

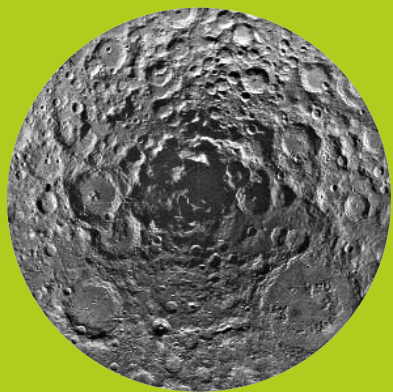


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ICE IN THE SHADOWS

LESSON DIRECTORY

PHOTO GALLERY



This lesson develops precursor understanding about how we detect the presence of ice on the permanently shadowed craters of Mercury and the Moon.

SCIENCE & LITERATURE

“...I had journeyed down
To where the shades were covered wholly by ice....
Through a round aperture I saw appear
Some of the beautiful things that Heaven bears
Where we once more came forth, and once more saw the stars.”

—Dante’s *Inferno*

Robert Pinsky translation



The discovery of ice in the forbidding shadows of impact craters on two airless inner planets is most surprising. That we have the knowledge and technology to detect—that through the round apertures of spectrometers and radar telescopes, we can even get a glimpse of places where sunbeams never strike is as amazing and as elegant as the evocative closing lines of Dante’s great 14th century poem.

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CONCEPT OVERVIEW

This lesson develops precursor understanding about how we detect the presence of ice on the permanently shadowed craters of Mercury and the Moon.

Concepts:

1. Sunlight striking spherical surfaces.
2. Detecting gamma rays & neutrons.

This lesson provides concrete experiences of:

1. The angle of sunlight striking a planetary surface.
2. Temperature and pressure conditions in a “cold trap.”
3. How science instruments detect ice on Mercury and the Moon.

PRE K–2 CONCEPTS

- Direct sunlight is warmer than indirect sunlight.
- It is extremely cold where there is no sunlight and no atmosphere.
- There are places on Mercury and the Moon where there is no sunlight and no atmosphere (no heat source, no air pressure)—in the permanently shadowed craters near the poles.
- We can detect the presence of ice in shadowed craters near the poles of Mercury and the Moon.

GRADE 3–5 CONCEPTS

- The more direct the angle of sunlight, the stronger its effect.
- The effect of sunlight shining on a spherical surface, like a planet or a moon with low obliquity is strongest in the equatorial region and weakest at the poles. (Obliquity is the tilt of a body with respect to its plane of orbit around the Sun).
- Cold traps exist where there is no sunlight (extremely low temperature) and no atmosphere (no air pressure), in the permanently shadowed craters near the poles of Mercury and the Moon.
- We detect the likely presence of ice in the cold traps by using different kinds of science instruments called *spectrometers* that measure gamma rays and energetic neutrons.

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LESSON SUMMARY & OBJECTIVES

When cosmic rays strike the surface of an airless world they create a moving cascade of photons and particles, including gamma rays and neutrons. By measuring this cascade with a Gamma Ray and Neutron Spectrometer, scientists learn a great deal about the composition of the world, including detecting the presence of ice in otherwise hidden places: such as the permanently shadowed craters of Mercury and the Moon.

Objective 1: Notice that sunlight strikes a planet at different angles.

A planetary object is spherical. As sunlight radiates from the Sun it strikes the surface of a planetary object most directly at its equatorial region and least directly at its poles. This means it is possible that on some Solar System worlds there are places near the polar region that NEVER get sunlight.

Objective 2: Notice that ice can exist where there is no sunlight and no air.

Infalling ice from the outer Solar System can strike places like Mercury and the Moon and stay intact for billions of years in a cold trap—where with no sunlight, the temperature is so low that there is virtually no molecular motion, and where with only a near-vacuum exosphere, there is no air pressure. Under these conditions, ice is stable.

Objective 3: Notice that we detect evidence of ice on Mercury and the Moon.

Water ice can be cold-trapped in permanently shadowed craters near the polar regions of Mercury and the Moon. In both cases, remote sensors have detected radar-bright patches that are likely indicators of ice. Looking for ice on the Moon has led to even more exciting ways to look for ice on Mercury.

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STANDARDS

BENCHMARKS:

4E The Physical Setting: Energy Transformations

GRADES K–2, PAGE 83

- The sun warms the land, air, and water.

4D The Physical Setting: the Earth

GRADES 9–12, PAGE 70

- Life is adapted to conditions on the Earth, including the force of gravity that enables the planet to retain an adequate atmosphere, and an intensity of radiation from the sun that allows water to cycle between liquid and vapor.
- Weather (in the short run) and climate (in the long run) involve the transfer of energy in and out of the atmosphere. Solar radiation heats the landmasses, oceans, and air. Transfer of heat energy at the boundaries between the atmosphere, the landmasses, and the oceans results in layers of different temperatures and densities in both the ocean and atmosphere. The action of gravitational force on regions of different densities causes them to rise or fall—and such circulation, influenced by the rotation of the Earth, produces winds and ocean circulation.

NSES:

Content Standard D Earth and Space Science: Objects in the sky

GRADES K–4, PAGE 134

- The sun provides the light and the heat necessary to maintain the temperature of the Earth.

Content Standard D Earth and Space Science: Earth in the Solar System

GRADES 5–8, PAGE 161

- The sun is the major source of energy for phenomena on the Earth's surface, such as growth of plants, winds, ocean currents, and the water cycle. Seasons result from variations in the amount of the sun's energy hitting the surface due to the tilt of the Earth's rotation on its axis and the length of the day.

