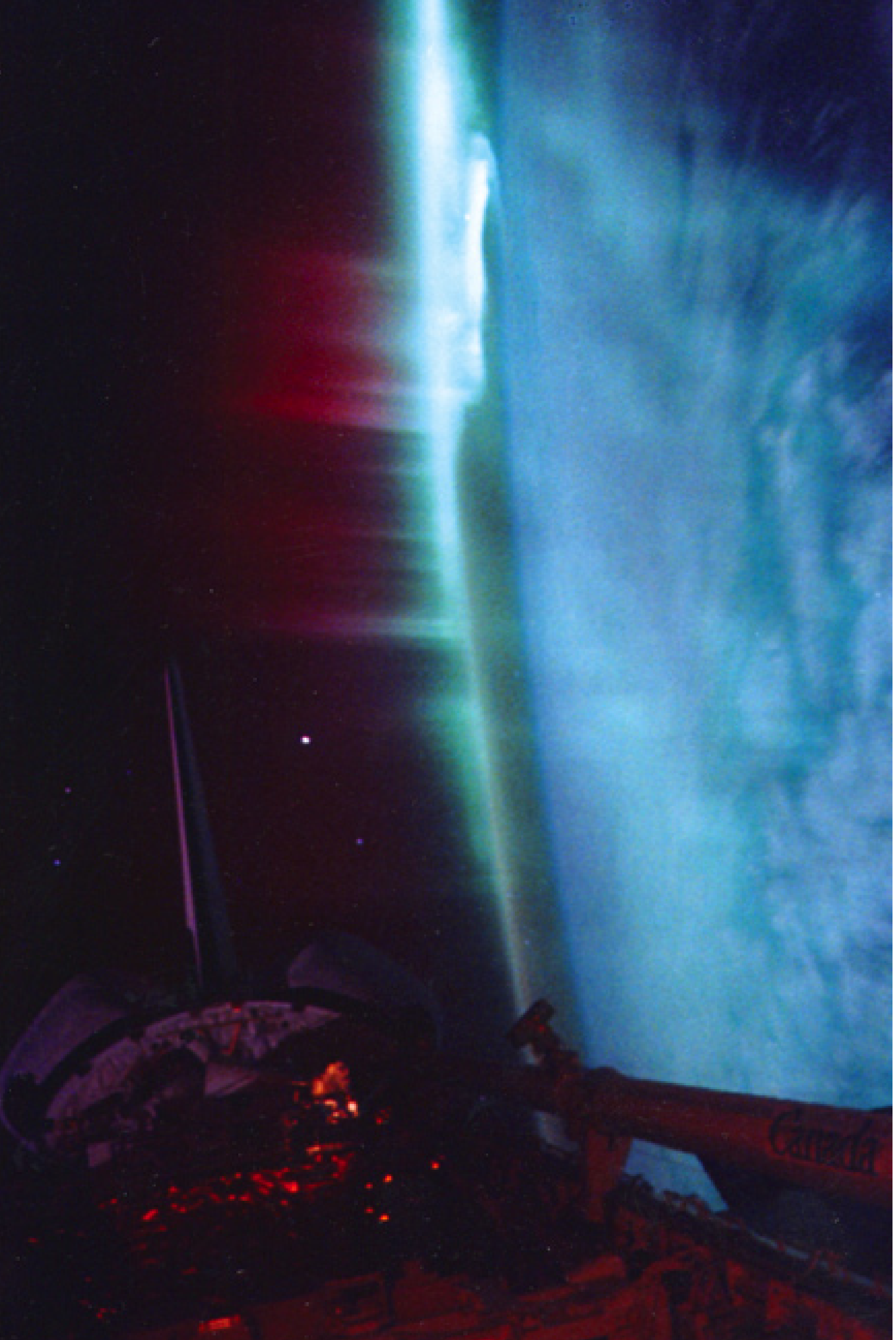
# COSMIC EXTREMES

*The Search for the Origin of Cosmic Rays*



NASA

Aurora light results from solar electrons and protons striking molecules in the Earth's atmosphere. This photograph of aurora australis, or southern lights, was taken by the Space Shuttle Discovery, which can be seen in the foreground.

