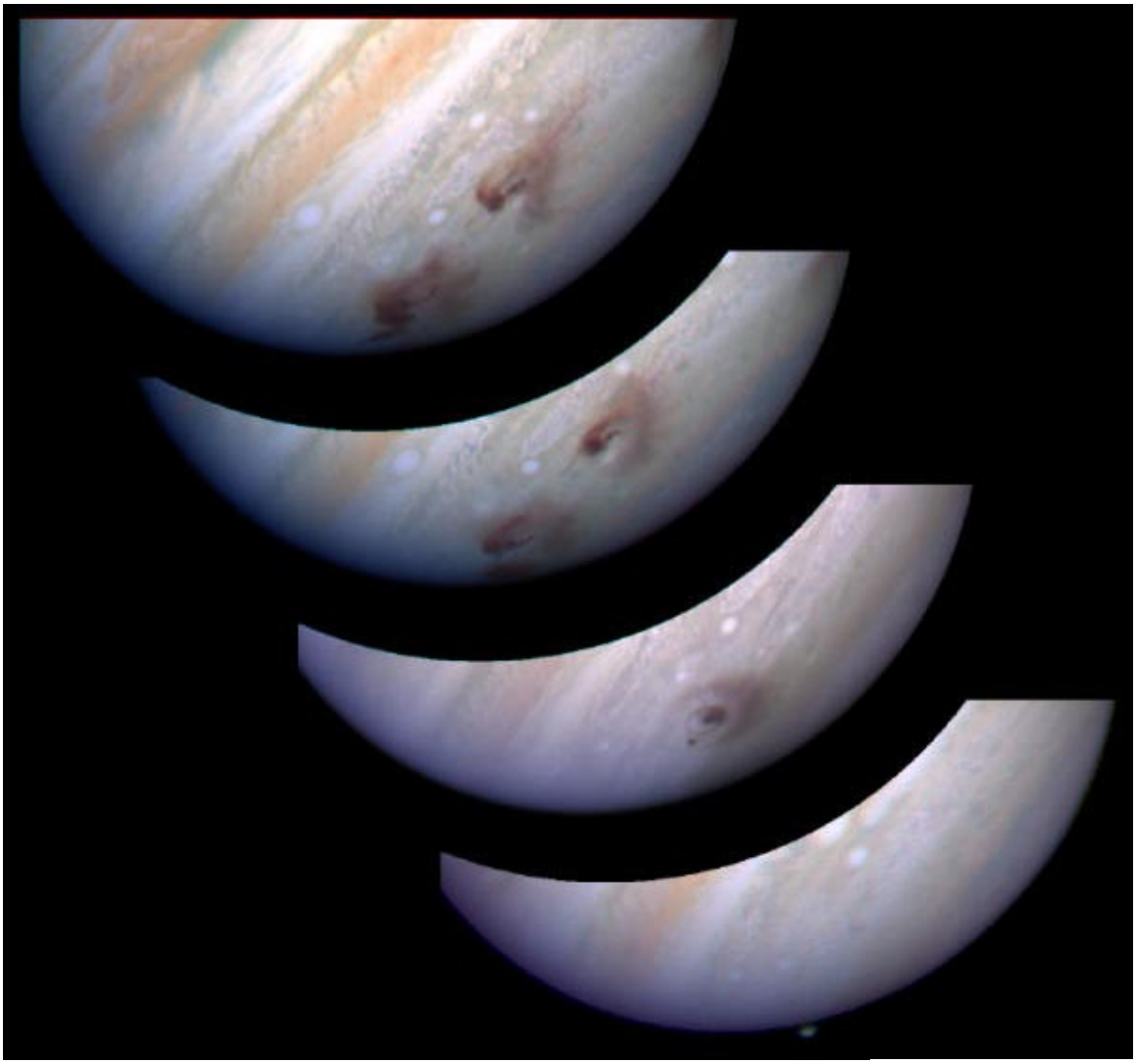


Photo Credit: HST/STScI

The diameter of Jupiter is 142,800 km

Appendix 2:
Current Scientific Thinking About Cratering
Background Science for Teachers