NCTM MATH STANDARDS

Geometry Standard for Grades Pre-K–2

Expectations: prekindergarten through grade 2 all students should:

- Analyze characteristics and properties of two- and three-dimensional geometric shapes and develop mathematical arguments about geometric relationships.
 - recognize, name, build, draw, compare, and sort two- and three-dimensional shapes
 - describe attributes and parts of two- and three-dimensional shapes
 - investigate and predict the results of putting together and taking apart two- and three-dimensional shapes



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- Specify locations and describe spatial relationships using coordinate geometry and other representational systems
 - describe, name, and interpret relative positions in space and apply ideas about relative position
 - describe, name, and interpret direction and distance in navigating space and apply ideas about direction and distance;
 - find and name locations with simple relationships such as “near to” and in coordinate systems such as maps
- Apply transformations and use symmetry to analyze mathematical situations
 - recognize and apply slides, flips, and turns
 - recognize and create shapes that have symmetry
- Use visualization, spatial reasoning, and geometric modeling to solve problems
 - create mental images of geometric shapes using spatial memory and spatial visualization
 - recognize and represent shapes from different perspectives
 - relate ideas in geometry to ideas in number and measurement
 - recognize geometric shapes and structures in the environment and specify their location

Geometry Standard for Grades 3–5

Expectations: In grades 3–5 all students should:

- Analyze characteristics and properties of two- and three-dimensional geometric shapes and develop mathematical arguments about geometric relationships
 - identify, compare, and analyze attributes of two- and three-dimensional shapes and develop vocabulary to describe the attributes
 - classify two- and three-dimensional shapes according to their properties and develop definitions of classes of shapes such as triangles and pyramids
 - investigate, describe, and reason about the results of subdividing, combining, and transforming shapes
 - explore congruence and similarity
 - make and test conjectures about geometric properties and relationships and develop logical arguments to justify conclusions



- Specify locations and describe spatial relationships using coordinate geometry and other representational systems
 - describe location and movement using common language and geometric vocabulary
 - make and use coordinate systems to specify locations and to describe paths
 - find the distance between points along horizontal and vertical lines of a coordinate system
- Apply transformations and use symmetry to analyze mathematical situations
 - predict and describe the results of sliding, flipping, and turning two-dimensional shapes
 - describe a motion or a series of motions that will show that two shapes are congruent
 - identify and describe line and rotational symmetry in two- and three-dimensional shapes and designs
- Use visualization, spatial reasoning, and geometric modeling to solve problems
 - build and draw geometric objects
 - create and describe mental images of objects, patterns, and paths
 - identify and build a three-dimensional object from two-dimensional representations of that object
 - identify and draw a two-dimensional representation of a three-dimensional object
 - use geometric models to solve problems in other areas of mathematics, such as number and measurement
 - recognize geometric ideas and relationships and apply them to other disciplines and to problems that arise in the classroom or in everyday life

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ESSENTIAL QUESTION

What Does Ice in the Shadowed Craters of Mercury and the Moon Tell Us About the Solar System?

How can ice remain stable in the shadowed craters? Where does the ice come from?

What can we learn by detecting and comparing the ice on Mercury and the Moon?

ACTIVITY QUESTION

Why Is There Ice at the Poles of Mars, Earth, Mercury, and the Moon?

Why are polar regions colder than the rest of the planet? What role does the angle of sunlight play? How can ice be on a planet so close to the Sun (Mercury)? How can we detect the presence of ice on places like the Moon and Mercury?

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BACKGROUND

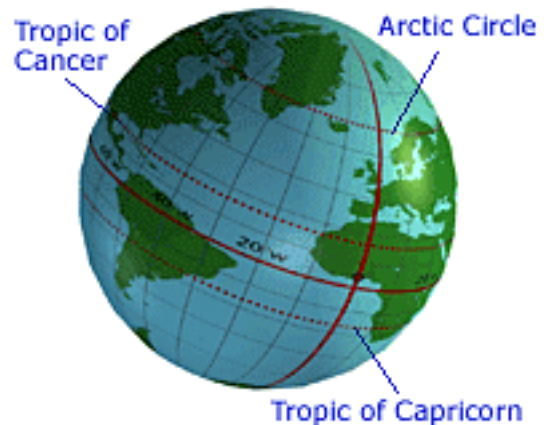
Earth's 23.5° Axial Tilt and Sphericity

In our era the Earth tilts at an angle of about 23.5° and aligns with the North Pole pointing toward Polaris, the North Star. In its orbital path around the Sun, the tilt of the Earth remains the same: always close to 23.5° pointing toward Polaris.

Generally the equatorial region of the Earth receives the most direct sunlight. The light at the poles varies within more or less grazing angles. (The angle of sunlight is only part of the story: Earth's atmosphere also influences how solar radiation is distributed with its resulting weather and climate conditions.)

The Tropic of Cancer marks the northernmost latitude (23.5° N) of direct sunlight, which occurs on the June solstice. On that day, the North Pole receives 24 hours of sunlight and the South Pole receives 24 hours of darkness.

The Tropic of Capricorn marks the southernmost latitude (23.5° S) of direct sunlight, which occurs on the December solstice. On that day, the South Pole receives 24 hours of sunlight and the North Pole receives 24 hours of darkness.



