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The topsy-turveying of planets, stars, and lava lamps

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A primer on convection

Stars do it, icy moons do it, even pots of coffee do it. From the small to the large, things undergo convection. Convection -- the movement of heat by the movement of matter -- is a recurring theme in science, and a vivid reminder that astronomical objects aren't really so different from everyday objects. They may be bigger and hotter and farther away, but the same laws of physics determine how they behave.

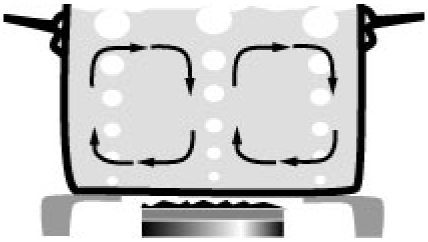

Figure 1
Convection in a pot. The flames under the pot heat the water on the bottom. As the water gets hotter, it expands and rises. The colder water above it sinks down to the bottom, where it too starts to get hot. The process continues until you shut the stove off. The convection cycle distributes the heat of the stove evenly throughout the water in the pot.

Convection is a consequence of the most basic drive in nature: Hot things want to cool down. If the thing is a fluid -- air, water, anything that can flow -- it can cool down by moving around. Hot air rises, cold air sinks: It's common sense. It's convection. And from this basic idea can come some funky phenomena.

The next time you boil water, fill a jar with hot water and notice how much lighter it is than a jar of cold water. (If you don't trust yourself, put the jars on a balance.) This difference in weight keeps convection going. If you put water in a pot on the stove, the water on the bottom gets hot first. The colder fluid above it is heavier, so it sinks. This forces the hot fluid on the bottom to go up on top. The stove heats up the cold water on the bottom; the air cools down the hot water on the top. So they switch places again. And so on. It sets up a cycle, as shown in Figure 1. This cycle transports heat from the stove up to the air.

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Cool It Down

It turns out that convection is an excellent way to move heat from one place to another. Stars and planets use this kind of cycle to get heat from the inside out. Heat loss is the biggest problem that stars and planets face. Stars generate heat from nuclear reactions; planets generate heat from radioactivity. Inside stars and planets, it's hot. If you went down into a gold mine 2 miles deep, the thermometer would rise above 170 degrees F. The heat has to escape somehow.

There are three ways how. First, heat can move by *conduction*: molecules bang into their neighbors and pass heat along in a domino effect. When you put your hand against a cold window on a winter's day, the window sucks the heat from your hand by conduction.

Second, heat can move by *radiation*. Usually, when people think radiation, they think nukes, mutants, Chernobyl. But to scientists, radiation just means any kind of light ray, either visible or invisible (such as infrared or ultraviolet). Hot things glow, giving off light that carries the heat away. That's why the Sun shines and warms the Earth. It's also why you feel hot when sitting in front of a fireplace or electric heater. The desert is so cold at night because you and the air around you are glowing in the infrared, losing heat to outer space. Survival kits contain "space blankets," basically big sheets of aluminum foil, and these keep you warm by reflecting the infrared radiation from your body back to your body.

Convection is the third way that heat can move. Instead of molecular domino-effects or streaming heat rays, convection relies on movement of fluid. When hot fluid moves, it carries the heat along with it. You can think of the three ways heat moves in terms of passing a love note to your sweetie across a classroom. You could give it to person sitting next to you and ask them to pass it along (like conduction), you could signal using a flashlight (like radiation), or you could get up, walk across the room, and give the note to the person directly (like convection).

Convection is a last-ditch way to get rid of heat. It takes effort to start convection, so heat usually prefers to escape by conduction or radiation. But conduction is slow, and radiation can't work where it's opaque: inside a planet and certain parts of a star. In those cases, only convection can do the job.

The mechanism of heat loss determines what a planet looks like. The inner planets of the solar system are composed of rock. Normally, we think of rock as a solid, but it can act as a liquid if you wait long enough; say, millions of years. Rock can transport heat either by conduction or by convection; rocks are opaque, so they block radiation. Small, cool planets, like the Moon and Mars, lose their heat by conduction. The Earth and Venus prefer convection (see Figure 2). Convection is much more exciting. It powers the plate tectonics and other fancy styles of geology that the Earth and Venus have.