The iron nickel meteorite that created Meteor Crater in Arizona over 50,000 years ago weighed several hundred tons and struck the Earth at a velocity of 40,000 miles per hour. In a fraction of second, the meteorite was brought to halt by the surface of the Earth and its kinetic energy was transferred and converted into other forms. Within ten seconds, a mile wide, 570 feet deep crater had been excavated on the desert floor. The universe conserves energy, and it is this energy conservation, this need to deal with a large amount of incoming kinetic energy, that drives the process of cratering.

Any moving body has kinetic energy. This energy is the product of its mass and the velocity (Kinetic Energy = $1/2mv^2$). The Meteor Crater impactor struck the Earth with an equivalent explosive force greater than 20 million tons of TNT. The crust of the Earth must somehow deal with this massive amount of energy when a meteor slams into its surface. The familiar crater formation is the result of the energy exchange. The kinetic energy of the impactor determines the amount of energy involved, but the material properties of the impacted body determine how the surface will respond to that energy.

When you drop an object at a low velocity on to a surface, such as dropping a pen onto the carpet or a dish on the kitchen tile, the energy of the impact may be passed through the target as a pressure or sound wave without permanently disturbing the target surface. A large portion of the energy is reflected back into the object itself, causing the pen to bounce or the dish to shatter. The surface absorbs little of the energy, its molecules are compressed and released elastically, returning to their original positions after the compression by the impacting body is released. Cratering experiments conducted in the classroom are low energy impacts. We use surfaces of loose particles such as flour and sand that are easily moved to simulate the effect that larger energies have on surfaces such as rock. The surfaces in our experiments are not significantly structurally altered, the particles are just moved into new positions by the energy of the impact.

However, when larger impacts take place, the surface may not be able to bounce back so easily. The amount of energy in large impacts is so great that the compression of the surface by the impactor creates pressures beyond what the material can absorb in any elastic way. Every material has a limit, known as its yield strength, beyond which its material will be permanently altered by stress. Material subjected to pressures greater than its yield strength will crack, melt, and undergo other transformations.

Solar System scale impacts transfer energy in shock waves, which function differently than the pressure and transverse waves with which we are familiar. In a pressure wave, or sound wave, the molecules of the material vibrate and then return to their original position. A shock wave, on the other hand, is a front that moves through the rock at supersonic speeds structurally altering the rock through which it passes.

Cratering is often divided into three phases for ease of discussion, although all three phases flow from one into the next and part of the impactor and target can be in one phase while another has already moved on to the next. The first phase is referred to as the contact and compression phase. The impactor hits the surface, accelerating the surface material downward while the target's resistance to penetration slows the impactor. Material in the contact zone is compressed, material outside is uncompressed, and the line between them, the shock wave, moves forward. The shock wave moves outward into the target body and a similar shock wave also moves back into the projectile. The pressure of this wave is often far beyond the yield strength of the impactor. The impactor can be vaporized by the energy carried in this wave. This stage is considered over once the projectile has stopped moving and the shock front has moved completely through the projectile. This usually takes only fractions of seconds. The initial compression of the surface can push materials around the side of the impactor, causing them to squirt out of the sides at a high velocity. This effect is known as "jetting".

The second stage is excavation. In this stage, the shock wave continues to travel outward through the target material, losing energy to the transformation of rocks as it travels outward. The shock wave leaves the material behind it in motion.

A second wave, the rarefraction wave, arises from the release of the high pressure of the shock wave as it moves past the material. The interactions of this wave and the motion of the material following the passage of the shock wave combine to form the excavation flow field, the motion that carriers material away into lower pressure areas and forms the crater behind.

The final stage of an impact event is referred to as modification. This begins after the crater has been fully excavated and the shock wave has been attenuated by the target body. During modification, gravity pulls loose particles down the walls of the crater. Large craters can have entire sections of the wall slide down, pooling on to the crater floor, or forming features known as slump terraces.