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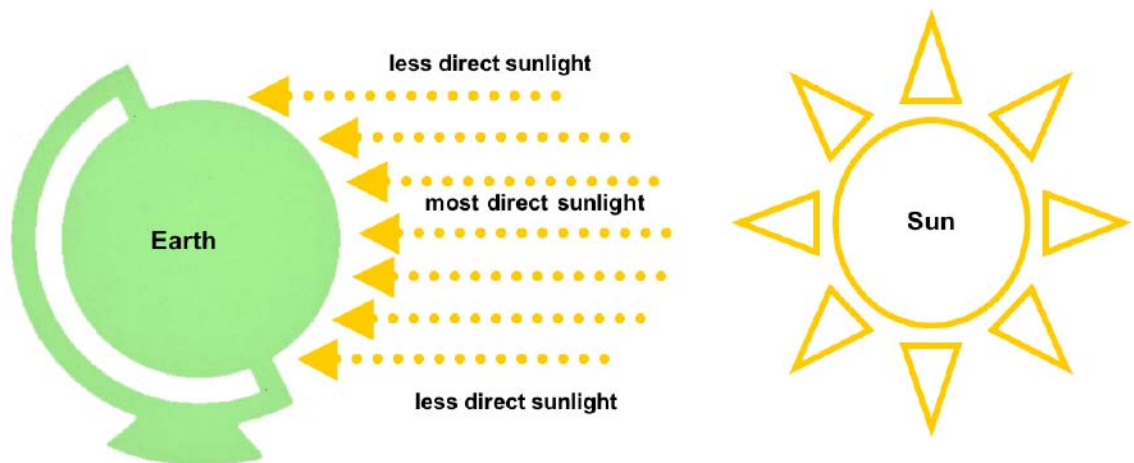
The position of the Earth in relation to the directness of the sunlight changes a bit each day, marked by four familiar transition points:

- The summer solstice—summer in the northern hemisphere, when sunlight is most direct at the Tropic of Cancer (23.5° N latitude); winter in the southern hemisphere
- The fall equinox—autumn in the northern hemisphere, spring in the southern, when sunlight is most direct at the Equator
- The winter solstice—winter in the northern hemisphere, when sunlight is most direct at the tropic of Capricorn (23.5° S latitude); summer in the southern hemisphere
- The spring equinox—spring in the northern hemisphere, autumn in the southern hemisphere, when sunlight is again most direct at the Equator

It's not surprising that this is hard to visualize. Our everyday experience on the surface of the Earth is a sensation of a flat expanse more than an expansive curvature. Only when we get a glimpse from space or project our knowledge of the Earth's curvature onto a model, like a globe, does our mind begin to cope with the meaning of living on a spinning, spherical, and tilted planet.

Depending on the time of year, the latitudes between 23.5° N and 23.5° S receive the most direct sunlight. As you move north or south toward the poles, the sunlight is less direct because the Earth's surface curves away from the direct sunlight. As the sunlight becomes less direct, the solar radiation and the heat it produces are proportionally less intense. So it is warmer in the tropics and colder at the poles. In between regions experience more seasonal variations.

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Likewise, depending on the time of day the angle of sunlight changes as the world turns: at midday, when the Sun appears highest in the sky, we receive the most direct sunlight, and that is usually the warmest part of the day. Sunlight is less direct in the morning and evening, also usually cooler times of day.

Moon's Axial Tilt is 1.5° and There is No Atmosphere to Distribute Solar Radiation

Although the plane of the Moon's orbit around the Earth is inclined about 5°, its equator is inclined about 6.5°, resulting in a 1.5° tilt of the Moon's spin axis to the orbital plane around the Sun. This means that sunlight always just grazes the poles of the Moon. Some craters in the lunar polar regions are permanently in the shadows and never receive any sunlight. At temperatures of 40 to 50 Kelvin, craters could act as "cold traps" that could keep ice so solidly frozen that almost none of it escapes into space.



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Mercury Axial Tilt is 0° and There is No Atmosphere to Distribute Solar Radiation



Similarly, Mercury's axis of rotation is oriented nearly perpendicular to its orbit, so that in the polar regions sunlight strikes the surface at a constant grazing angle. Its poles have been pointing in the same direction ever

since the planet was formed.

The interiors of large craters at the poles are permanently shadowed and remain perpetually cold, below -350° F (60 K). Below 80 K, the molecular motion of ice is nearly nonexistent. Ice is stable at that temperature even in a near vacuum and does not sublime as vapor into space.

Possibly, the tiny influx of ice from infalling comets and meteorites could be cold-trapped in these Mercurian polar caps over billions of years. Or water vapor might originate from the planet's interior and be frozen out at the poles.

Alternatively, it has been suggested that the polar caps consist of a different material, perhaps sulfur sublimated over the eons from minerals in the surface rocks.





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So which is it? How can water ice be cold-trapped in craters of polar regions even on small worlds, even close to the Sun, such as Mercury and the Moon?

Hmmm, How Could the Ice Get There?

Is there water that outgasses from the planet's interior that then freezes at the surface?

Could comets deliver ice? Such impacts might be so powerful (several megatons) that any ice would be obliterated by the energy of the impact, and could destroy any ice that might already be there.

Micrometeorite? Ice is traveling in abundance in interplanetary space. Over billions of years, perhaps many micrometeorite hits brought in the ice.

How Could the Ice Stay There?

After impact, ice molecules would hop around in the exosphere. Some might be lost over time due to photodissociation, solar wind, sputtering, and micrometeoroid gardening. Some jump straight out into space.

But some hop across the surface only to land and hop again, unable to escape the Moon's or Mercury's gravitational field. These molecules continue to move around in a process aptly called, a 'random walk', slowing down as they jump into cooler areas until they reach an area that is below 80 degrees Kelvin (80 K). Once inside these 'cold traps', the molecules are so cold they stop hopping altogether and could lie trapped for billions of years.

Recapping the Evidence

In 1994, the Clementine mission confirmed that conditions for a cold trap that could support lunar ice existed by bouncing radar and receiving highly reflective signals, indicating the likely presence of ice. In 1999, the Lunar Prospector mission found somewhere between 10 to 300 million tons of water ice scattered inside the craters of the lunar poles, based on data from its neutron spectrometer.

