CALCULATING IRIDIUM FALLOUT FROM AN ASTEROID IMPACT

OVERVIEW

This lesson serves as an extension to the Howard Hughes Medical Institute short film *The Day the Mesozoic Died*. It challenges students to develop a reasoned estimate of the amount of iridium contained in an asteroid similar in size and composition to the one that struck Earth 66 million years ago, causing the K-T mass extinction. Several correction factors and assumptions are introduced to carry out these calculations.

KEY CONCEPTS AND LEARNING OBJECTIVES

- The chemical composition of a rock layer can provide evidence of past events on Earth.

Student will be able to:

- apply the law of conservation of mass to estimate the abundance and distribution of a substance, such as iridium.
- describe the value of chemical analysis for identifying the origin of a substance or material.
- integrate multiple sources of information to solve a scientific problem.
- evaluate a hypothesis by forming rough estimates to verify data presented in support of the hypothesis.
- synthesize information from multiple sources to develop a coherent understanding of an event.

CURRICULUM CONNECTIONS

Curriculum	Standards
NGSS (April 2013)	HS-ESS1-6, HS-ESS1.B, HS-ESS1.C, HS-ESS2.A, HS-PS1.B, HS-PS3.B
Common Core (2010)	CCSS.Mathematics.MP.2, CCSS.Mathematics.MP.4, CCSS.Mathematics.HSN-Q.A.1, CCSS.Mathematics.HSA-CED.A.4, CCSS.Mathematics.HSA-SSE.A.1, CCSS.ELA-Literacy.RST.9-12.1, CCSS.ELA-Literacy.RST.9-12.4, CCSS.ELA-Literacy.RST.9-12.8, CCSS.ELA-Literacy.WHST.9-12.1

KEY TERMS

Cretaceous, Tertiary, meteor, chondrite, stratosphere, "parts per" notation, iridium

TIME REQUIREMENT

This activity can be completed in class or at home with a follow-up in-class discussion. An in-class format requires approximately 50 minutes.

SUGGESTED AUDIENCE

This activity is appropriate for high school level classes in physics, chemistry, and earth science.

PRIOR KNOWLEDGE

Students should be proficient in algebra and familiar with the application of volume and surface-area calculations for spherical bodies. Students are assumed to be proficient in the use of scientific notation and the conversion of metric units, as well as in the mathematical use of density and "parts per" notation.

MATERIALS

Students will need

- the student version of the handout (note that there are two versions, one with guided calculations)
- a calculator

TEACHING TIPS

- This activity is useful for connecting math and science and making links across scientific disciplines.
- The worksheet breaks up the problem into discrete steps that should be a reasonable challenge for most students in a high school level science class.
- For students needing step-by-step support, the "Guided Calculations" version of the worksheet would be more appropriate.
- Additional supporting information is included on the last page of this document. The page can be printed separately as an additional resource to address the needs of students who may struggle with the math, the use of "parts per" notation, and keeping consistent units throughout the calculation.
- Students may be divided in groups when performing the calculations to allow them to crosscheck and critique one another's solutions, and/or when discussing the questions at the end of the activity.
- If this activity is assigned as homework after watching the film, it could be followed by small-group evaluations of peer calculations and brainstorming on the discussion questions, followed by whole-class discussion.

ANSWER KEY

CALCULATIONS

A. *Determine the volume of a spherical 10-km-diameter asteroid. Convert units so that your final answer is in* m^3.

$V = 4/3 \prod r^3$, where $r = 5{,}000$ m

$V = 5.24 \times 10^{11}\ m^3$

B. *Using the answer from step 1 above, calculate the total mass of the asteroid.*

Using a density of 2200 kg/m^3 for a C1 chondrite:

Mass of the K-T asteroid = $5.24 \times 10^{11}\ m^3 \times 2200\ kg/m^3 = 1.15 \times 10^{15}$ kg

C. *Based on the expected composition of a C1 chondrite, calculate the total mass of iridium in the asteroid.*

Mass of iridium (Ir) = mass of asteroid × average abundance of Ir in chondrites

1.15×10^{15} kg x 500×10^{-9} g Ir/g chondrite

Mass of Ir in K-T asteroid = 5.76×10^{8} kg

D. *Assume that when the asteroid collided with the Earth, it vaporized and all of the asteroid's contents, including iridium, settled evenly on the Earth's surface within a few years following the impact. Calculate the expected distribution of iridium over the Earth's surface produced by the asteroid impact in terms of grams per square centimeter* (g/cm^2).

