DETERMINING SIZE AND ENERGY OF THE K-T ASTEROID

OVERVIEW

This lesson serves as an extension to the Howard Hughes Medical Institute short film *The Day the Mesozoic Died*. In that film, independent teams of scientists led by Dr. Walter Alvarez and Dr. Jan Smit analyzed a strange layer of clay at the boundary between the Cretaceous and Tertiary rock layers (the K-T boundary). Through chemical analysis, they discovered that it contained an extraordinary concentration of the element iridium, which is rare in Earth's crust but common in asteroids and comets. As a result, they proposed that the iridium had come from a large asteroid that struck the planet, causing catastrophic damage. (Both groups of scientists published their results in 1980.) In this lesson, students will conduct similar calculations to the ones both Dr. Alvarez and Dr. Smit and their colleagues independently conducted to estimate the mass and size of the K-T asteroid based on the total abundance of iridium in the K-T boundary layer. The size of the asteroid will then be used to estimate the kinetic energy of the meteorite as it struck Earth and compare the amount to that of other high-energy events.

KEY CONCEPTS AND LEARNING OBJECTIVES

- Based upon measurements of iridium levels in the K-T boundary layer clays, scientists have been able to estimate the size, mass and energy of the asteroid that struck the planet.

Students will be able to:

- Apply the law of conservation of Mass to determine a realistic estimate for the size of a chondritic asteroid necessary to supply the global abundance of iridium in the K-T boundary layer.
- estimate the kinetic energy of an extraterrestrial impacting body.
- identify changes in forms of energy resulting from the K-T impact.
- evaluate the degree of energy necessary to produce global change in Earth's ecosystems.

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

TIME REQUIREMENT

This activity requires one 50-minute class period for viewing the film and completing the calculations on the worksheet. Most students will likely need some additional time, perhaps as homework, to complete the worksheet. A short, 10-minute follow-up discussion the following class period to go over the worksheet and student responses would be a useful closing activity.

SUGGESTED AUDIENCE

This activity is appropriate for high school physics (all levels including AP and IB) and introductory college astronomy and/or earth sciences, geology.

PRIOR KNOWLEDGE

Students should be familiar with the use of exponential notation, "parts per" notation, the calculation of volume and surface area of spheres, the application of density information to determine mass, and the calculation of kinetic energy.

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MATERIALS

Students will need:

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

TEACHING TIPS

- The HHMI activity "Concentrations of Elements in Earth's Crust" is a short reading lesson that provides a good introduction to concepts discussed in the film and that relate to this worksheet. It may be helpful for students to complete that reading lesson before viewing the film and completing this worksheet.
- If students are not familiar with the meaning and use of "parts per" notation, it will be helpful to discuss this prior to completing this worksheet. The Supporting Information provided at the end of this document is a useful resource.
- Two options are provided within the student worksheet. The first version expects students to reason through the calculations on their own. For students who need more help with the calculations, a version with guided calculations is also provided.
- As part of a post-activity discussion, ask students how this activity relates to the HHMI short film. Scientists often make rough calculations to check the plausibility of a new idea. By completing this worksheet, students will have done the same thing. Developing an awareness of the use of estimates to evaluate the merits of a hypothesis is an important science skill that translates into a range of life activities.
- This activity closely follows the calculations made by Alvarez and his team in their 1980 paper with the following modifications: (1) Alvarez and colleagues assumed that the levels of iridium (8×10^{-9}g/cm^2) found in Gubbio, Italy, were representative of iridium levels worldwide. We now have data from more than 300 K-T boundary sites and know that the amount of iridium found at Gubbio is a low estimate. In this activity, students are given the iridium amount found at the site in Spain (3×10^{-8} g/cm^2), measured by Jan Smit, which is more representative of the global average. (2) They assumed that a small portion of the asteroid vaporized and spread around the globe. They based that assumption on the 1883 explosion of the Sumatran volcano, Krakatau, in which only 22% of the 18 km^3 of material blasted out and spread throughout the planet. The remaining 78% of this material consisted of particles too large to be transported by the atmosphere and settled close to the volcano. Scientists now have data, based on mathematical modeling, suggesting that the asteroid was almost completely vaporized and spread throughout the world. Ask your students how these two assumptions affect the calculation of the size of the asteroid.

ANSWER KEY

1. *In this activity, we will use the iridium concentration Dr. Smit found in the Spain clay layer (about 3×10^{-8} g/cm^2). Dr. Smit assumed that a similar amount of iridium would be found in the K-T boundary worldwide. Based on this estimate and the data in Table 1, calculate the* total mass of iridium *deposited on Earth in this layer.*

A (surface area Earth) = $4 \times \prod \times r^2$; r = radius of Earth = diameter of Earth ÷ 2

$A = 4 \times \prod \times 6378\ \text{km}^2$

$A = 5.112 \times 10^8\ \text{km}^2$

$A = 5.112 \times 10^{18}\ \text{cm}^2$

Mass iridium (Ir) = A × Ir deposited

Mass Ir = $5.112 \times 10^{18}\ \text{cm}^2 \times (3 \times 10^{-8}\ \text{g/cm}^2)$