Radar echo images of Mercury's polar regions, first obtained from ground-based radar telescopes at Arecibo in 1991, show that the large craters' interiors are highly reflective at radar wavelengths suggesting the presence of ice.

We know that large craters in both polar regions of Mercury and the Moon are:

1. C-c-c-cold, below -350°F ($40\text{--}60\text{ K}$)
2. In perpetual shadow
3. Highly reflective at the radar wavelength (an indicator of water ice)

But to know for sure whether it's ice or hydrogen sulfide we need new data:

- High flux of low-energy thermal neutrons—indicates hydrogen (H)
- Ultraviolet and gamma ray detectors—indicates sulfur or oxygen



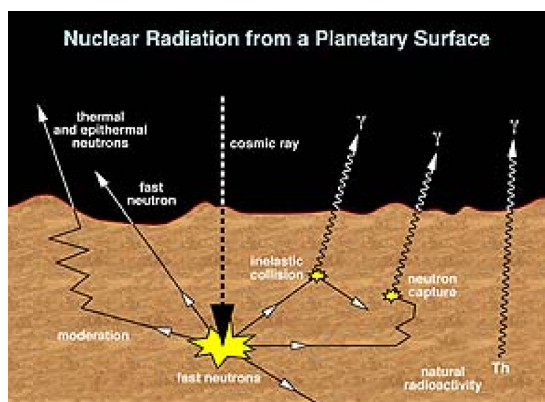
Cosmic Rays and a Cascade of Neutrons and Gamma Rays

It sounds like science fiction, but it's true: high-energy subatomic particles traveling at nearly the speed of light, called cosmic rays, zip in from galaxies and stars (even our own Sun) and rain onto planetary objects in the Solar System everyday. Where there is no atmosphere to filter the cosmic rays, they collide with atoms in the soil. When atoms are hit with such energy, "fast" neutrons are released, which scatter in all directions. Some jet immediately into space, while others first collide with other atoms. When neutrons collide with relatively large atoms, they only lose a little energy, and when they jet out into space they are detected as medium-level, "epithermal" neutrons. But if they strike something their own size—such as an atom of hydrogen, they

slow down a great deal before hopping into space. Meanwhile with each collision, the atoms get "excited" in the process, and emit gamma rays to release the extra energy so they can return to their normal rest state. Gamma rays are very short wavelength, high frequency, high-energy photons produced by a nucleus changing quantum energy states, the shifting of protons. It is light that is so energetic, it goes through most things, and would not even bounce back in a mirror. Gamma rays have characteristic energy signatures for each nucleus. So, by measuring the energy of the emitted gammas, scientists can determine which nuclei are in a sample.

A clever combination of sensors can read the ratios of the different neutron energy levels and the signatures of the gamma rays. If the detector sees few or no medium-energy neutrons, hydrogen must be present. Combined with data from other detectors, we can with confidence infer the presence of specific elements and their concentrations.

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**Testing the Difference: Oxygen or Sulfur?**

How can we tell whether the hydrogen is combined with oxygen as ice (H_2O) or combined with sulfur as hydrogen sulfide (H_2S), a product of volcanic activity?

Different wavelengths of light are associated in different ways with the changing energy states of elements of matter. Ultraviolet light can reveal the signature presence of an element such as sulfur. A gamma ray sensor can detect the presence of oxygen.

Open Questions

On the Moon, the big question is whether the ice is in big enough chunks that could be used by human explorers. On Mercury, the question is still to determine whether it is ice for sure. Once the MESSENGER Mission reaches Mercury and the Gamma Ray and Neutron Spectrometer sends back its data, we will have a more definitive understanding of ice in its permanently shadowed craters.

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This table summarizes the Background Information

<p>a. How do we detect ice on the Moon and Mercury?</p>	<ul style="list-style-type: none"> ■ Ice is inferred from readings of science instruments that detect presence of hydrogen, such as Radar and Neutron Spectrometers. ■ Might <i>NOT</i> be ice—might be hydrogen combined with sulfur.
<p>b. If it is ice, how did it get there?</p>	<ul style="list-style-type: none"> ■ Cometary and meteoritic impact ■ Water-rich asteroid impacts ■ Water vapor might originate from the planet's interior and be frozen out at the poles.
<p>c. How could the ice stay there?</p>	<ul style="list-style-type: none"> ■ Exists in perpetual shadow in cold traps colder than 80° K.
<p>d. How does a Gamma-Ray & Neutron Spectrometer work?</p>	<ul style="list-style-type: none"> ■ Gamma-Ray mode measures emissions from radioactive elements and gamma-ray fluorescence stimulated by cosmic rays; it's used to map elemental abundances in crustal materials. Neutron Mode provides sensitivity to hydrogen in ices at Mercury's poles.
<p>e. How do we rule out that it might not be ice?</p>	<ul style="list-style-type: none"> ■ Use an Ultra Violet Spectrometer to double-check that hydrogen is not from a patch mixed with sulfur.

