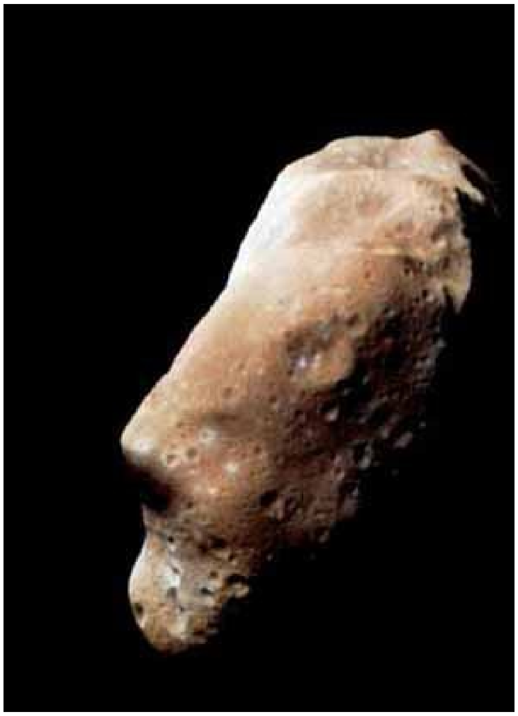
Asteroids and Ice


Asteroid Gaspara

Astronomers studying the asteroid 24-Themis detected water-ice and carbon-based organic compounds on the surface of the asteroid.

NASA detects, tracks and characterizes asteroids and comets passing close to Earth using both ground and space-based telescopes.

NASA is particularly interested in asteroids with water ice because this resource could be used to create fuel for interplanetary spacecraft.

On October 7, 2009, the presence of water ice was confirmed on the surface of this asteroid using NASA's Infrared Telescope Facility. The surface of the asteroid appears completely covered in ice. As this ice layer is sublimated (goes directly from solid to gaseous state) it may be getting replenished by a reservoir of ice under the surface. The orbit of the asteroid varies from 2.7 AU to 3.5 AU (where 1 AU is the 150 million km distance from Earth to the sun) so it is located within the asteroid belt. The asteroid is 200 km in diameter, has a mass of 1.1 x 10^{19} kg, and a density of 2,800 kg/m^3 so it is mostly rocky material similar in density to Earth's.

By measuring the spectrum of infrared sunlight reflected by the object, the NASA researchers found the spectrum consistent with frozen water and determined that 24 Themis is coated with a thin film of ice. The asteroid is estimated to lose about 1 meter of ice each year in a process called sublimation, so there must be a sub-surface reservoir to constantly replace the evaporating ice.

Problem 1 – Assume that the asteroid has a diameter of 200 km. How many kilograms of water ice are present in a layer 1-meter thick covering the entire surface, if the density of ice is 1,000 km/$meter^3$? (Hint: Volume = Surface area x thickness)

Problem 2 – Suppose that only 1% by volume of the 1-meter-thick 'dirty' surface layer is actually water-ice and that it sublimates 1 meter per year, what is the rate of water loss in kg/sec?

Problem 1 – Assume that the asteroid has a diameter of 200km. How many kilograms of water ice are present in a layer 1-meter thick covering the entire surface, if the density of ice is 1,000 km/meter^3? (Hint: Volume = Surface area x thickness)

Answer: Volume = surface area x thickness.