Most of what we know about the cratering process comes from our studies of planetary impacts (including the Earth), explosion weapons testing, theoretical models, and laboratory experiments. Even though small in scale, laboratory studies allow the isolation of variables. Theoretical studies allow extrapolation and comparisons with craters found on the Earth and other planets allow for the testing of these extrapolations. One of the earliest scaling laws developed from weapons tests in the 1940's and 1950's found that the crater diameter is proportional to the cube root of the kinetic energy for hard targets. Laboratory experiments later revealed that crater diameter is proportional to the quarter to sixth root of a combination of energy and momentum for craters limited by gravity (very large craters and craters in sand).

A more detailed form of scaling treats the diameter of the crater as a function of a number variables; impact velocity, projectile density, target density, the yield strength of the target, gravity, and projectile mass and the effect of an atmosphere. The relationship between these variables is determined by holding all variables but one of interest fixed. To a minor extent, this is the sort of modeling that your students conduct in Activity 3: Predicting Crater Size. From the relationships discovered with this form of modeling, we find that we can predict crater size fairly well if the density of the impactor and the target bodies are similar. Calculations are also easier to make if the impact is "gravity dominated" as opposed to "strength dominated", meaning that the gravitational force pulling the impactor down is significantly larger than the material strength of the target that is resisting that downward motion. The porosity of the material may also be important in predicting crater size. In a highly porous material, energy goes into the compression of the pores, and the shock wave is attenuated more quickly.

Another factor of importance in cratering is the angle of impact. This is also a factor where the differences between low energy impacts, such as those in classroom experiments, and high energy solar system scale impacts are clear. In low energy impacts, as the angle of impact moves away from vertical, the shape of the crater becomes elliptical. High energy impacts still create a spherical shock wave, and therefore a circular crater, although the intensity of that shock is lessened and the crater will not have as great a depth. This discrepancy between the classroom model and the solar system scale reality is important to point out to your students and is discussed in Activity #4: Cratering in the Classroom, the Lab, and the Solar System.

How does all of this apply to the specific problem of cratering on Comet Tempel 1? The list of variables gives us some insight into the problem. We can control the projectile density, the impact velocity, and the projectile mass. Ideally, to determine what values to choose for those factors, we would like to know the target controlled variables – target density, gravity, yield strength, and porosity. However, these things are not well known. In fact, the driving purpose of the experiment is to learn these and other characteristics of the comet from watching the crater formation. The challenge is to use what we do know about the comet to choose an impactor configuration that will help us get the most new information out of the impact. We have a general range for the size of the comet and some ideas about density. We can make guesses about yield strength from what we know of the materials that compose the comet's surface. Ground based observations of the comet conducted by both professional and amateur astronomers in the years leading up to the mission will hopefully yield more information about the comet's rotation period and the size of the nucleus. Pooling all of this information together allows the mission design team to design an impactor and schedule an impact that will hopefully provide us with a lot of new information about the composition and structure comets.

References:

For more information on cratering, see the chapters on cratering in the two books listed below

Beatty, J. Kelly et al (Ed.) The New Solar System. Cambridge University Press, 1998.

Weissman, Paul R. et al. (Ed.) Encyclopedia of the Solar System. Academic Press, San Diego, 1998.

Appendix 3:
Deep Impact Cratering Research
Scientific Modeling in Action

In science, we work to develop methods of describing and understanding what is going on around us in ways that allow us to make useful predictions about how the world works. We call these descriptions "models". Think for a minute about a model airplane. In some ways, the model airplane is just like the original aircraft and you can learn a lot about the original by building the model. However, in other ways, the model is significantly different from the original. You can adjust the model or build new models that are more and more like the aircraft, but a model is still not the aircraft itself. In a similar way, scientific models can be useful in allowing us to learn about a physical phenomenon or to test our theories about a phenomenon, but they are not the actual phenomenon itself. Scientific models can take the form of graphic descriptions of how the pieces of something are arranged or how they interact, such as in the Bohr and electron cloud models of atoms. They can take the form of mathematical formulas, such as those used for calculating speed, acceleration, force, etc. Or, scientific models might take the form of simulations, smaller scale events that recreate some, but not all, of the factors involved in the actual event. Modeling is a useful way to understand the world around us. To make it really work for us, however, we need to be aware of the limitations of what our models can show us as well as their strengths.