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ACT OUT THE SCIENCE

Narration and Mime Activity: Movement

Integration Mediating Experience

The Story of Ice in the Shadows

Narrative	Movement	Concept
<p>There was once a polar region of a small spherical world just minding its own business. It was mainly a rocky outcropping that hardly ever got visitors. The light of the Sun only barely grazed the surface, hurrying on by to the next planet. Every once in a while some particles from the solar wind zipped in and tossed up some exospheric dust. From the other direction, micrometeorite dust particles hit the surface from time to time, kicking up a fuss and tilling the soil like a garden; in fact, we call it micrometeorite gardening.</p>	<p>Invite two or three students to play the polar region.</p> <p>Have them stand together with arms outstretched.</p> <p>Identify a direction of the room to be the sun and invite some students to be the “sunlight” passing by and a “solar wind particle” that kicks up some dust</p> <p>Invite a student from the other direction to enter as a “micrometeorite dust particle”</p> <p>The various particles hop about, back to their seats.</p>	<p>The dynamics of the polar regions of a planetary object such as Mercury or the Moon</p> <p>Ice is traveling in abundance in interplanetary space. Over billions of years, perhaps many micrometeorite hits brought in the ice.</p>
<p>Occasionally things got exciting. Like when a comet tumbled in toward the sun and struck the surface of the world. That little world would open its arms and catch that comet of ice, which would vaporize almost as quickly as it had crash landed.</p>	<p>A “comet” strikes the polar region, in a slow motion version of a major impact, the comet, “vaporizing” back to his or her seat.</p>	<p>Such impacts might be so powerful (several megatons) that any ice would be obliterated by the energy of the impact, and could destroy any ice that might already be there.</p>
<p>But best of all was when a water-rich asteroid struck just right and made a crater at the polar region, like a burrow, so that the block of ice it carried came to rest there in the shadows, while scattering diamonds of ice all around.</p>	<p>Invite several students to become the water-rich asteroid; upon impact, some become the cold trap, others are ice hoppers who skitter and hop, some skip right out into “space” escaping back to their seats...</p>	<p>Water-rich asteroid impacts.</p>

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Narrative	Movement	Concept
<p>The scattered ice molecules would hop around because they have nothing else better to do, depending on how energetic or kinetically hot they are. Some hop right out into space, most hop and land somewhere else and then hop again.</p>	<p>More hopping about.</p>	<p>Kinetic theory: the principles of molecular motion.</p>
<p>Some take a “random walk” hopping about until they find themselves down in the crater with the big ice in a “cold trap,” a place colder than 80° K—there they would stay huddled and frozen, hidden from view in the total darkness for billions of years.</p>	<p>Identify a “crater space” where several ice hoppers get “cold trapped” and huddle together...</p>	
<p>The story could end right there. We’d never know about the place, because no telescope or spacecraft would ever see it because it was never illuminated by the sunlight, always hidden by the darkness.</p>		<p>Telescopes and other optical detectors depend on the sun’s illumination to retrieve data.</p>
<p>Wait! Look! There! In the Sky! From a distant star in a distant galaxy! It’s a cosmic ray, a particle traveling nearly at the speed of light zipping in toward the polar region!</p>	<p>Invite a student to be a cosmic ray source.</p>	<p>Cosmic rays are subatomic particles from high energy events traveling at near the speed of light, from galaxies, stars, or the Sun.</p>
<p>Stop the Action!</p>	<p>Freeze!</p>	
<p>If that cosmic ray strikes near the ice in the shadows, where it’s been cold trapped for billions of years, we might be able to be at just the right place at the right time to measure its cascading effect.</p>	<p>Explain, foreshadows next action...</p>	



Narrative	Movement	Concept
<p>We need to position a spacecraft with a Gamma Ray and Neutron Spectrometer and an Ultraviolet Spectrometer to boot.</p>	<p>Create a spacecraft with two spectrometers.</p>	
<p>Here we are. Ready. Ultra slow motion.</p>	<p>Let the cosmic ray strike!</p>	
<p>As cosmic rays strike the nuclei of atoms on the surface, they knock loose fast neutrons: some move fast enough to escape the planet directly.</p>	<p>Transform some ice hoppers into fast neutrons escaping.</p>	<p>When neutrons collide with relatively large atoms, they only lose a little energy, and when they jet out into space they are detected as medium-level, “epithermal” neutrons.</p>
<p>Other, slower neutrons strike ultra frozen nuclei just their own size—like hydrogen! Those neutrons then move really slowly, and hop out into space.</p>	<p>Transform other ice hoppers into neutrons escaping getting slowed down by the presence of ice...</p>	<p>But if they strike something their own size—such as an atom of hydrogen, they slow down a great deal before hopping into space.</p>
<p>The neutron sensor on the spacecraft can measure how fast the neutrons are going—and an absence of medium neutrons and enough slow ones means a patch of hydrogen has been detected! But what was that hydrogen combined with? Oxygen to make ice? Or Sulfur to make hydrogen sulfide?</p>	<p>Hopping into space, the “neutrons” get detected, counted by the spacecraft sensors.</p>	<p>It detects neutrons in three energy bands: fast, those that were loosened with the cosmic ray burst immediately; epithermal, on their way to being slowed down; thermal, slowed down, waiting to be absorbed in the regolith (and a signature of the presence of hydrogen).</p>
<p>As they move out, gamma rays, high-energy photons of nuclear light, are also released with a detectable signature of the neighboring atoms—the gamma ray sensor can tell whether it was—“oxygen!” and the Ultraviolet sensor checks for sulfur.</p>	<p>A student releases a gamma ray (with rapidly waving arms) with O signature and gets detected.</p>	<p>Gamma rays have characteristic energy signatures for each nucleus. So, by measuring the energy of the emitted gammas, scientists can determine which nuclei are in a sample.</p>

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Narrative	Movement	Concept
Ice in the Shadows? Or not Ice? That is the question.	Everyone pose dramatically.	
Either way, whatever the actual results, we learn more about how the Solar System has evolved. By looking at the polar region in several ways, we get the whole picture!	Return the focus to the polar region, the cold-trapped ice, the spacecraft, as this closing thought is spoken.	Future missions such as MESSENGER, Bepi-Colombo and new efforts to explore the Moon will answer these compelling questions.

