Laboratory 15: Meteor Impact

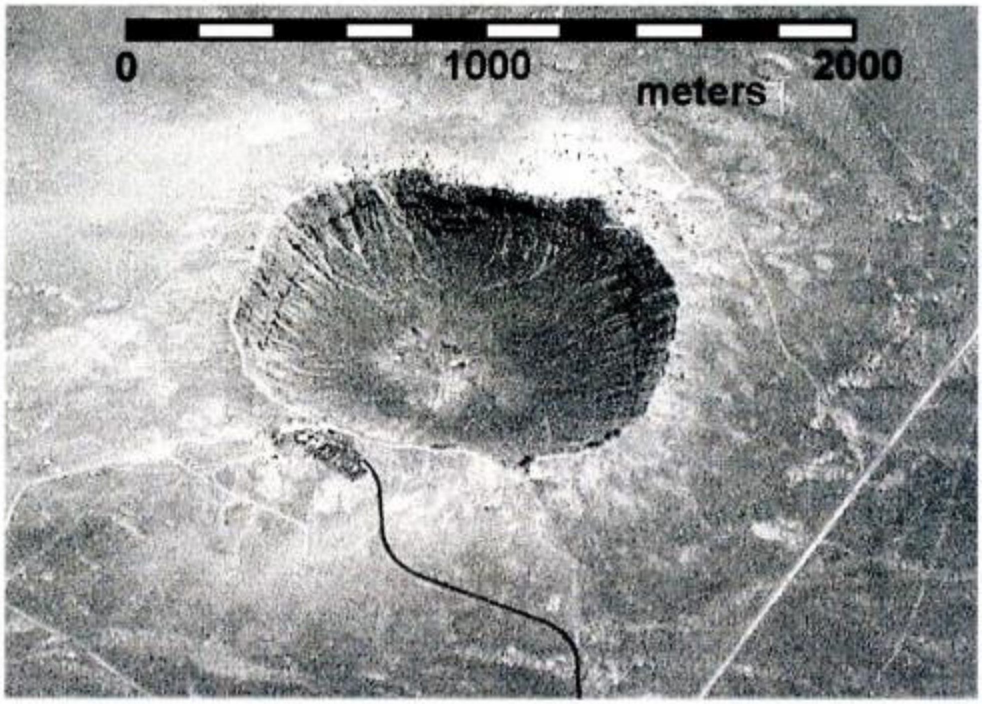

Figure 1: Meteor Crater

Meteor Crater was formed about 50,000 years ago by a massive meteorite striking the Earth. There were no humans living in North America at that time: no one was around to observe it. One might think that we could never guess how large the meteorite was that formed the crater since some matter was vaporized, some matter was ejected outward, still other matter was buried. However, through experimentation we can make a reasonable estimate of the meteorite's diameter. First, from the picture above, estimate the diameter (in meters) of Meteor Crater. Enter this on the Data Sheet.

To estimate the diameter of the meteorite that created Meteor Crater we need to understand what the possible variables arc that might determine the diameter. It turns out that the crater diameter is a function of a single variable. What is that variable? Well, ask yourself if the following list of meteorite properties covers the possibilities: mass, radius, velocity, kinetic energy. Some of these variables are dependent on others. Your task in this laboratory is twofold, to determine what variable, X, is the important one for determining the diameter and the functional dependence of the diameter on X.

We will be studying ball bearings. Bearing mass can be measured with a microbalance. Radius can be measured with a vernier caliper. We will now discuss velocity and kinetic energy.

While not all meteorites have the same elemental constituency, most are similar enough that we can treat them so and assume they have approximately the same density. Then their masses, *M*, and sizes are easily related, i.e.

$$M = density \times volume = \rho\ \frac{4}{3}\pi r^3,$$

where ρ is the density and r is the radius of the spherical object. If the density is the same, then mass and radius of the object are directly related. Thus, we can control the mass of a spherical object by choosing the radius of the object and by choosing the density of the object. The energy associated with motion is called the kinetic energy (KE) and is defined as:

$$KE = \frac{1}{2}Mv^2 \quad (1)$$

where M is the mass and V is the velocity of the object. Equation 1 implies that a fast-moving meteorite will have more kinetic energy than the same meteorite moving more slowly. By the same reasoning, a relatively small, fast-moving meteorite can deliver as much kinetic energy as a larger, slower-moving meteorite.