Mass Ir = 15.3×10^{10} g

2. *In step 1 above, you calculated how much iridium was required to produce a global layer with an average abundance of iridium of 3×10^{-8} g/cm^2. We will assume that when the asteroid hit Earth it vaporized, blasting fine particles high into the atmosphere. Most of the asteroid material, including iridium, was transported around the planet and settled on Earth's surface within a few years following impact. The asteroid that caused the K-T extinction is thought to have had the chemical composition of a carbonaceous chondrite of the C1 group (a C1 chondrite). Based on the information presented, determine the mass of the asteroid needed to supply that amount of iridium. Be sure to convert your answer into kilograms.*

Mass of asteroid (C1 chondrite) = Mass Ir ÷ fraction of Ir in C1 chondrites (ppb)

Mass of asteroid (m_a)= 15.3 × 10^{10} g (calculated in step 1) Ir ÷ 500 × 10^{-9} g Ir/g chondrite (from Table 1)

Mass of asteroid = 3.06 × 10^{17} g

Mass of asteroid = 3.06 × 10^{14} kg

3. *In step 2, you calculated a reasonable estimate of the mass of the asteroid that caused the extinction of the dinosaurs. You can now calculate the volume of the asteroid using the average density of a C1 chondrite listed in Table 1. Once you determine the volume, find the average diameter for an asteroid of this size that was roughly spherical in shape.*

Volume (V) = Mass of asteroid ÷ Density of asteroid

So, V asteroid = 3.06 × 10^{14} kg (calculated in step 2) ÷ 2200 kg/m^3 (density of C1 chondrite from Table 1)

V asteroid = 1.39 × 10^{11} m^3

$V_{sphere} = 4/3 \times \prod \times r^3$

So, $r^3 = 1.39 \times 10^{11}$ $m^3 \times 3/4 \div \prod = 3.322 \times 10^{10} m^3$

radius of asteroid (r) = 3214 m

diameter of asteroid = r × 2 = 6.43 km

Note to Teachers: The film states that the asteroid was 10 km in diameter. This estimate is based on several different calculations and the size of the Chicxulub crater. Ask your students why the calculations done in this activity yield a different number from the actual size of the asteroid. One reason may be that the starting iridium concentration was too small. The iridium concentration used in this activity is an average for a 1-cm clay layer. However, weathering and reworking of the layer have spread the iridium above and below the 1-cm layer so the actual amount of iridium initially deposited around the planet is higher than what is measured today. Some of the iridium is thought to have been deeply buried at the site of the impact, but this remains to be demonstrated by drilling within the crater. If such a burial occurred, not all the asteroid material would have been spread throughout the world.

4. *Asteroids of this size that impact Earth are called Earth-crossing asteroids. The term simply means that the orbit of the asteroid intersects the orbit of our planet on a regular basis and collision is only a matter of time. If the asteroid crosses Earth's orbit at the same time that Earth crosses the asteroid's orbit, they will collide. Scientists have identified thousands of Earth-crossing asteroids, and NASA has classified 1027 of them as potentially hazardous. This classification means that their orbits bring them within at least 7.5 million kilometers of Earth's orbit and they are at least 150 m in diameter. Studies have determined that asteroids of this group would typically impact Earth at an average of 25,000 m/s. Using your results from step 4 and this new information, determine the kinetic energy that the K-T asteroid would have had.*

Kinetic energy (KE) = ½ $m_{(a)} \times v^2$; v = velocity of asteroid

KE of asteroid = ½ × 3.06 × 10^{14} kg (calculated in step 3) × $(25{,}000\ m/s)^2$

KE = 9.56 × 10^{22} joules (J)

5. *Using the Internet or another resource, find the amount of energy released by the largest atomic bomb ever exploded. How does this compare to the energy released by the asteroid that caused the K-T extinction? How many times bigger was the K-T event?*

The largest nuclear detonation released 50 megatons of kinetic energy (210,000 TJ = 2.1 × 10^{17} J)

The K-T impact would have had an energy yield about 450,000 times larger!

6. *Find some other benchmarks of energy to compare the K-T event to. Examples might include the amount of the sun's energy that strikes Earth in a single minute or the amount of energy released by a hurricane. Feel free to make up your own comparisons too. (Example: This is equivalent to all the food energy needed by the world's 7 billion people over the next 58.6 million years!)*

Students' answers will vary.