Small Group Mime Activity: Movement Integration Mediating Experience

Invite students to form small groups (about three to five students), look at images of features on Mercury and the Moon and create

their own mime and narrated story about how ice may have gotten there. Encourage students to act out a sequence that results in the drawing science questions from the story.

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MATERIALS

For All Activities, to Record Reflections, Observations, Calculations, etc.

Science Notebooks: writing and drawing utensils.

Demonstration

- Musical Horn
- Electric or battery-operated fan

Warm Up Activity

- Two 5-10 lb. chunks of ice
- Globe of the Earth

Main Activity

- Hair dryer or heat lamp
- Ice cubes
- Modeling Clay
- Toothpicks

Ice in the Shadowed Craters

- Gallery with NASA images of Mercury and the Moon (See Resources)

DEMONSTRATION

The purpose here is to help young children relate the notion of how a more direct or less direct angle of sunlight can make a difference.

The angle of the sunlight hitting a planet is different at different locations because a planet is spherical. The angle makes a difference in the heat generated at the surface. Consider different ways of showing a difference in effect between more direct and less direct angles.

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PRE K–2***The Analogy of Sound***

Does the directness of the angle between you and the source of the sound make a difference in how well you hear it?

Invite a student to come up to the front. Have in hand a simple musical horn or noisemaker. Ask the student to practice making a continuous sound with it. Now instruct the child to start by facing away from the class. Start blowing the horn and slowly turn around in a full circle, turning toward and then away from the class.

Lead a discussion about what students observed about the loudness of the sound. Why is the loudness different at different angles? At what position did it sound the loudest? When the horn is blowing straight at you, is it the loudest? Is it as loud when it is at a glancing angle or when it is pointed away from you altogether?

Repeat the demonstration several times. Point out the different angles involved. Connect this experience to the main activity: drawing upon the experience with the sound to explain how sunlight is “loudest” when it strikes more directly at the Equator and “quieter” when it strikes indirectly at the poles.

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3–5***The Analogy of a Fan***

Does the directness of the angle between you and the source of the breeze make a difference in how well you feel it?

Invite a student to come up to the front. Have at hand a movable electric fan. Ask the student to practice controlling the direction of the fan in a continuous smooth motion. Now instruct the student to start by facing away from the class. Start the fan blowing and slowly turn around in a full circle, turning toward the class and then away again.

Lead a discussion about what students observed about the intensity of the breeze. At what position did it seem the breeziest? When the breeze is blowing straight at you, is it the most intense? Is it as strong when it is at a glancing angle or when it is pointed away from you altogether?

Repeat the demonstration several times. Point out the different angles involved. Lead a discussion about why students think it feels different at different angles. Connect this experience to the main activity: drawing upon the experience with the fan to explain how sunlight is “breezier” when it beams more directly at the Equator and less “breezy” when it beams at a grazing angle at the poles.

MAIN ACTIVITY

This activity involves modeling the effect of the angle of sunlight on a planet and connecting to ice on polar regions.

PREPARATION

- Devise exploratory zones for small groups to construct spheres of modeling clay and to embed ice cubes.
- Devise exploratory zones to look at polar regions of the Moon and Mercury, using NASA images.

TEACHING TIPS

Explore

These exploratory zones aim at making the complexity of spherical geometry simple and direct. Best not to rush the students toward premature closure. A lot of mental gymnastics are involved to visualize how to translate our experience of standing on the Earth to a projection of our position on the spherical Earth and the curvature in relation to the incoming sunlight. Allow students to repeat the steps several times as they encounter the phenomenon and model it.

Diagnose

Listen to student ideas about the spherical shape of the Earth, the Moon, and Mercury. How well do students grasp the change in the angle of sunlight due to the curvature? Listen to student ideas about the implications of being at different places on the globe. What knowledge do the students bring in to the table as they examine the information about how ice may form in permanently shadowed craters at the poles of Mercury and the Moon? Do they connect the dots?

Design

Have students work in collaborative teams to research questions that arise from the visits to the exploratory zones, especially drawing comparisons between their controls and variables. Have students design a mission with astronauts that would accomplish the exploration of ice on the Moon.

Discuss

How do scientists learn about places like Mercury and the Moon? Observation of places like Mercury and the Moon is technologically challenging. What are the big questions scientists are asking? Explore how students view a new era of lunar exploration.

Use

This activity connects concepts about detecting ice with a gamma ray and neutron spectrometer. Invite students to explore how this technology is used on Earth to detect things of interest. How does this exploration relate to other concepts about the Solar System?

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WARM-UP AND PRE-ASSESSMENT

A day or so before the main activity set out two big chunks of ice (5 or 10-lb chunks), one in the direct sunlight and one in indirect sunlight, in the shade. Ask students to predict which chunk of ice will melt faster and then to observe and propose an explanation.

Just before the main activity, lead a discussion about their predictions, observations and proposed explanations.

Then invite the students to briefly examine the spherical features of the Earth: Examine a globe of the Earth. Guide students to notice explicitly that the Earth is spherical and tilted at an angle with respect to the Sun. Manipulate the globe in such a way as to guide students to notice the area of the Earth that receives the most direct sunlight is bounded by the Tropic of Cancer and the Tropic of Capricorn. The North and South Poles are at the top and bottom of the world where the sun shines at a grazing angle.

Point out that a sphere presents different angles due to its curvature. Illustrate this explicitly by using a modeling clay sphere and placing toothpicks to show that this is why the angle of sunlight changes as you move from the Equator toward either pole.

Go on to point out that the Moon and Mercury are also spherical, but are not significantly tilted with respect to the Sun.

With this in mind, but without seeking an answer at this moment, ask students to discuss the question: *Where on these worlds would a chunk of ice melt faster and where would it melt slower or not at all?* (See discussion and reflection)

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PROCEDURES

PART 1.