The first question to ask is, how do we control velocity and kinetic energy in the laboratory? When an object is dropped in a gravitational field, gravitational potential energy is converted into kinetic energy plus a certain amount of heat due to friction of the object passing through the air. In the case of smaller meteors entering the Earth's atmosphere and striking the Earth, it might be a reasonable supposition that these meteorites reach *terminal* velocity because of air friction. On the other hand, truly large meteors probably punch their way through Earth's atmosphere without being slowed appreciably. We will assume this latter condition.

In the first case, we cannot emulate these conditions in the laboratory with balls of any reasonable density, i.e. we cannot drop an object at a high enough distance in most cases for it to reach terminal velocity. We will use only objects with enough density to ignore terminal velocity effects over short distances. Then gravitational energy lost equals kinetic energy gained, i.e.

$$MgH = \frac{1}{2}M\,v^2$$

$$\Rightarrow v = \sqrt{2gH} \tag{2}$$

where H is the height of the fall in meters and $g = 10\ m/s^2$ is the acceleration due to gravity at the surface of the Earth. Thus, the velocity at impact does not depend on mass. Galileo proposed this result after dropping different sized objects from the tower at Pisa.

We are going to drop balls into a sandbox and measure the width of the resultant crater in a sand box. Make a list of the possible experiments you can make to determine which variable(s) determines the size of the crater. You want to design the experiments so that as a single parameter is varied, the other parameters being fixed or assumed to be irrelevant. I will start the list.

1. Drop several steel ball bearings with the same density from the same height. In this case we hold density, height, and velocity constant. Mass and kinetic energy are the variables and kinetic energy varies directly as the mass. The size of the ball bearing changes, but this variable is not considered in this experiment.
2. Drop the same steel balls from different heights so they will have different impact velocities. In this case velocity is the variable.
3. Drop several balls with the same radius but different densities from the same height. Mass is the variable.
4. There are other possibilities. As you go along you will think of others to try and conduct these additional trials as before.

Variable Mass, Same Velocity

In this lab, you will simulate a meteorite's impact crater by dropping steel ball bearings into a sand box. You can control the kinetic energy of the bearings by changing the diameter of the balls. The balls will be dropped from the third floor of Bowers Hall. Remember to wear a hard hat at all times. It is easy to lose a ball bearing in the sand, so be patient. If you can figure out a way to recover the ball bearings in a more efficient manner than just sifting the sand with your hands, try it. A large magnet would be a good idea for sifting the sand.

Before taking crater data measure the mass of the seven steel ball bearings we will be using. Use the laboratory balance to measure their masses and record the data in Table I. Now make a plot of mass versus volume. Make a least squares fit to this data and extract the density of the ball bearings and the error in the density. Compare this to the Handbook value for the density of steel. Is your measurement reasonable?

You will drop seven steel ball bearings with the same density from the same height. Everything is held constant except the mass of the bearings. Mass is the variable. Note that in this part of the experiment kinetic energy and mass are not independent as kinetic energy is directly proportional the mass. Size of the ball bearings is not considered. Whether or not size is significant must be determined later using a different set of data.

In Table II you should calculate the final velocity and kinetic energy of objects dropped from the third floor. Do this using equation 2.

Anyone on the first floor (near the box of sand) MUST wear a hard hat and safety goggles at all times!

Go to the stairwell. One group member should be up on the third floor (to drop balls) and the other(s) should be on the first floor to measure crater diameters. Start with the smallest steel ball first (1 /8 inch) and work your way up to the largest (1.5 inches). When measuring crater diameter, measure from rim to rim (highest points on both sides). Measure crater diameter in meters and record your data in the fourth column in Table II.