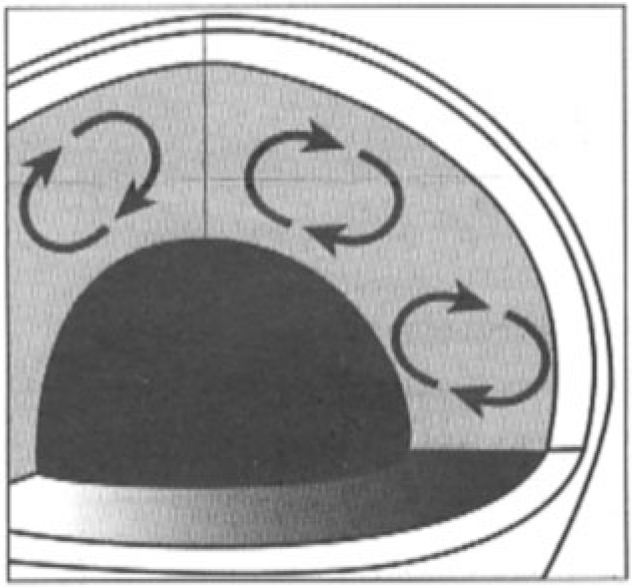

Figure 2
The interior of the Earth or Venus. We build our buildings and eat our Eggos on top of a thin crust of solid rock, like scum on a pond. Underneath is a vast sea of fluid rock called the mantle, continually churned by convection. The mantle itself sits on a core composed of molten iron.

Inside a star, conduction doesn't work because the molecules are too far from one another, so heat moves either by radiation or by convection. Radiation operates where the gas of the star is transparent, as it is when it is especially hot. In medium-sized stars like the Sun, radiation transports heat deep within the star, where it's hottest (see Figure 3), and convection operates toward the outside, where it's cooler. In small, cool stars, convection is the main mechanism; in large, hot stars, radiation dominates.

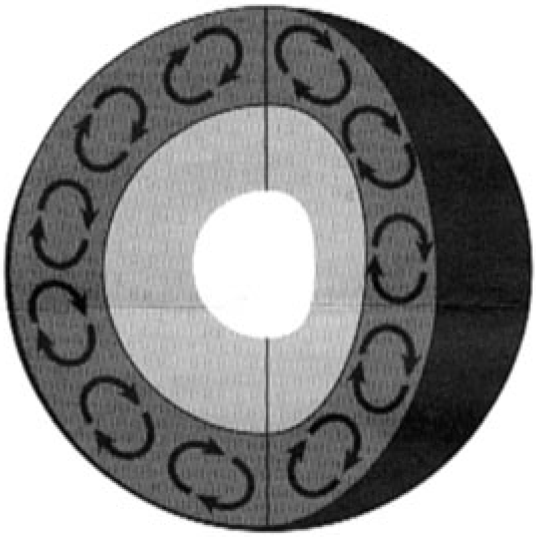

Figure 3
The interior of the Sun. Only a small part of the Sun, its core, actually generates energy. The rest of the gas just gets in the way as the heat tries to get out. Most of the Sun's interior is filled with transparent gas, and the energy passes through it in the form of radiation. But toward the surface, the gas is cooler and opaque, so radiation can't get through. Convection takes over.

Convection gives the Sun a mottled appearance, as astronomers see when they look at the Sun with specially designed telescopes (see Figure 4). Each of the little granules in Figure 4 marks a place where convection is gurgling up from below. Convection dredges up atoms manufactured in the core of the star. Astronomers like this because it gives them some idea what's happening deep within the star, where they can't see.

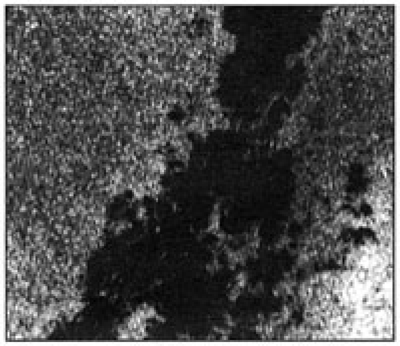

Figure 4
Fire burn and cauldron bubble. This highly magnified picture of the surface of the Sun shows a sunspot (dark splotches in center) and granules (light-colored grains). Each granule, small as it looks, is about the size of Texas. The granules flicker rapidly, making the Sun look like a burbling witch's brew. Granules are the top of convection cycles that bring material from deep within the Sun to the surface. Photo courtesy of Sacramento Peak Observatory.

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Oh, Smoggy Day

Not all hot fluids convect. A smoggy day in Los Angeles or any other big city illustrates what happens when things *don't* convect. The air just sit there and doesn't get stirred. Why not?

Convection can't occur unless certain conditions are right. The most important condition is the temperature profile. Normally, the air is hottest near the ground and gets cooler as you go up. Outside an airplane window at 30,000 feet, the air temperature drops to -40 degrees F. The reason is straightforward: Because air is transparent, sunlight passes right through it and heats the ground. The ground, in turn, heats the air near the ground. Air further away from the ground doesn't get heated directly by the Sun.