Modeling the Sphericity of Mercury and the Moon

Have each student make a spherical “Mercury” or “Moon” out of modeling clay. Have students notice the different angles in relation to the “Sun,” explicitly, by having them place toothpicks straight in and noticing that they point out in different directions (angles).

Have each student scratch a line to mark the Equator, where the Sun shines most directly; and to mark the north and south poles, the “top” and “bottom” of Mercury or the Moon, where the Sun shines least directly.

Optional: Make the spheres and position them accordingly and then cool the clay prior to the ice melting experiment.

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PART 2.

Do Angles Make a Difference?

Have students work as partners, with two modeling clay worlds (a control and a variable). Have one student be ready with the heat source (hair dryer or heat lamp) to aim directly toward the Equator of the variable world. (This represents the thermal effect of solar radiation.)

The control sphere is off to the side to account for any effect of room temperature and the warmth of the clay itself.

Once the heat source is in position, ready to be turned on, embed ice cubes in modeling clay spheres, at 90° apart, representing an equatorial and a polar region. Push each ice cube in far enough so that its top surface matches or sits below the clay surface.

Turn on the heat source and aim it directly at the Equator of the variable world.

Notice the effect on the ice cubes. Observe and time how quickly the ice cubes melt.

Write and illustrate new understandings that result from this activity.

Ask students: *Which ice cube is likely to melt faster?*

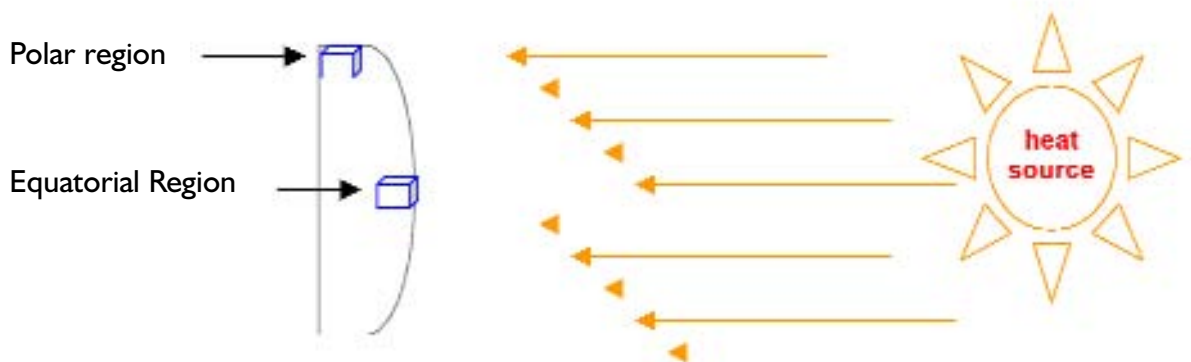
Have students switch roles and repeat: Using one “world” as a control, do nothing. Toward the other, aim the heat source in such a way as to create warm air blowing toward it. Make sure the air current reaches the whole sphere from one direction.

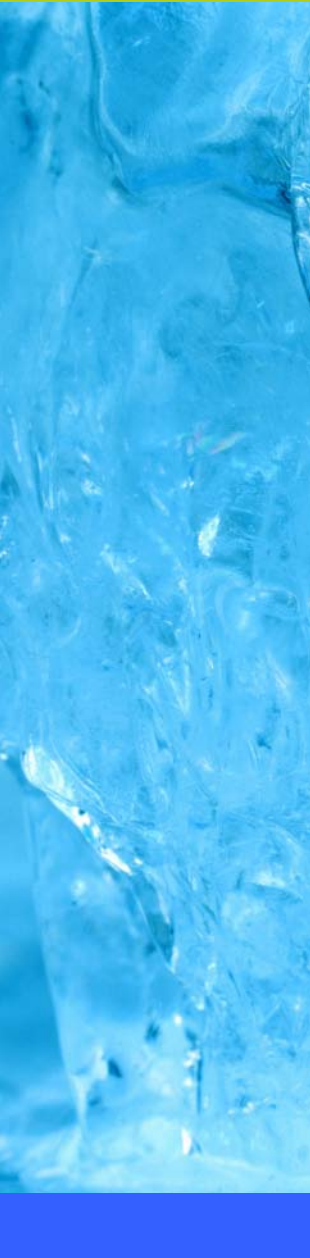
The “equatorial ice” receives a more direct angle of warmth. The “polar ice” receives a less direct angle of warmth. Also, see what happens if the ice cube sits in a “crater” near the pole.

Be sure to compare the variable to the control. Because we are in a classroom on Earth and not in a laboratory or in space, the ice on the control is also melting. If the ice melts more rapidly with the hair dryer, can we infer that the hair dryer made the difference?

Does melting occur differently at different angles (that is, does a direct equatorial angle melt the ice more readily than the warmth moving over the top? What happens where you created a “crater,” where the warmth rides over it altogether?

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What happens?	Control World	Variable World
Ice Cube at Equator		
Ice Cube at the Pole		

Optional: Invite students to examine the situation in greater depth.