# WHAT ARE COSMIC RAYS?

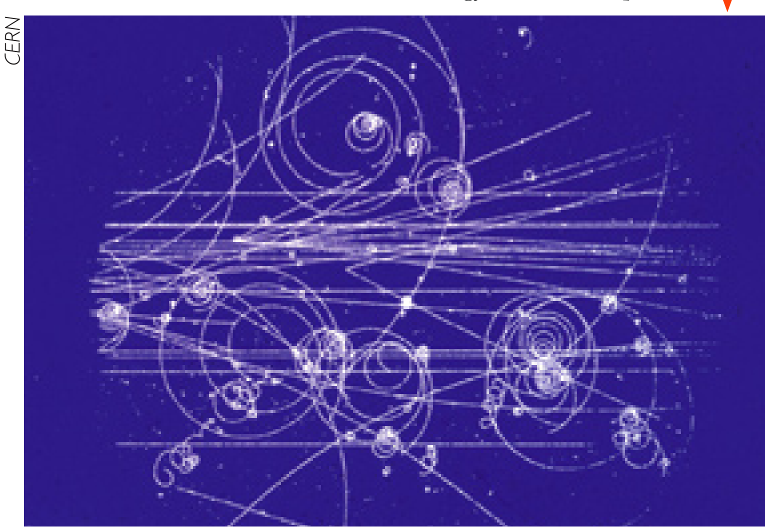
The Earth is constantly bombarded by *cosmic rays*, tiny particles from outer space. These particles are smaller than atoms and invisible to the naked eye, but they have enormous amounts of energy. Compared to the most energetic particles produced in manmade particle accelerators, naturally occurring cosmic rays can have over ten million times more energy. We know little about where these mysterious particles come from or how they are produced. We know that some low-energy rays come from the Sun, but high-energy rays probably come from somewhere outside our solar system or even outside our Galaxy.

## *If cosmic rays are invisible to the naked eye, how do we know they exist?*

Understanding cosmic rays requires complex particle detectors on satellites, balloons, or special telescopes on Earth. However, some of the *effects* of cosmic rays can be seen with the naked eye. For example, *aurora borealis* and *aurora australis* (the northern lights and southern lights, respectively) appear in the night sky when swarms of cosmic rays from the Sun enter our atmosphere.

*In large particle accelerators, scientists accelerate and collide subatomic particles to understand them better. This image shows the tracks of high-energy particles made visible in a particle detector. However, naturally existing subatomic particles—i.e., cosmic rays—can have ten million times more energy than manmade particles.*

CERN



Cosmic rays with a wide range of energies hit the Earth. While aurorae are the most spectacular and beautiful signs of cosmic rays, the particles that cause aurorae have rather low energies by cosmic ray standards. In fact, the most energetic cosmic ray particles have one trillion times more energy than those produced by the Sun.

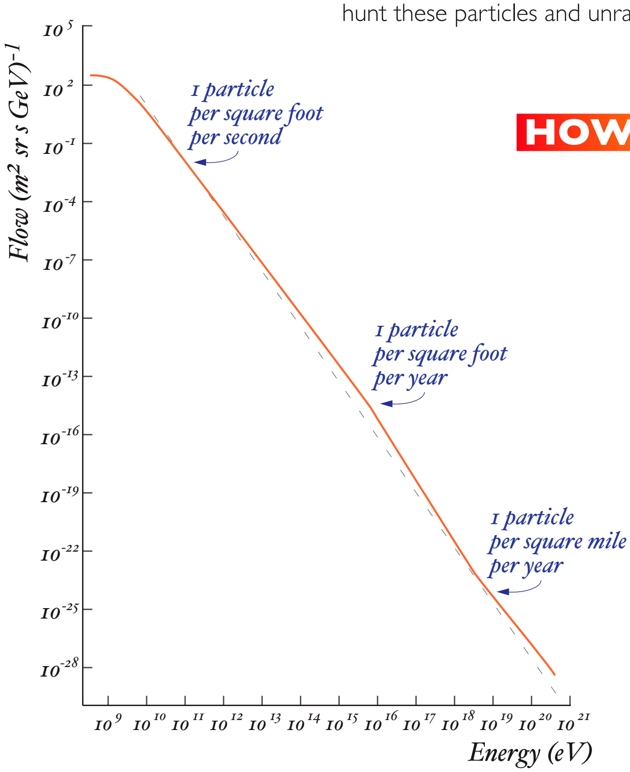
The higher the energy of cosmic rays, the rarer they are. The most energetic rays, often called ultrahigh energy cosmic rays, enter our atmosphere at a rate of less than one per square mile per year.

*Understanding the origin of ultrahigh energy cosmic rays is one of the biggest challenges in astrophysics today.*

A mystery surrounds these ultrahigh energy particles. They are the most energetic particles known to exist in the Universe, but we currently do not know where in the Universe these particles are accelerated to such incredible energies.

Around the world, physicists build and operate large detectors to hunt these particles and unravel their secrets.