$SA = 4 \pi r^2$

$= 4 (3.14) (100{,}000 \text{ meters})^2$

$= 1.3 \times 10^{11} \text{ meters}^2$

$\text{Volume} = 1.3 \times 10^{11} \text{ meters}^2 \times 1 \text{ meter}$

$= 1.3 \times 10^{11} \text{ meters}^3$

Mass of water = density x volume

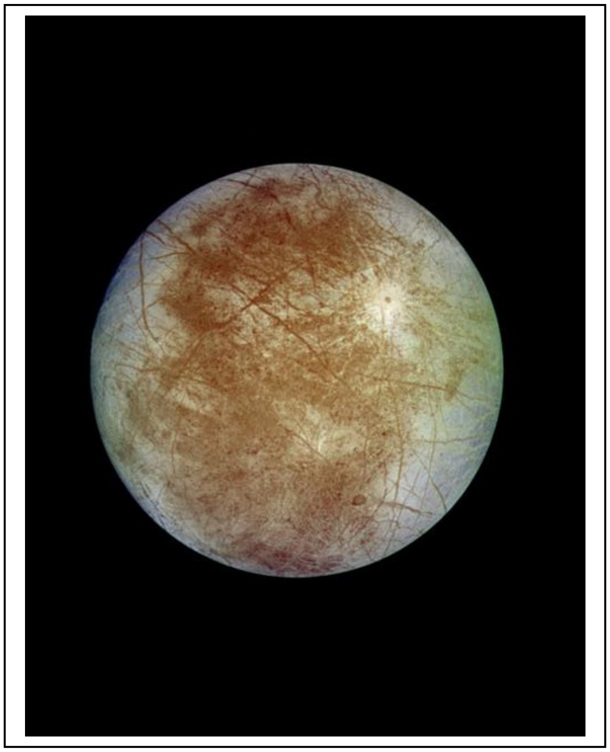
$= 1{,}000 \text{ kg/meter}^3 \times 1.3 \times 10^{11} \text{ meter}^3$

$= \mathbf{1.3 \times 10^{14}}$ **kg** (or 130 billion tons)

Problem 2 – Suppose that only 1% by volume of the 'dirty' 1-meter-thick surface layer is water-ice and that it evaporates 1 meter per year, what is the rate of water loss in kg/sec?

Answer: The mass of water in the outer 1-meter layer is 1% of 1.3×10^{14} kg or 1.3×10^{12} kg. Since 1 year = 365 days x 24h/day x 60m/hr x 60 sec/min = 3.1×10^7 seconds, the mass loss is just 1.3×10^{12} kg / 3.1×10^7 sec = **42,000 kg/sec or 42 tons/sec**.

Ice or Water?



There are no known terrestrial organisms that can exist at a temperature lower than the freezing temperature of water without special adaptations. It is also believed that liquid water is a crucial ingredient to the chemistry that leads to the origin of life. To change water-ice to liquid water requires energy.

First, you need energy to raise the ice from wherever temperature it is, to 0 Celsius. This is called the Specific Heat and is 2.04 kiloJoules/kilogram C

Then you need enough energy added to the ice near 0 C to actually melt the ice by increasing the kinetic energy of the water molecules so that their hydrogen bonds weaken, and the water stops acting like a solid. This is called the Latent Heat of Fusion and is 333 kiloJoules/kilogram.

Let's see how this works!

Example 1: You have a 3 kilogram block of ice at a temperature of -20 C. The energy needed to raise it by 20 C to a new temperature of 0 C is Eh = 2.04 kiloJoules/kg C) x 3 kilograms x (20 C) = 2.04 x 3 x 20 = 122 kiloJoules.

Example 2: You have a 3 kilogram block of ice at 0 C and you want to melt it completely into liquid water. This requires Em = 333 kiloJoules/kg x 3 kilograms = 999 kiloJoules.

Example 3: The total energy needed to melt a 3 kilogram block of ice from -20 C to 0C is E = Eh + Em = 122 kiloJoules + 999 kiloJoules = 1,121 kiloJoules.

Problem 1 - On the surface of the satellite Europa (see NASA's Galileo photo above), the temperature of ice is -220 C. What total energy in kiloJoules is required to melt a 100 kilogram block of water ice on its surface? (Note: Calculate Eh and Em separately then combine them to get the total energy.)

Problem 2 - To a depth of 1 meter, the total mass of ice on the surface of Europa is 2.8 x 10^{16} kilograms. How many Joules would be required to melt the entire surface of Europa to this depth? (Note: Calculate Eh and Em separately then combine them to get the total energy. Then convert kiloJoules to Joules)

Problem 3 - The sun produces 4.0 x 10^{26} Joules every second of heat energy. How long would it take to melt Europa to a depth of 1 meter if all of the sun's energy could be used? (Note: The numbers are BIG, but don't panic!)