Because it gets colder as you go up, the atmosphere wants to convect. Cold air is sitting on top of hot air. The hot air wants to rise, the cold air wants to sink. A convection cycle develops.

Sometimes, though, the ground manages to become cooler than the air above it. This can happen after a clear night during which the ground cooled more than usual, and it can happen in valleys where the walls shade the floor and trap cool air close to the ground. In these cases, the air is cold near the ground and hotter as you go up. This situation is a temperature *inversion*. The air doesn't want to convect, because hot air is sitting on top of cold air. The cold air has already sunk, the hot air has already risen. The atmosphere is happy; it has no reason to change the status quo.

Without convection, the air stagnates -- as does anything in the air, like smog. Usually, convection whisks away car fumes. When a temperature inversion occurs, car fumes have no place to go, except into your eyes and lungs.

Fortunately, this is unusual. The lower 6 miles of the Earth's atmosphere -- the air below you when you fly in an airplane or climb Mount Everest -- is almost always convecting. This churning region, known as the *troposphere*, is where the weather takes place (see Figure 5). All of the planets have tropospheres.

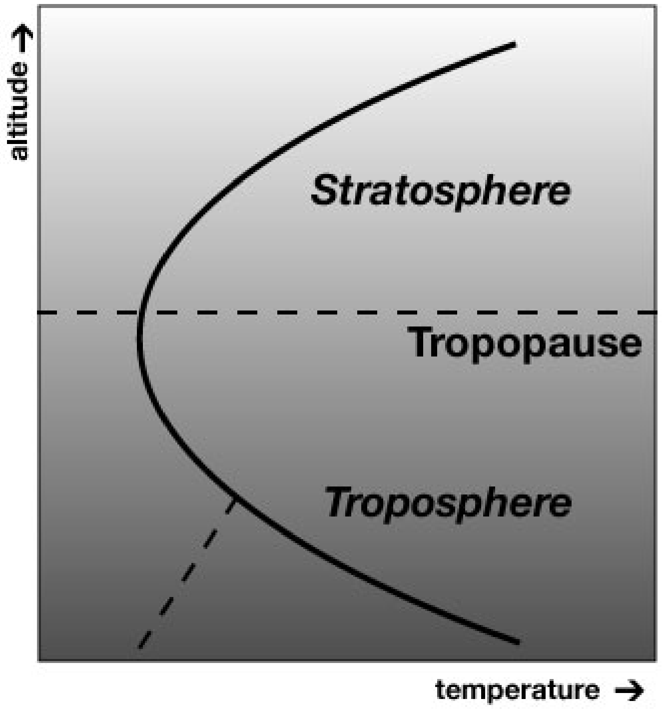

Figure 5
The temperature profile of the Earth's atmosphere. Tornadoes, thunderstorms, and other weather patterns take place in the lowermost layer of the atmosphere, the troposphere. Convection is responsible for much of the meteorology. If it weren't for the temperature profile, convection wouldn't occur: Because the temperature decreases with altitude, cold air sits on top of hot air, allowing convection. But if for some reason the temperature increases with altitude (dotted line), convection grinds to a halt. This happens on smoggy days in urban areas and everyday in the stratosphere.

Many weather patterns in the troposphere occur because of convection. Sea breezes are a good example. During the day, the land warms up faster than the sea. The air above the ground is hot, the air above the water is cold. The hot air above the land rises, and the cold air above the sea swoops in to take its place. This causes a wind to blow from the ocean toward the land, a sea breeze. At night, the situation reverses. The land cools down faster than the sea, so the air above the ground is colder than the air above the water. The hot air above the water rises, the cold air from the land rushes in, and you have a land breeze.

The same thing happens on a global scale. The tropics are warmer than the poles, and this discrepancy powers giant convection cycles called *Hadley cells*. In such a cycle, air rises in the warm low latitudes, moves toward the pole, sinks at higher latitudes, and rushes along the ground back toward the equator. (These convection currents don't quite go due north or due south; they veer off course because of the Earth's rotation, creating the easterly trade winds in the tropics and the prevailing westerlies at temperate latitudes.) The Northern and Southern hemispheres each have three sets of Hadley cells, one set for the tropics, one for temperate latitudes, and one for the polar regions. In the Northern Hemisphere, the boundary between the Arctic and temperate cells, called the *polar front*, seldom stands still. It weaves north and south, and we have its fidgeting to blame for the weather patterns in Europe, North America, and northern Asia. Venus and Mars also have Hadley cells, but only a single set.

