Lab 1  Preparation Questions - Tear off this page and turn in at the beginning of Lab

Name  

Section Day  

Date  

1) Name one factor that influences the crater diameter size. If this value increases, would the crater diameter increase or decrease?

2) REFER TO THE LAB DEMO SECTION: Make a rough sketch of what you think your data table might look like. Think about things like projectile and target size, density, composition and what you’ll be measuring and calculating.
ES 110L Lab 1
Impacts, Earth Accretion and their Thermal Effects

Impacts have plausibly played a major role in the evolution and extinction of life on Earth, a role which will be explored in great detail in the last several weeks of the class. Less widely appreciated (but arguably no less important for Earth history) is their role in the formation and early history of the Earth. The goal of this lab is to explore the energies released in impacts, use scaling relations related to the dimensions of craters generated by impacts, and finally to examine some of the thermal effects of impacts, by converting some of the kinetic energy release into increased temperature of the planet.

General Information:

Impactors: Typically, impactors come in three separate (but often mixed) flavors: ices (or comets), stony (or chondritic), or metallic. Ices generally have a density of around 1000 kg/m$^3$ (sometimes less, if they contain lots of methane and ammonia), stony meteorites have densities around 3000 kg/m$^3$, and metallic meteorites are close to 8000 kg/m$^3$.

Targets: Well, water is 1000 kg/m$^3$, sedimentary rocks (sandstones, etc.) are around 2400 kg/m$^3$ (or a little less), and good igneous rocks (like granites) are around 2600 kg/m$^3$.

Other things that might be useful:
- the mass of the Earth is about $6.0 \times 10^{24}$ kg;
- the mass of the moon is about $7.0 \times 10^{22}$ kg.

The Kinetic Energy (KE) of an impactor (or anything else) is equal to $1/2 * \text{mass} * \text{velocity}^2$. The mass of the impactor is calculated from its density ($\rho$) times its volume (V). The volume of a sphere is calculated from $4/3 * \pi * r^3$ where $r$ is the radius of the impactor. Thus, the density of the impactor and its velocity are inputs in this model.

Velocities of Impactors: These are generally estimated at between 5.0 and 45 km/sec, primarily from ballistics analyses of ejecta from the impact. Usually, between 10 and 20 km/sec is a pretty reasonable guess for most asteroidal/cometary bodies. Note that these are far in excess of "terminal velocity" (around 0.05 km/sec), which is air friction dominated: these bodies come in so fast that air friction simply doesn't have time to slow them down (although if they're small enough, they can be, and generally are, vaporized).

Crater Diameter: From a wide range of data on impacts (usually things like steel into steel, steel into concrete, steel into sand, depleted uranium into steel, etc., etc.) and explosions, a semi-theoretic expression for crater diameter has been derived by Gault and co-workers. It is:

$$D_{\text{crater}} = 1.8 * (\rho_{\text{projectile}}^{0.11}) * (\rho_{\text{target}}^{-0.33}) * (g^{-0.22}) * (D_{\text{projectile}}^{0.13}) * (KE_{\text{impact}}^{0.22})$$

where:
- $D$ = diameter
- $g$ = acceleration due to gravity
- $\rho$ = density
- KE = kinetic energy

The crater diameter comes out in meters (*see note about UNITS below)
These dependencies are pretty intuitive: denser projectiles make bigger craters, denser targets make smaller craters (harder to excavate material out of them), larger gravity makes smaller craters (harder to excavate), larger projectiles make slightly larger craters, and more energetic impacts make larger craters.

*A note about UNITS*: Usually, units are conserved in science equations (so that, let's say, 5 meters/second * 5 seconds would equal 25 meters; i.e. the seconds cancel) and usually it is a good check to keep track of the units in the problem to make sure the answer is in units that fit the problem (i.e. if the problem asks how fast a car is going, and you get '50 kilometers' instead of '50 km/hour' as an answer, you have probably gone astray). However since this crater size relation is a model and not a fundamental law of physics (it cannot be derived), the units are not conserved (which means the answer you get depends on which units you use!), and thus requires input in SI (meters, kilograms, seconds) units.

**Acceleration Due to Gravity**: on Earth, it's 9.8 m/s²; on the moon, it's 1.67 m/s². For smaller, less massive bodies, gravitational acceleration is less.

**Caveats**: The model here is for 90 degree impacts (straight down into the target). A simple factor of sin (theta) could be included if one actually knew the angle at which the impactor was coming in. Also, the cratering depths and diameters are for transient craters (analogous to splashes): these are quite close to final crater dimensions for moderate sized impactors, but for very large sized impacts, geomorphic effects (backfall of ejecta, wall collapse, infilling) are clearly going to follow the initial crater formation (e.g., 2000 km deep craters simply don't last). Also, this sort of crater scaling doesn't work so well for very small impactors (speeding marshmallows, etc.)

The estimated Richter magnitude of earthquake that each impact will generate has been included. Since the Richter scale is energy based (log E_{seismic} = 4.8 + 1.5 * Richter magnitude), the Richter magnitude of an impact is estimated to be = 0.67 log E_{impact} - 5.87. The estimated efficiency, or amount of energy which actually goes into ground motion, of impacts is only 1 part in about 10000! The rest of the energy goes into local heating, deformation, ejecting stuff, etc.)