Problem 1 - On the surface of the satellite Europa, the temperature of ice is -220 C. What total energy is required to melt a 100 kilogram block of water ice on its surface?

Answer: You have to raise the temperature by 220 C, then

E = 2.04 x 220 x 100 + 333 x 100
= 44,880 + 33,300
= **78,180 kiloJoules.**

Problem 2 - To a depth of 1 meter, the total mass of ice on the surface of Europa is 2.8 x 10^{16} kilograms. How many joules would be required to melt the entire surface of Europa to this depth?

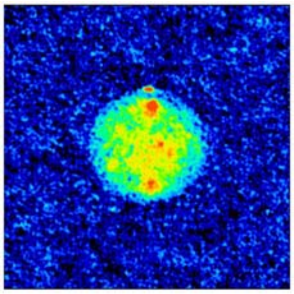
Note: The radius of Europa is 1,565 km. The surface area is 4 x π x (1,565,000 m)^2 = 3.1 x 10^{13} meters^2. A 1 meter thick shell at this radius has a volume of 3.1 x 10^{13} meters^2 x 1 meter = 3.1 x 10^{13} meters^3. The density of water ice is 917 kilograms/m^3 ,so this ice layer on Europa has a mass of 3.1 x 10^{13} x 917 = 2.8 x 10^{16} kilograms.

Energy = (2.04 x 220 + 333) x 2.8 x 10^{16} kg
= 2.2 x 10^{19} kiloJoules
= **2.2 x 10^{22} Joules.**

Problem 3 - The sun produces 4.0 x 10^{26} Joules every second of heat energy. How long would it take to melt Europa to a depth of 1 meter if all of the sun's energy could be used?

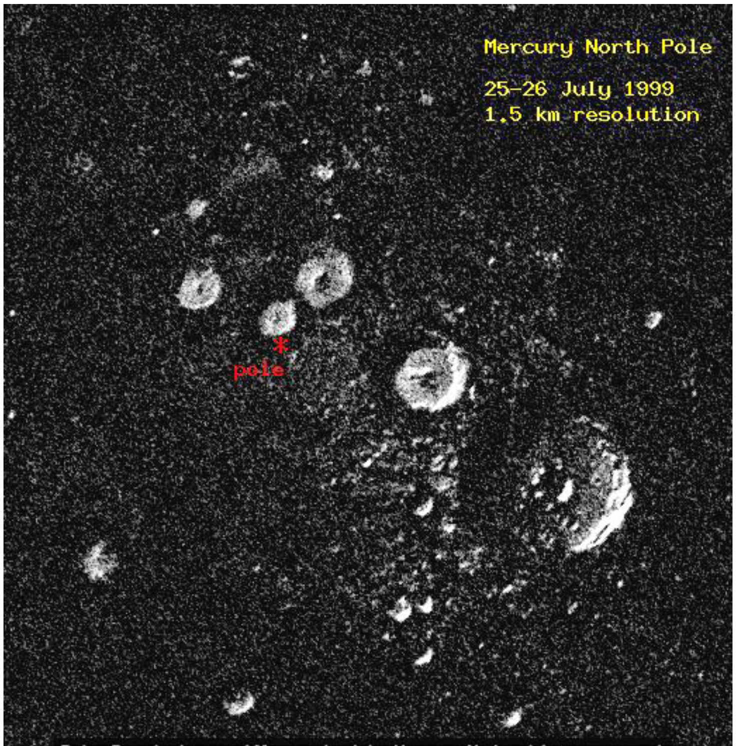
Answer: Time = Amount / Rate
= 2.2 x 10^{22} Joules / 4.0 x 10^{26} Joules
= **0.000055 seconds.**

Is there Ice on Mercury ?



The NASA MESSENGER spacecraft performed its first flyby of Mercury on January 14, 2008. In addition to mapping the entire surface of this planet, one of its goals is to shed new light on the existence of ice under the polar regions of this hot planet. Ice on Mercury? It's not as strange as it seems!