Surface area of a sphere = $4 \prod r^2$

Surface area of Earth = $4 \times \prod \times 6{,}378^2\ km^2 = 5.11 \times 10^8\ km^2$ (to convert km^2 to cm^2 multiply by 10^{10})

Surface area of Earth = $5.11 \times 10^{18}\ cm^2$

Average Ir distribution over Earth's surface:

5.76×10^{11} g Ir / $5.11 \times 10^{18}\ cm^2 = 1.13 \times 10^{-7}\ g/cm^2$

E. *Calculate the abundance of iridium resulting from the asteroid impact in ppb in a 1-cm layer of sediment. We will assume that this is the average thickness of the K-T boundary layer, although it varies from location to location.*

Average abundance of Ir = Average mass of Ir spread over 1 cm^2 ÷ mass of 1 cm^3 of sediment

Average abundance of Ir = 1.13 x 10^{-7} g ÷ 2.7 g

Average abundance of Ir = 4.17 × 10^{-8}

Adjust exponent to 10^{-9} to get parts per billion; 41.7 × 10^{-9} or 42 ppb

F. *Compare the abundance of iridium from the asteroid strike to the natural abundance in the Earth's crust. How many times more iridium would an asteroid impact add to the iridium found on the Earth?*

42 ppb ÷ 0.02 ppb = 2,100 times the average crustal abundance of Ir

GUIDED CALCULATIONS

A. *Determine the volume of a spherical 10-km-diameter asteroid. Convert units so that your final answer is in m^3.*

- Convert the diameter to meters. 10 km = **10000** meters
- Calculate the volume of a sphere. The formula is V = 4/3 ∏ r^3. Remember that r is radius, which is ½ the diameter.

  V = 4/3 ∏ r3, where r = 5,000 m

  V = 5.24 x 10^{11} m^3

B. *Using the answer from step 1 above, calculate the* ***total mass of the asteroid****.*

- What is the density of a C1 Chondrite? **2200 kg/m^3**
- Use the formula for density (density = mass / volume) to calculate the mass of the asteroid.

  Mass of the K-T asteroid = 5.24 x 10^{11} m^3 x 2200 kg/m^3 = 1.15 x 10^{15} kg

C. *Based on the expected composition of a C1 chondrite, calculate the* ***total mass of iridium in the asteroid****.*

- What is the average abundance of Ir in chondrites? **500 ppb**
- Convert that number to scientific notation (ppb is parts per billion, which is 1 x 10^{-9}): **500 x 10^{-9}**
- Calculate mass of iridium (Ir) = mass of asteroid × average abundance of Ir in chondrites

  Mass of Ir in K-T asteroid = 1.15 x 10^{15} kg x 500 x 10^{-9} g Ir/g chondrite = 5.76 x 10^{8} kg

D. *Assume that when the asteroid collided with the Earth, it vaporized and all of the asteroid's contents, including iridium, settled evenly on the Earth's surface within a few years following the impact. Calculate the* ***expected distribution of iridium over the Earth's surface*** *produced by the asteroid impact in terms of grams per square centimeter (**g/cm^2**).*

- Look at the units you need for your answer. Convert the Mass Ir (from part C) to grams: **5.76 x 10^{11} g**
- Surface area of a sphere = 4 ∏ r^2. You need the radius of the earth! What is it? **6378 km**
- Look at the units you need for your answer – cm! Convert the radius to centimeters: **6.378 x 10^{8} cm**
- Calculate the surface area of Earth in cm^2: **5.11 x 10^{18} cm^2**
- Calculate average Ir distribution over Earth's surface = mass of iridum in grams / surface area of Earth.

  Average Ir distribution over Earth's surface= 5.76 x 10^{11} g Ir / 5.11 x 10^{18} cm^2 = 1.13 x 10^{-7} g/cm^2

E. *Calculate the* ***abundance of iridium resulting from the asteroid impact*** *in ppb in a 1-cm layer of sediment. We will assume that this is the average thickness of the K-T boundary layer, although it varies from location to location.*

- Calculate the mass of 1 cm^3 of sediment (use the density of Earth's crust): **2.7 g/cm^3 / 1 cm^3 = 2.7g**
- Calculate average abundance of Ir = Average mass of Ir spread over 1 cm^2 / mass of 1 cm^3 of sediment
  Average abundance of Ir = 1.13 x 10^{-7} g ÷ 2.7 g = 4.17 × 10^{-8}

- Adjust exponent to 10^{-9} to get parts per billion: **41.7×10^{-9} or 42 ppb**

F. Compare the abundance of iridium from the asteroid strike to the natural abundance in the Earth's crust. How many times more iridium would an asteroid impact add to the iridium found on the Earth?

- Divide the answer from Part E by the average Ir abundance in Earth's crust.
  42 ppb ÷ 0.02 ppb = 2,100 times the average crustal abundance of Ir

DISCUSSION QUESTIONS

Answers will vary; below are some sample answers students might provide.

1. *Iridium in the K-T boundary layer has been studied at more than 100 sites around the world. Scientists have documented iridium abundance ranging from about 1 ppb to 25 ppb at these sites. Does your calculation of how much iridium should have been spread on Earth by this asteroid fit within this range?*

The calculations performed in this activity resulted in a slightly larger value than the range of iridium concentrations documented by scientists. However, 42 ppb is close to those measurements, especially compared to the average abundance of iridium in Earth's crust, which is over 2000 times less.