Subtracting the melting of the control world from the melting of the variable world might reveal that virtually *no melting* occurs due to the heat source when the ice cube is embedded in a shadowed crater. That is, if you could establish that the melting of the control and the variable at the pole is *the same*, then you can infer that the heat source had no effect because the heat did not reach the ice, *just as ice in the permanently shadowed craters of Mercury and the Moon can only remain stable if NO sunlight ever reaches it.*

This Table Connects the Model to the Phenomenon to guide discussion

Precursor Concept	Mercury and Moon Connection
Ice melts faster in direct sunlight than in the shade.	Ice melts or sublimates rapidly in direct sunlight; slowly in indirect light.
Compare angles with modeling clay worlds and toothpicks, in relation to a reference point.	Aimed at communicating that that a sphere presents different angles to a reference point (the Sun).
Ice cube placed at equatorial region melts faster than ice cube placed at polar region.	Directness of sunlight at equatorial regions versus grazing angle at the polar regions.
Ice cube at pole in variable world shows almost no difference in melting compared to ice cube at pole in control world.	Any ice that receives sunlight would sublimate very rapidly, evaporating into space; For ice to exist on an inner planetary world, it must be permanently shadowed in craters that craters allow NO sunlight or heat.

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PART 3.

Gallery of Moon and Mercury Images

Have students look at a gallery of images of the polar regions of Mercury and the Moon. Ask students to relate the activity they just completed to the exploration of Mercury and the Moon. Have students ask questions and pose explanations about what they noticed.

DISCUSSION & REFLECTION

Where On These Worlds Would a Chunk of Ice Melt Faster and Where Would It Melt Slower or Not At All?

Scientists were surprised that ice exists in the shadowed craters of Mercury and the Moon. In the near vacuum conditions of the exosphere, with the vapor pressure at zero, over time, ice molecules at the surface would be expected to sublime, to hop off going directly from solid to vapor. The only explanation is that in these regions, it is sooooooo c-c-c-cold that the ice molecules are way beyond shivering—they stop moving altogether and just stay there, huddled together for billions of years. If sunlight were to strike the cold trap directly or indirectly even for a small

part of a year, it would raise the temperature enough for the ice to shiver and hop free into space. So, wherever sunlight strikes directly, the temperature goes way up, the ice would disappear fast, sublimating and melting away. Only in places that NEVER get sunlight or its warmth—permanently shadowed craters and underground in the polar regions can ice remain stable.

How is a Gamma Ray and Neutron Spectrometer Part of Everyday Experience?

Have you ever traveled by air? Then gamma ray and neutron spectrometers are part of your experience. If you have traveled, then your baggage has been scanned at airport security checkpoints. Gamma ray and neutron spectrometers are not only used for space exploration, they can detect combinations of elements that are typical of explosives. They are most useful in detecting traces of radioactivity and have been used to inspect for weapons of mass destruction.

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And What About Those Cosmic Rays?

Just how amazing does it seem to you that a particle flying in from another galaxy can help us find ice hidden in the shadows of Mercury and the Moon?

CURRICULUM CONNECTIONS

This lesson challenges the students to think about the geometry of spheres and to project that thinking to what it means to be standing on a slightly tilted, spinning sphere. This lesson connects to geometry and thinking about angles.

K–5 students are expected to be able to analyze characteristics and properties of two- and three-dimensional geometric shapes and develop mathematical arguments about geometric relationships. This lesson provides direct experience with three-dimensional spheres and the opportunity to wrestle with geometry.

The most important realization is in understanding how the angle of incidence of light from the sun differs, not because the angle from the Sun is changing, but that the curvature of the spherical Earth changes as you move north or south from the middle regions—so it depends on your position at a given time of day and time of year. Mercury and the Moon are slightly simpler systems because their tilt is negligible—but they are both still spherical.

Students are asked to comprehend the connection between the world, and the way we represent it in textbooks, drawings, and models. This activity creates an opportunity for students to apprehend a spherical object in this context.

This activity also lays the groundwork for precursor understanding of fundamental phenomena such as why the seasons change the way they do.

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ASSESSMENT CRITERIA

Exemplary

- Students write and illustrate new understandings that result from the exploratory zones and share it with both a small group and the whole group.
- Students display drawings, constructions, and dynamic models drawn from their science notebooks and web-based research.
- Students identify and extend science questions drawn from research about ice in the shadows.
- Students ask a rich and extensive range of questions about ice on Mercury and the Moon: micrometeorite gardening, cratering, and the exosphere.
- Students extend learning by considering implications of the view that ice may reside in “cold traps” in craters at the poles of Mercury and the Moon.
- Students relate ideas to whole context of exploring ice in the Solar System.

Emerging

- Students write and illustrate a description of the conditions of ice on Earth, Mercury and the Moon, sharing ideas with a small group and the whole group.
- Students pose basic science questions drawn from their observations and research about ice in the shadows.
- Students observe images and data about ice on Mercury and the Moon.
- Student display results using a variety of ways to represent examples of ice on Mercury and the Moon.
- Students ask a rich range of questions about the origin, structure and composition of polar ice on Mercury and the Moon.
- Students make speculations about possible explanations for ice on Mercury and the Moon.

Formative

- Students recognize places in the inner Solar System where polar ice has been detected: Mercury and the Moon.
- Students pose science questions about ice on Mercury and the Moon and why the angle of sunlight makes a difference.

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RESOURCES

Mercury

http://nssdc.gsfc.nasa.gov/planetary/ice/ice_mercury.html

Ice on Mercury

<http://messenger.jhuapl.edu>
MESSENGER Mission site

http://nssdc.gsfc.nasa.gov/planetary/ice/ice_mercury.html

Ice on Mercury, discussion of evidence for ice on Mercury

Moon

<http://www.psr.d.hawaii.edu/Dec96/IceonMoon.html>

Ice on the Bone Dry Moon

Written by Paul D. Spudis

Deputy Leader of the
Clementine Science Team

<http://lunar.arc.nasa.gov>

Lunar Prospector site, including discussions of ice on the Moon and a relatively easy to understand explanation of the neutron spectrometer

http://nssdc.gsfc.nasa.gov/planetary/ice/ice_moon.html

Ice on the Moon, discussion of Lunar Prospector results

Images

Link to image gallery

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