Modeling is particularly useful in studying events that are difficult to get to or to recreate. Cratering is just such an event and scientists interested in cratering rely on modeling as a regular part of their research. You have just modeled cratering in your classroom. You designed and conducted experiments that explored the effects of a variety of factors and then used your results to create some quick mathematical models for making predictions. Your experiments gave you some ideas about how some factors, such as impactor mass and velocity, can effect crater diameter and depth. However, as you examined in class today, your experiments modeled low energy impacts, which do have some significant differences from the high energy impact the Deep Impact mission plans to carry out on Comet Tempel 1. Deep Impact scientists are also modeling cratering using both numerical and laboratory models to find out more about what to expect in the actual cratering event.

Laboratory Tests

Dr. Peter Schultz is a member of the Deep Impact Science team and a professor at Brown University. He conducts laboratory cratering experiments using the AVGR (Ames Vertical Gun Range) at the NASA Ames Research Facility in California.

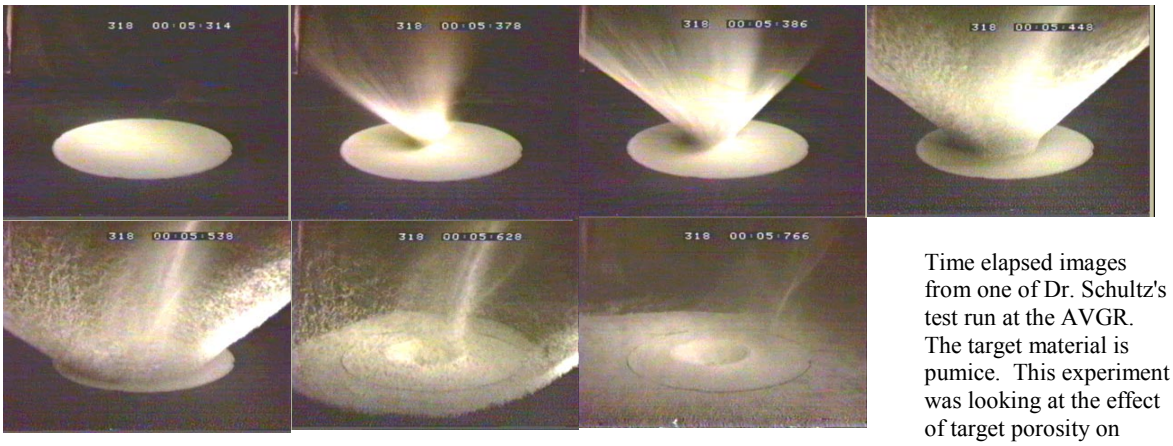
The AVGR consists of a large gun barrel on a hinge that allows the angle of impact to be varied from 0 to 90 degrees in 15 degree intervals. There are three available launchers at the facility, an air gun, a powder gun, and a gun that uses a combination of hydrogen and gun powder. The guns can fire a number of differently shaped projectiles, such as spheres, cylinders, irregular shapes, and even collections of particles, that are made of a number of materials, such as metal, glass, or minerals. The equipment at AVGR allows Dr. Schultz to achieve impact speeds much greater than those we were able to achieve in the classroom. "Our gun can shoot up

to 7.5 km/s for small (1/8 inch) projectiles," says Dr. Schultz. The guns are fired into a 2.4 m vacuum chamber. A large variety of surfaces and atmospheres can be placed within the chamber.