Above the restless troposphere is the subdued *stratosphere*. In the stratosphere, unlike the troposphere, the air gets hotter as you go higher. On the Earth, this is because the ozone layer absorbs solar ultraviolet radiation. Not only does the ozone preventing these deadly rays from reaching the surface, it also heats up the stratosphere. As a result, the stratosphere is stagnant. The air doesn't circulate much.

Jupiter, Saturn, and Titan also have stratospheres. On those worlds, the stratosphere owes its existence to the absorption of solar radiation by methane and dust, rather than by ozone. Venus has a sort of stratosphere -- the temperature remains roughly constant with height, instead of increasing with height -- due to nasty clouds of sulfuric acid at an altitude of 40 miles. These thick clouds absorb nearly all of the sunlight falling on Venus and prevent us from seeing the surface.

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The Yearn to Churn

The temperature profile isn't the only requirement for convection. The force driving convection -- the weight difference between hot fluid and cold fluid -- must overcome the fluid's natural resistance to motion, known as *viscosity*.

Heinz ketchup commercials used to compare Heinz to other, runny brands. If you believe those ads, Heinz is more viscous than its competitors. It's harder to get Heinz to flow out of the bottle. It would be harder to start convection in a vat of Heinz than in a vat of another ketchup.

Air, too, is viscous. Its resistance to motion is what slows raindrops and parachutists down to reasonable speeds. If the viscosity of air were smaller, raindrops would fall so fast that they could smash car roofs and kill small dogs. But the air's viscosity is small enough that it doesn't stop convection from occurring in the atmosphere.

In some cases, the viscosity is *too* small, and convection gets out of control. It goes haywire, and the nice orderly patterns of Figure 1 degenerate into unsteady, unpredictable turbulence. In turbulent convection, the fluid gets bunched up in spiral eddies. These eddies pop up without warning, as airplane passengers who've been on a bumpy flight will testify. The chaotic curlicues in rising cigarette smoke, or projected on the wall behind an electric heater, are turbulent convection. So are the swirls in the clouds of Jupiter (see Figure 6).

Figure 6
Planetary paisley. Like cream in coffee, clouds on the giant planet Jupiter bend and twist and curl into psychedelic patterns. These storm systems dwarf the Earth, superimposed for scale. Such turbulence is what happens when convection gets carried away. The Great Red Spot is the tilted oval in the upper right corner. Photo courtesy of NASA.

Deep underground, the problem isn't too little viscosity, but too much. The continents and ocean floor of the Earth float on a gargantuan sea of hot rock, known as the *mantle* (see Figure 2). The viscosity of the mantle is enormous, so enormous that the mantle seems not to move at all. But over thousands and millions of years, the mantle moves. Its slow slithering creates many of the geologic landforms we see.

One way we know the mantle moves is by watching how the ground has responded since the last Ice Age ended. During the Ice Age, Scandinavia and other northern areas were covered by glaciers miles thick. The enormous weight of the glacier pushed down on the land. When the ice melted, the land wanted to pop back up. But for the land to bounce up, the mantle underneath it must be able to flow. It takes 150 years for the land to pop up by one foot, and by measuring this, geologists have calculated the viscosity of the mantle.

Because the mantle is fluid, and because it is hot, it can convect. To overcome the high viscosity takes a lot of heat, supplied by radioactive uranium, thorium, and potassium in a sort of slow-simmering nuclear reactor. The mantle churns in giant convection cycles 450 miles deep and 900 miles wide. In so doing, it drags along the plates that form the Earth's surface. When these plates rub against each other, they cause earthquakes; when these plates crash into one another, they crinkle into mountains. Earthquakes and volcanoes are just a way for the Earth to cool off.

Other planets also have mantles. On Venus, the mantle doesn't shuffle plates horizontally. Instead, the venusian mantle likes to push the surface vertically. In some areas, this vertical shove has created highlands.

Miranda, one of the moons of Uranus, appears to have a mantle made of ice, rather than of rock. Convection in this icy mantle contorts the surface into gnarled patterns of mountain ridges and valleys (see Figure 7).