*Cosmic rays can be found over a large range of energies. However, the flow of cosmic rays decreases sharply as their energy increases.*




## HOW MUCH ENERGY IS ULTRAHIGH ENERGY?

The largest atom smashers in the world collide particles with one trillion electron Volts (eV) of energy. That is equal to the energy of a brick dropped a tiny distance—the diameter of ten atoms, or 1/100,000th the width of a human hair.

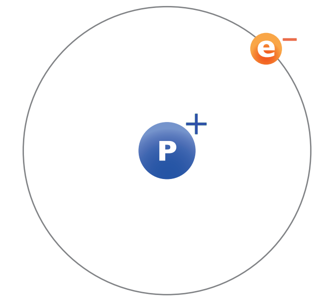
In contrast, an ultrahigh energy cosmic ray has the energy of a brick dropped five feet!

### What are cosmic rays made of?

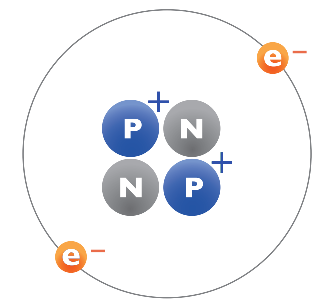
Understanding what cosmic rays are made of may help reveal their origin. Although they come from far away, cosmic rays are composed of the same subatomic particles that make up all matter on Earth.

As the name suggests, subatomic particles are what constitute atoms, the building blocks of matter. A typical atom is made of protons, neutrons, and electrons. Electrons surround the atom's nucleus, which is composed of protons and neutrons. Hydrogen, which has one proton, and helium, which has two protons, are among the smallest atoms.

Protons, electrons, and certain combinations of protons and neutrons can exist by themselves in nature. About 75 percent of all cosmic rays are nuclei of hydrogen atoms (which are simply protons) and almost 25 percent are nuclei of helium atoms. The rest consists of electrons, nuclei of larger atoms, and extremely energetic light rays known as *gamma rays*.

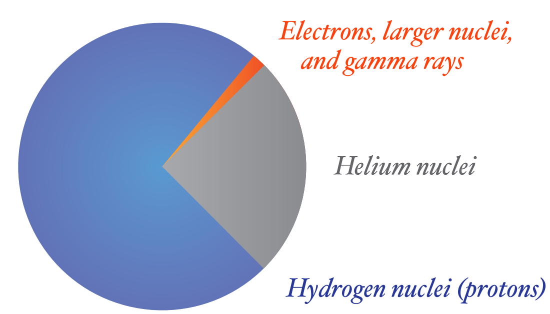



*Hydrogen*




*Helium*

*Atoms, the building blocks of nature, are made of protons, neutrons, and electrons.*




*The majority of cosmic particles are the nuclei of hydrogen atoms and helium atoms.*

# HOW WERE COSMIC RAYS DISCOVERED?

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At the start of the 1900s, French physicists Henri Becquerel and Marie and Pierre Curie discovered that certain elements changed into other elements over time and, in the process, emitted what appeared to be particles. These emitted particles were named *radiation*, and the process itself was named *radioactive decay.*

Scientists studying radioactivity soon noticed that electroscopes (instruments that measure electric charge) spontaneously lost their charge in the presence of radioactive materials. Thus, in the first decades of the twentieth century, the electroscope became a standard instrument for studying radiation and radioactive materials.

However, physicists also found that electroscopes slowly lost their charge under *all* conditions whether or not radioactive matter was present. This observation suggested the existence of some kind of low-level background radiation everywhere on the Earth's surface.

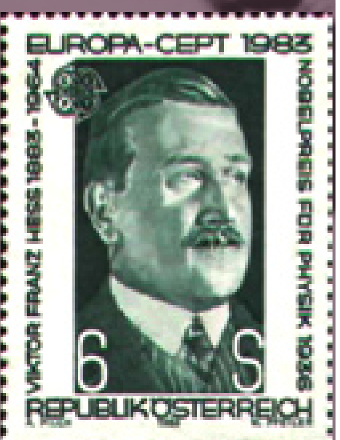
At the time, this background radiation was thought to come from the Earth. In 1912, the Austrian physicist Victor Hess decided to test this theory. He realized that if the Earth were the source of the radioactivity, levels of radioactivity would decrease farther from the Earth's surface. But when Hess used an electroscope on a hot air balloon to measure radiation levels at different altitudes, he found that the radiation actually *increased* as he climbed higher.