QUESTIONS WITH GUIDED CALCULATIONS

1. *In this activity, we will use the iridium concentration Dr. Smit found in the Spain clay layer (about 3×10^{-8} g/cm^2). Dr. Smit assumed that a similar amount of iridium would be found in the K-T boundary worldwide. Based on this estimate and the data in Table 1, calculate the total mass of iridium deposited on Earth in this layer.*

- First, figure out the Earth's surface area:
  - What is the diameter of the Earth? **12756km** What is the radius? **6378 km**
  - Notice the units in the final answer. Convert the radius to centimeters. **6.378×10^{8} cm**
  - Calculate the Earth's Surface Area. Surface Area = $4 \times \prod \times r^2$ **5.112×10^{18} cm^2**

- Now use the surface area and the concentration of Iridium the Spanish clay to estimate the total mass of Ir in the KT layer worldwide.
  - Calculate the mass of iridium. Mass iridium (Ir) = Surface Area x Concentration of Ir **15.3×10^{10} g**

  Mass Ir = 5.112×10^{18} cm^2 × (3×10^{-8} g/cm^2) = 15.3×10^{10} g

2. *In step 1 above, you calculated how much iridium was required to produce a global layer with an average abundance of iridium of 3×10^{-8} g/cm^2. We will assume that when the asteroid hit Earth it vaporized, blasting fine particles high into the atmosphere. All of the asteroid material, including iridium, was transported around the planet and settled on Earth's surface within a few years following impact. The asteroid that caused the K-T extinction is thought to have the chemical composition of a* ***carbonaceous chondrite*** *of the C1 group (a* ***C1 chondrite****). Based on the information presented, determine the mass of the asteroid needed to supply that amount of iridium. Be sure to convert your answer into kilograms.*

- Convert the Average iridium abundance in C1 chondrites from ppb to scientific notation. **500×10^{-9}**
  - Remember that ppb is the same as 1×10^{-9}.
- Calculate the mass of the asteroid. Mass of asteroid = Mass Ir (from step 1) ÷ fraction of Ir in C1 chondrites

  Mass of asteroid (m_a)= 15.3×10^{10} g (calculated in step 1) Ir ÷ 500×10^{-9} g Ir/g chondrite (from Table 1)

  Mass of asteroid = 3.06×10^{17} g
- Your answer should be in grams. Convert your answer to kg. **3.06×10^{14} kg**

3. *In step 2, you calculated a reasonable estimate of the mass of the asteroid that caused the extinction of the dinosaurs. You can now calculate the volume of the asteroid using the average density of a C1 chondrite listed in Table 1. Once you determine the volume, find the average diameter for an asteroid of this size that was roughly spherical in shape.*

- Calculate the volume of the asteroid. Volume (V) = Mass of asteroid ÷ Density of asteroid (C1 chondrite)

V asteroid = 3.06×10^{14} kg (calculated in step 2) ÷ 2200 kg/m^3 = 1.39×10^{11} m^3

- Now use the other formula for volume to determine the radius of the asteroid. $V_{sphere} = 4/3 \times \prod \times r^3$

$r^3 = 1.39 \times 10^{11}$ m^3 × 3/4 ÷ $\prod$ = 3.322×10^{10}m^3 = 3214 m

diameter of asteroid = r × 2 = 6.43 km

- Double the radius to calculate the diameter: **6428 m**. Convert the diameter to km: **6.43 km**

Note to Teachers: The film states that the asteroid was 10 km in diameter. This estimate is based on several different calculations and the size of the Chicxulub crater. Ask your students why the calculations done in this activity yield a different number from the actual size of the asteroid. One reason may be that the starting iridium concentration was too small. The iridium concentration used in this activity is an average for a 1-cm clay layer. However, weathering and reworking of the layer have spread the iridium above and below the 1-cm layer so the actual amount of iridium initially deposited around the planet is higher than what is measured today. Some of the iridium is thought to have been deeply buried at the site of the impact, but this remains to be demonstrated by drilling within the crater. If such a burial occurred, not all the asteroid material would have been spread throughout the world.

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- Calculate the Kinetic Energy of the asteroid. Kinetic energy (KE) = ½ $m_{(a)} \times v^2$.
    - m = mass in kg and v = velocity of asteroid
    - A unit of energy is a Joule (J).

KE of asteroid = ½ × 3.06 × 10^{14} kg (calculated in step 3) × (25,000 m/s)^2

KE = 9.56 × 10^{22} joules (J)

5. *Using the Internet or another resource, find the amount of energy released by the largest atomic bomb ever exploded. How does this compare to the energy released by the asteroid that caused the K-T extinction? How many times bigger was the K-T event?*

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SUPPORTING INFORMATION

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 ($^{0}/_{00}$), 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$^{0}/_{00}$ (parts per thousand). Thus, in 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 this by 35$^{0}/_{00}$ to get your answer in kilograms.

2,500 kg seawater × 35$^{0}/_{00}$ 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 <u>billion</u> (ppb). A typical chondrite of this type has about 514 ppb iridium in its mass (the other 999,999,486 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 514 ppb (514×10^{-9}). The units of your answer would be the same as the mass unit of the chondrite.

Calculating properties of spheres

The surface area and volume of a sphere are calculated as follows:

Area = $4 \prod r^2$ Volume = $4/3 \prod r^3$

Calculating kinetic energy

Kinetic energy is calculated according to the formula $KE = ½\, m \times v^2$, where m is mass in kilograms and v is velocity in meters per second. The answer has the units of $kg \cdot m^2/s^2$, which is defined as a *joule*.

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