In 1991, Duane Muhleman and her colleagues from Caltech and the Jet Propulsion Laboratory, created the first radar map of Mercury. The image, shown here, contained a stunning surprise. The bright (red) dot at the top of the moon image to the left indicates strong radar reflection at Mercury's North Pole, resembling the strong radar echo seen from the ice-rich polar caps of Mars.



Delay-Doppler image of Mercury by John Harmon, National Astronomy and Ionosphere Center, Arecibo Observatory, Puerto Rico.

In 1999, astronomer John Harmon at the Arecibo Observatory in Puerto Rico, repeated the 1991 study, this time using the powerful microwave beam of the Arecibo Radio Telescope. The microwave energy reflected from mercury and was detected by the VLA radio telescope array in New Mexico, where a new image was made.

The radio-wavelength image to the left shows Mercury's North Polar Region at very high resolution. The image is 370 kilometers wide by 400 kilometers tall.

All the bright features are believed to be deposits of frozen water ice, at least several meters thick in the permanently shaded floors of the craters.

Reference: Harmon, Perillat and Slade, 2001, Icarus, vol 149, p.1-15

Problem 1 - From the information provided in the essay, what is the scale of the image in kilometers per millimeter?

Problem 2 - Measure the diameters of the craters, in kilometers, and estimate the total surface area covered by the large white patches in A) square kilometers and B) square meters.

Problem 3 - Suppose the icy deposit is mixed into the Mercurian surface to a depth of 10 meters. What is the total volume of the ice within the craters you measured in cubic meters?

Problem 4 - Suppose half of the volume is taken up by rock. What is the total remaining volume of ice?

Problem 5 - The density of ice is 917 kilograms/cubic meter. How many kilograms of ice are present?

Problem 6 - If this ice were 100% water ice, and 3.8 kilograms of water equals 1.0 gallons, how many gallons of water might be locked up in the shadowed craters of Mercury?

Answer Key:

Problem 1 - From the information provided in the essay, what is the scale of the image in kilometers per millimeter?

Answer; The image is 370 kilometers wide by 400 kilometers tall. The image is 95 millimeters wide by 104 millimeters tall. The scale is therefore about **4.0 kilometers / millimeter.**

Problem 2 - Measure the diameters of the craters, in kilometers, and estimate the total surface area covered by the large white patches in A) square kilometers and B) square meters.

Answer: Students should measure the diameters of at least the 5 large craters that form the row slanted upwards from right to left through the center of the image. Their diameters are about 90 km, 40 km, 30 km, 20 km and 25 km. The area of a circle is πR^2, so the crater areas are 6,400 km^2, 700 km^2, 314 km^2 and 490 km^2. The total area A) in square kilometers is about **7,900 km^2** or B) 7,900 x (1000 m/km) x (1000 m/km) = **7.9×10^9 meters^2**. Students may reasonably ask how to estimate the area of partially-filled craters such as the largest one in the image .They may use appropriate percentage estimates. For example, the largest crater is about 1/2 filled (white color in image) so its area can be represented as 6,400 x 0.5 = 3,200 km^2.

Problem 3 - Suppose the icy deposit is mixed into the Mercurian surface to a depth of 10 meters. What is the total volume of the ice within the craters you measured?

Answer: Volume = surface area x height = 7.9×10^9 meters^2 x 10 meters = 7.9×10^{10} meters^2.

Problem 4 - Suppose half of the volume is taken up by rock. What is the total remaining volume of ice?

Answer; 7.9×10^{10} meters^2 x 0.5 = **8.0×10^{10} meters^2**

Problem 5 - The density of ice is 917 kilograms/cubic meter how many kilograms of ice are present?

Answer: 8.0×10^{10} meters^2 x 917 kg/meters^3 = **7.3×10^{13} kilograms**

Problem 6 - If this ice were 100% water ice, and 3.8 kilogram of water equals 1.0 gallons, how many gallons of water might be locked up in the shadowed craters of Mercury?

Answer: 7.3×10^{13} kilograms / 3.8 kg/gallon = **1.9×10^{13} gallons or 19 trillion gallons!**