Go back to the lab. I recommend using R to do your calculations. You are looking for some straight line behavior linking the various variables to the diameter of the crater. Plot the results. If the plot is not linear see if you can manipulate the data to make it so, i.e. take logs of the values or exponents. For instance, you might try to take the logarithm of one of the quantities, or both. Don't be satisfied with something that looks vaguely linear.

Write out the relationship explicitly between the crater diameter and the variable, X, i.e

d = function(X).

Variable Mass, Different Velocity

Repeat what you did in the previous section taking data from the second floor. Record your data in Table III. Fit your results. Are there any significant differences in the linear relationship between crater diameter and kinetic energy with the previous result?

Combine the data taken at different heights for the different ball bearings. Fit your results. Write out the relationship explicitly between the crater diameter and the variable X.

Balls of Different Density

You have a number of balls with different densities. Measure their masses and radii. Calculate their velocities and kinetic energies when dropped from the third floor. Are these data satisfied by the relationship that you have previously derived?

Other Possibilities

If you have the time you might want to try some other possibilities. For instance, does the size of the ball make any difference? Take three different ball bearings: small, medium, and large. Calculate the heights from which these balls can be dropped so that they have the same kinetic energy on impact. Are the crater sizes any different? What does this say?

Interpreting Diameters of Past Meteorites

The goal here is to estimate the *diameter of past meteorites* using the diameter of their impact craters and the data you've gathered so far. Use your derived relationship for crater diameter in terms of one of the variables: mass, radius, velocity, kinetic energy. Now, let's start with some widely known impact sites:

Meteor Crater, Arizona.

From your equation you can predict some variable X. Let us relate this variable to meteorites. You will need to know the density of the meteorite and the velocity of the meteorite. The meteorite that struck the Arizona high desert to form Meteor Crater was composed of mostly iron (there are still pieces of it laying in and on the rim of the crater). This kind of meteorite has a density similar to that of the ball bearings (about 7.9 $\frac{g}{cm^3}$). Let us assume the velocity is 50,000 miles per hour. Determine the size of the impact crater diameter from the front page of the laboratory.

Calculate the volume of the meteorite and extract the diameter of the meteorite. Record this value.

So what is the correct value? Search Google for an estimate of the diameter of the meteorite that produced Meteor Crater. You might try this site (if it is still active): http://neo.jpl.nasa.gov/images/meteorcrater.html Is your estimate reasonable?

Chicxulub Crater, Yucatan Peninsula, Mexico

This impact crater was discovered in 1991, by Alan Hildebrand. It is buried under sedimentary rocks in the northwestern part of the Yucatan Peninsula, Mexico and out into the Gulf of Mexico. Radiometric dates on melt rocks from drill holes are exactly 65 million years old, the time when the dinosaurs became extinct. This is widely believed to be the so called "smoking gun," i.e., the actual crater left behind by the meteorite that killed the dinosaurs. Because this meteorite had such a global impact on life on Earth, it's important to estimate its diameter so that one could compare it to modern-day asteroids in our region of the solar system. This can help answer the question: Is the Earth at risk of a catastrophic meteorite impact?