2. *The calculations in this exercise were based on a number of assumptions. The first assumption is that all the iridium in the asteroid was spread over the Earth. In addition, we assumed that the iridium is evenly distributed in the Earth's crust. Are these reasonable assumptions?*

Scientists believe that the asteroid was completely vaporized upon impact; however, it's possible that the iridium it contained will not all be in the 1-cm layer. Reworking, weathering, erosion, and diagenesis may have spread it above and below the K-T boundary layer. Also some iridium could have been deeply buried at the site of the impact.

The assumption that the abundance of iridium in Earth's crust is homogeneous might be a simplification. Localized weathering and biological or chemical processes cannot be ruled out as having an effect on iridium concentrations at particular locations. Thus, these processes may contribute to the abundance of iridium in the boundary clay and should be accounted for.

3. *Why might iridium deposited after the K-T impact be more abundant at some locations than others? How might this affect our effort to understand this event?*

Some factors that might affect iridium abundance at different locations include distance from the impact, post-depositional weathering, and physical, biological, or chemical processes that affect iridium concentrations after the impact in soil and water. Such processes could be local in nature and lead to significant variation of iridium abundance in sediments between locations. However, based on many measurements taken over many years, we now know that the concentration of iridium is fairly homogeneous at most locations across the globe. Iridium concentrations are lower in close proximity to the crater because the K-T layer is much thicker at those sites and the iridium is diluted by debris deposits laid down by tsunamis.

The variability in iridium concentrations means that they were not great clues in the search for the crater. For example, the abundance of iridium in the K-T boundary does not increase with proximity to the impact site. The contribution of iridium to our understanding of this event is that it was a global catastrophe.

SUPPORTING INFORMATION

Hints for Solving Calculations

- Look up the mathematical formula for the volume of a sphere and use it to calculate the asteroid's volume. Remember to use the radius of the asteroid and not its diameter. The problem asks for an answer in m^3, so figure out the diameter and radius of the asteroid in meters before proceeding.
- If you don't remember it, look up the formula for calculating density. The data table gives you the density of an average asteroid and you determined the volume in Part A, so you should be able to solve for the mass.
- To figure out the mass of iridium in the asteroid, use the "Average Iridium Abundance in C1 Chondrites" listed in the data table. Parts per billion notation (ppb) is dimensionless, and you can treat it like a fraction of the asteroid that's made out of iridium.
- To calculate the distribution of iridium, Start by determining the surface area of Earth. Because your answer has to be expressed in units of g/cm^2, you might convert the diameter of Earth listed in the table into centimeters before starting. You probably figured the answer to Part C in kilograms, so be sure your answer to this problem is expressed in g/cm^2.
- Remember that parts per billion notation is dimensionless. You're going to need to divide the mass of iridium in a cubic centimeter of sediment by the mass of a cubic centimeter of sediment. Because "mass"/"mass" is g/g, the units cancel. Adjust the exponent in the answer to 10^{-9}, and you will have parts per billion.

More About "Parts Per" Notation

The abundance of any particular element in a sample is often expressed in "parts per" notation. Typical scales are parts per thousand (‰), parts per million (ppm), parts per billion (ppb), and parts per trillion (ppt). These are not units. They are dimensionless terms that represent a fraction, with the denominator being the specified base quantity. Seawater has a salt concentration of about 35‰ (parts per thousand). Thus, given 1000 kg of seawater, about 35 kg would be salt and the remaining 965 kg would be water.

Parts per notation can be used to determine the quantity of a component substance in any particular amount of the mixed substance it is part of. If you want to know how much salt is in 2,500 kg of seawater, simply multiply by $35^0/_{00}$ to get your answer in kilograms.

2,500 kg seawater x 35‰ salt = 87.5 kg salt

Iridium is much less abundant in the universe than salt is in the ocean, and in a C1 chondrite its abundance is measured in parts per billion (ppb). A typical chondrite of this type has about 500 ppb iridium in its mass (the other 999,999,500 parts being other elements and compounds). To find the amount of iridium in a chondrite of a particular mass, multiply the mass of the chondrite by 500 ppb (500 x 10^{-9}). The units of your answer would be the same as the mass unit of the chondrite.

AUTHORS

Written by Scott Wahlstrom, Wachusett Regional School District
Edited by Laura Bonetta, PhD, and Mark Nielsen, PhD, HHM; Susan Dodge, editorial consultant
Reviewed by Philippe Claeys, PhD, Vrije Universiteit Brussel
Copyedited by Linda Felaco

FIELD TESTERS

Linda Rachele Burke, John Jay High School; Jite Lark, Foundations Academy