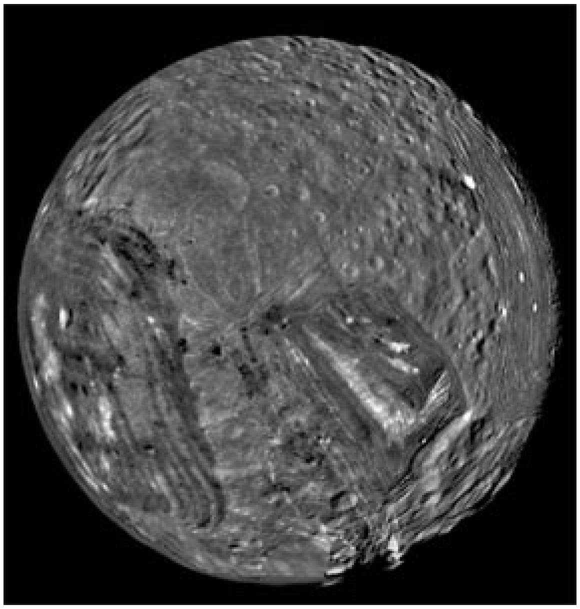

Figure 7
The Chevron Moon. Miranda, one of the satellites of Uranus, looks more like a military badge than a moon. The little moon, about 300 miles across, is stamped with weird diamond shapes. This Voyager 2 picture shows three such shapes: Elsinore (left), Inverness (center), and Arden (right). The shapes may result from convection inside the tormented moon. Photo courtesy of Jet Propulsion Laboratory.

From Lava Lamps to Lava Flows

The urge of the mantle to lose heat can also cause rock to bubble up toward the surface in blobs. Blobs are smaller and shorter-lived than the gigantic, full-blown convection cycles, but they too help planets to cool off.

Lava lamps work on the same principle. Heat causes blobs to form and float up. If you turn a syrup bottle upside down, you can see blobs of air slowly rise upwards. The same basic thing happens inside planets, except that the blobs are made of hot rock, instead of air. In fact, scientists have watched bubbles in syrup in order to understand the effect of rock blobs on the surface of planets. Because blobs carry hot rock from the interior of the planet toward the surface, they supply volcanoes with lava. This is what happens in the volcanoes of Hawaii and East Africa. Ten percent of the Earth's heat escapes this way.

On Venus, blobs are even more important than on Earth. The venusian surface is peppered with volcanoes and roundish terraces called *coronae*. Coronae are several hundreds miles across and appear to form when hot blobs push and stretch the surface (see Figure 8).

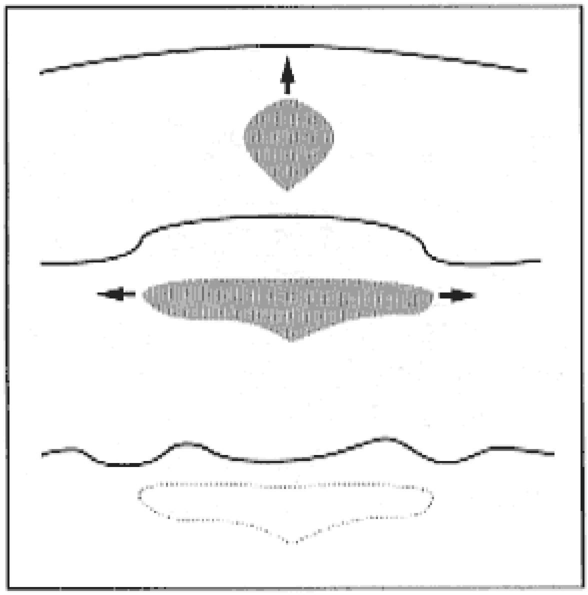

Figure 8
Blobology on Venus. Rising blobs of hot rock, a hundred or so miles across, can push up the venusian surface and form mountains. When the blob is still far underground, it squeezes the fluid between it and the surface, causing the surface to bow out (top). As the blob gets closer to the surface, it begins to flatten like pizza dough into a pie shape (center). After a while, the blob cools down, and the surface sags (bottom). Diagram courtesy of Steven W. Squyres, Cornell University.

Convection cycles can be tens of thousands of miles tall, as they are in stars; hundreds of miles tall, as they are in planets; or just a few inches tall, as they are in tea kettles. But no matter how big or small, the basic idea is the same. Remember that the next time you boil water.

Activities in the Classroom

Convection currents in water

This demonstration requires a glass jar and a stove, bunsen burner, or other heater. An automatic drip coffee pot is perfect. Fill the jar with water and add sawdust, iron filings, peppercorns, or other small particles to the water. Give the particles time to settle on the bottom, and then turn on the heat. The water will begin to convect, and the particles will follow the convection currents.

If you shine the light from a slide projector through the hot water and project it onto a screen, you can see vivid shadows of the hot water vapor convecting upwards.

Convection currents in air Hold a pinwheel above a candle or burner. The hot flame will set up convection currents in the air, causing the pinwheel to spin.