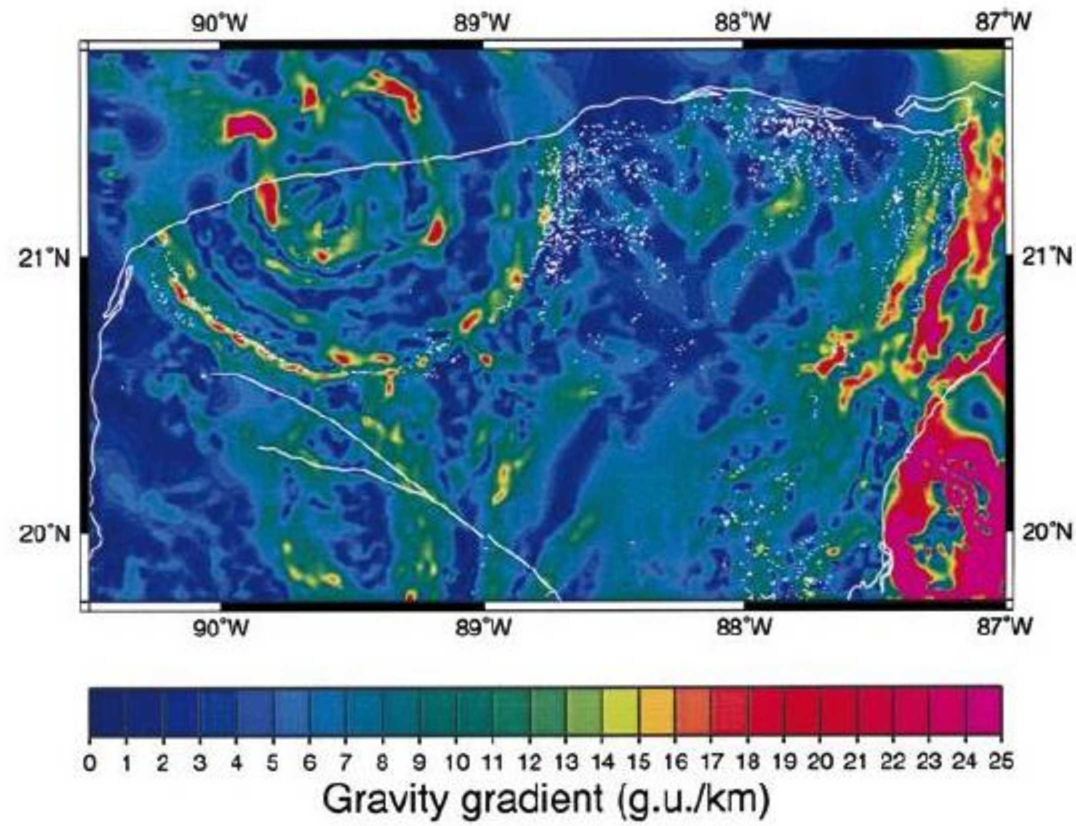

Figure 2 Chicxulub Crater from "The Chicxulub multi–ring impact crater, Yucatan carbonate platform, Gulf of Mexico"
http://www.scielo.org.mx/scielo.php?pid=S0016-71692011000100009&script=sci_arttext

This crater is not exposed at the surface but does manifest itself in geophysical maps of the region. This map shows the circular structure of Chicxulub Crater. The lighter areas are "gravity highs" whereas the darker areas are "gravity lows." The white line is the northwestern shoreline of the Yucatan Peninsula, The white dots are the location of limestone sinkholes, which are located on the outer rim of the crater. Why the sinkholes arc located on the rim is unknown, but may be related to the way in which groundwater has moved in the past.

Can you estimate the size of the object which created this crater?

Data

Table I: Mass of the Ball Bearings

Ball	Diameter (Inches)	Diameter (mm)	Volume (m^3)	Mass (kg)
1	0.125	3.18		
2	0.188	4.76		
3	0.250	6.35		
4	0.500	12.7		
5	0.750	19.1		
6	1.000	25.4		
7	1.500	38.1		

density of the steel = ρ= σ_ρ=

book value of density of steel % difference =

Table II: Crater Diameter 3rd Floor

Ball	Mass (kg)	Velocity (m/s)	Kinetic Energy (J)	Crater Diameter (m)
1				
2				
3				
4				
5				
6				
7				

Table III: Crater Diameter 2nd Floor

Ball	Mass (kg)	Velocity (m/s)	Kinetic Energy (J)	Crater Diameter (m)
1				
2				
3				
4				
5				
6				
7				

Table IV: Balls of Different Density

Table V: Other Possibilities