Dr. Schultz is interested not only in the final size of the crater, but in the entire process of cratering. He uses a variety of high-speed imaging devices that allow him to examine cratering events in slow motion. Some of the devices capture images of the cratering event at a rate up to 35,000 frames per second. Other devices allow for measurement of the brightness of the light produced in the impact. He also uses spectrometers, which allow him to break the light into its different components, like a prism, and examine the effect cratering has on the chemical signature of materials that can be found in light. His equipment also allows him to measure the velocity of the excavated particles as they are thrown away from the crater.

The Ames Vertical Gun Facility

Dr. Schultz will conduct a large number of experiments in the course of preparing for the Deep Impact mission, looking for the effects of different projectile mass and densities on a variety of different targets. Currently, he is conducting experiments looking at the effect of the porosity of the target surface on the growth of the crater. Porosity is a measure of the amount of empty space in a material. A highly porous material is one in which there are lots of empty cavities. Think about a sponge and a brick as an example. The sponge is more porous or has a higher porosity than the brick. We don't currently know much about the porosity of comets and hope to learn more from the results of the Deep Impact cratering event. Dr. Schultz is exploring the effect of porosity on crater growth so that by examining the growth of the Deep Impact crater on Tempel 1, we will be able to learn something about the porosity of comets.



Time elapsed images from one of Dr. Schultz's test run at the AVGR. The target material is pumice. This experiment was looking at the effect of target porosity on cratering.

Mathematical Modeling

In activity three of this module, "Looking for Patterns and Making Predictions", you examined your classroom data for patterns and put together a rough mathematical formula to make predictions about cratering results for previously untested masses, impact velocities, and other factors. These were fairly rough estimates based on only a few measurements taken over a narrow range of possible values. Imagine how much better your predictions would be if you had a greater number of measurements taken over a larger range of variables. Over the course of the last century, scientists have put together a large collection of data about the process of cratering. This data comes from laboratory tests like those mentioned above, studies of impact craters on Earth and elsewhere in the Solar System, and the study of craters produced by explosive weapons tests. Scientists have examined this base of data and put together mathematical models of cratering known as scaling laws.

Dr. H. Jay Melosh of the University of Arizona is another member of the Deep Impact Science Team. Dr. Melosh works with computer programs originally developed to model nuclear explosions. "These (computer) codes simulate all of the physical processes that occur in a real impact and have successfully reproduced many small-scale impact experiments. We are making simulations of the Tempel 1 impact to explore the range of possible outcomes of the actual experiment and decide how to distribute the mass in the impactor to make the biggest possible crater in spite of not knowing the exact physical properties of the comet, " says Dr. Melosh, describing his work for the Deep Impact mission.

While there are quite a number of unknowns about the comet, many of the questions about cratering center around the comet's density, porosity, and strength. Thus many of the numerical simulations run by Dr. Melosh are designed to explore these variables. The focus of his work at this point is to use the test results to make decisions about the design of the impactor.

Limits to Deep Impact Modeling

While the scientists on the Deep Impact team are working with some of the best impact laboratory facilities and the most complete numerical code information, there are limits to these models just as there are to any scientific modeling process. The biggest hurdle to modeling the Deep Impact event is the information that we don't have about the nature of the target body - Comet Tempel 1. In fact, we are hoping to learn much of what we don't know from watching the formation of the actual crater. If we could exactly model the event, then we wouldn't need to make the crater!

The scientists involved in cratering research on the Deep Impact team explore a variety of possible conditions and compositions for the comet. Their goal is to choose an impactor design that is highly likely to give us a large enough crater to allow us to measure and learn what we would like to know about the interior of comets. By examining the effect of different conditions on crater size and formation in the laboratory and in numerical simulations, the Deep Impact scientists are developing an understanding of cratering that will allow them to discover some of the unknown traits of the comet by examining the Deep Impact cratering event.