**Some comparison energies**: A Chevy Suburban (~ 2000 kilos going 100 km/hr) hitting your stalled car on the freeway: ~ 8x10^5J
Energy of the food intake of everybody in the US (assume 2000 food calories/person/day): ~1.7x10^{15}J

**LAB DEMO** (25 points)

To illustrate impact events, we will fire impactors into tubs of targets, and measure the size of the craters produced. Using the equation above and assuming an impact velocity of 5.00 m/s, calculate the expected crater diameters for these impacts. How do these compare to the actual craters produced? Why might the calculated and observed crater sizes differ?

Choose impactor and target materials so you can make a statement about the relationship between density and crater size. Make sure to document the materials and use the correct densities in your calculations. Think about your experimental design before starting—what is your question? Do you have a hypothesis about how different materials/densities will affect crater diameter? How will you organize your data?
Make sure to write down your hypothesis, answer all the questions, and turn in your data table to receive full credit for your lab demo. Also, record all measures with 2-3 significant figures.

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**PROBLEM 1** (25 points)

For starters, let's just look at the difference produced by composition on the impact effects of different 5.0 km bolides: calculate the crater diameter, Richter magnitude* and kinetic energy release of an impact by a 5.0 km wide comet (a cosmic snowball), a 5.0 km wide rock, and a 5.0 km wide chunk of metal, each moving at 20 km/sec. Assume that they're impacting into igneous rock. Which bolide creates the biggest impact? Which, the smallest?

*Remember, the estimated efficiency, or amount of energy which actually goes into ground motion, of impacts is only 1 part in about 10,000.

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**PROBLEM 2** (25 points)

The average density of the Earth is about 5500 kg/m³, and its radius is 6371 km. Assume that it accreted from 3.0 km diameter objects of the same density as the planet. How many such objects would be required to form the Earth if no material is lost during planet formation?

Assume that the average infall velocity is about 5.0 km/sec (when it's just starting to accrete, the gravitational acceleration of the planet will be very small, so the incoming velocities will be, on average, smaller and as the planet gets larger, so will its gravitational acceleration. But we will assume, for ease of calculation, that all of the objects that go into the accretion have infall velocities of 5.0 km/sec). Given the resultant energy produced by accretion of the Earth from bodies of this size, we can (with one or two other pieces of information) calculate how much we expect the early Earth to have heated up.

The average heat capacity (C_p) of rock is about 1000 J / (kg * K): this parameter describes how much energy it takes to heat up one kilogram of rock by one degree Kelvin. With the mass of the Earth, and your calculated accretionary energy, calculate how much the early Earth heats up if all of this energy were retained as thermal energy (and not lost, or re-radiated to space) and all the kinetic energy of it goes into heating (hint: use dimensional analysis….). Does your answer seem reasonable? Why or why not?

How much does the Earth heat up if only 50% of the heat is retained?

How much does the Earth heat up if 10 km bolides aggregated to form the Earth? How does that compare to the heat from 5.0 km impacts? Does this make sense? *Do this mathematically, to prove to yourself that you’ve thought through this carefully.

Note: This does not include heating from short-lived radioactivity or core formation, so any estimates here could be conservative.
PROBLEM 3  (12 points)

Dinosaurs, and 60% of all life on Earth disappear from the stratigraphic record around 65 million years ago. This is an example of a mass extinction, and is the basis for defining the boundary between the Cretaceous and Tertiary periods of geologic history, i.e. the K/T boundary, which we will talk about more in lecture.

The cause of historic extinction is particularly interesting to us because it would be of some distress to experience another extinction event (especially if it occurs in our lifetimes!). Coincidentally, a large crater, called the Chicxulub crater, has been found off of the Yucatan Peninsula of Mexico, which has been dated to 65 million years ago. A very popular hypothesis to explain the K/T extinction is the impact of a large bolide that vaporized and suspended enough material to catastrophically affect the atmosphere’s transparency to sunlight, and subsequently kill most life.

The original diameter of Chicxulub is difficult to determine since so much time has elapsed since its formation and it is buried under 300 - 1100 m of carbonate sediments, but it is clearly quite large. It is likely that the impactor was a comet. Comets travel really fast, let’s say 40.0 km/s. Let’s assume the comet impacted sedimentary rock. If we also assume a typical comet diameter of 15 km, and a density of 1100 kg/m$^3$; how large of a crater diameter would this predict?

PROBLEM 4  (13 points)

It is widely believed (with a rather good basis) that the final major event during Earth accretion involved the impact of an approximately Mars-sized object into the proto-Earth. Assuming a bolide diameter of 3200 km, an impact velocity of 6.00 km/sec, and an initial density of 4500 kg/m$^3$, how much rock is vaporized during such an impact? Assume that all the energy of the impact goes into vaporizing some portion of the planet (while the rest remains cool) and that any portion of the planet heated to 4000 °C is vaporized. Assume the Earth was at 500 °C before the impact. Such vapor is usually jetted off during the impact, and could have easily wound up in orbit. What do you think happened to it?