Appendix 4
Deep Impact Project Journal
Teacher Instructions

The main purpose of the journal assignments is to help foster a sense of continuity and encourage the students to keep looking at how what they are doing in class relates to the overall goal for the project. They provide you with homework assignments over the course of the unit and a chance to get a look at your students' thought processes as they move through these activities. These are just some suggested questions to assign and there are suggested times for assignments to appear throughout the activity instructions. You may want to alter these to meet your own classes needs or fit into your own structure. You may want to collect them as the unit progress as a progress check on your students' thinking about the process, or you may want to review them together at the end. The general goal is just to keep your students thinking about **why** they are doing what they are doing.

Deep Impact Project Journal

Project Goal: 1) To figure out how to make a crater of a particular size on a comet.
2) To learn more about the process of science inquiry

Over the course of the next 2 weeks, the class will be working towards the project goals. Your project journal will give you a chance to think about how what you did in class each day helps move the class towards those final goals. When you are assigned a journal writing assignment, answer the question as completely as possible, writing down everything you think of as you think about the questions. Taking the time to write complete responses and think about these questions as they are assigned will make the final report you need to make much easier to write and will help you focus on what is important each day in class.

Assignment #1

1) Think about the list of possible factors that influence crater size generated by your class. write a paragraph on which factors you they are the most important factors for determining crater size, why you selected those factors, and what effect you expect those factors to have.
2) If you were designing an experiment to test one of the factors, how would you do it? How would you set it up? What things would you change in each trial? What would you keep the same? What measurements would you make?
3) How did what we did in class today contribute to our goal for the project?

Assignment#2

1) What factors seemed to have the most effect on cratering? Why do you think those factors were having an effect?
2) What needs to be done differently from today's exploration to prove that there is a definite relationship between a factor and the crater's size?
3) How did what we did in class today contribute to our goal for the project

Assignment #3

1) Why do formal experiments designed to find a relationship between two quantities need to be more structured that the initial explorations into cratering we conducting?
2) What results to you expect to get from your experiment?

Assignment#4

1) Is there anything in your data or experiment that has surprised you so far? Explain your answer.
2) Did your group collect additional data today or research some strange points in your data? If so, what did you find?
3) How does your experiment contribute to our overall goal for the project?

Assignment #5

1) Write a paragraph describing what happens during an impact event and the formation of a crater. Include all factors in your answer and discuss why you think those factors are influencing crater size.

Assignment #6

1) Why is it useful to find patterns in data?
2) How did what you did in class today contribute to our overall goal for the project?

Assignment #7

1) How did what you did in class today contribute to our overall goal for the project?

Appendix 5
Communicating with the Deep Impact Team

Thank you for taking the time to look over these materials and use them with your students! The Education and Outreach team would like you to know that support for your use of these materials does not have to end with the directions printed here. There are a number of ways in which you can interact with us outlined below.

Submitting Student Reports

Your students are told at the beginning of these activities that their final activity will be a report to NASA on the results of their experiments. The Deep Impact team is interested to see what the students come up with and would like to acknowledge the work they have done. If you are willing to send your classes' final reports in to us, we will send an acknowledgement and thank you letter (printed on official letterhead!) to your students. Please mail reports to:

Gretchen Walker
Dept. of Astronomy
University of Maryland,
College Park, MD 20742-2421

Scientific and Teaching Questions

Have questions about comets or cratering? Have a great idea about how to use these materials in the classroom? Have a problem implementing the materials that you would like to share or get some help with? Visit the message boards in the Education section on the Deep Impact web site. http://deepimpact.jpl.nasa.gov

Participate in Educational Research

Deep Impact is interested not only in researching what happens in comets, but also in finding out how effective our materials are at relating the experience of science inquiry to students. If you are interested being a part of this research, contact Gretchen Walker at the address above or phone 301-405-0355, e-mail: gwalker@astro.umd.edu

Find Local Community Events

Our web site is also has an index of community events sponsored by science museums, star parties, and local speakers. Take a look and see if there is something happening near you!