*For his work on cosmic rays, Victor Hess won the Nobel Prize for Physics in 1936.*

**BUILD YOUR OWN ELECTROSCOPE!**

All you need is some wire, foil, clay, and a spaghetti jar.

Turn to page 16 for instructions.



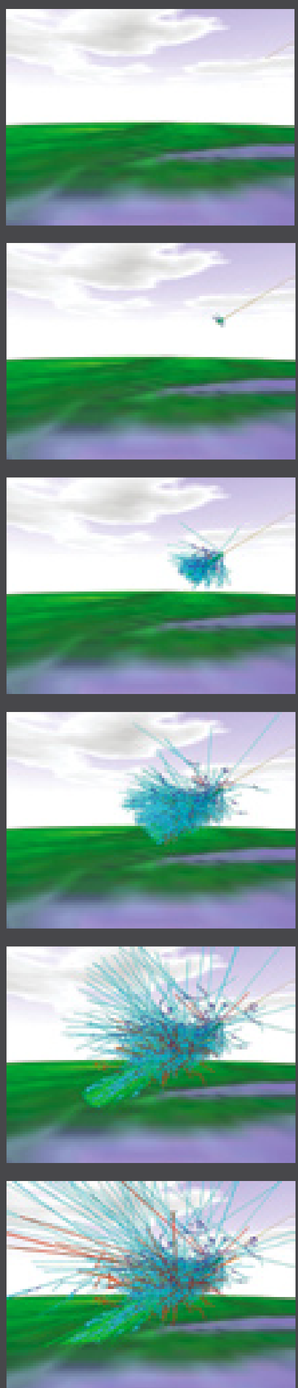

*Countries around the world honored Victor Hess for his accomplishments in physics. Austria, his native country, issued this stamp in 1983.*

*To study the origin of cosmic particles, Victor Hess took his balloon as high as 17,500 feet, or over three miles—without oxygen tanks!*

Hess interpreted this unexpected result to mean that radiation enters the atmosphere from outer space. He named this phenomenon *cosmic radiation*, which later evolved into *cosmic rays*.

*Although these rays were later understood to be particles, the term "cosmic rays" has persisted.*

*Courtesy of Martin A. Pomerantz*



Hans-Joachim Drescher

# WHAT HAPPENS TO COSMIC RAYS IN THE ATMOSPHERE?

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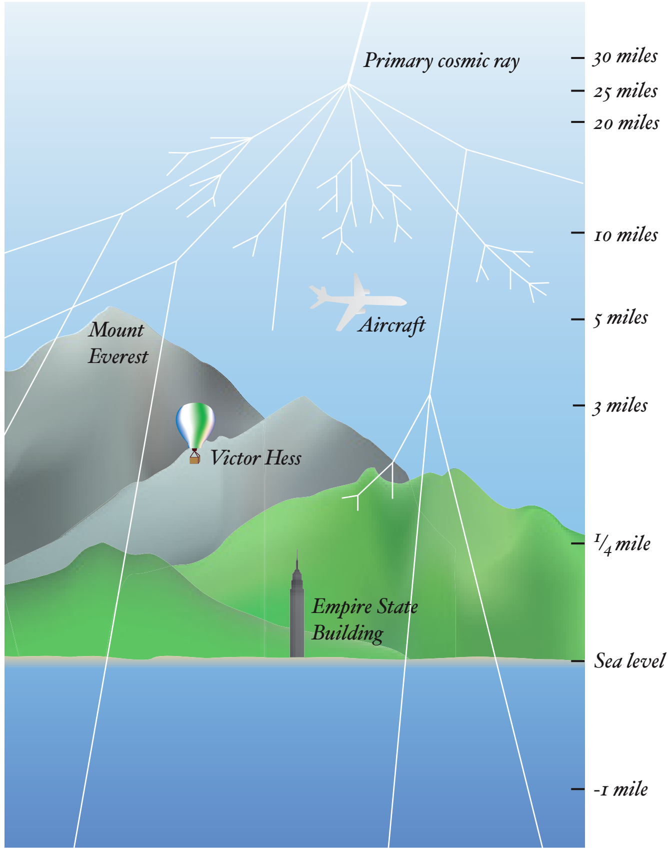
ATMOSPHERE? ATMOSPHERE? ATMOSPHERE?

On Earth, we never detect cosmic rays directly. Instead, we see the products of the rays' interaction with the atmosphere.

When a cosmic ray enters the Earth's atmosphere, it eventually smashes into a nitrogen or oxygen atom in the air. This collision causes a chain reaction in which the broken bits of the atom move on to break apart other atoms and so on. The result is an *air shower* of particles in the atmosphere.

Most of these particles have very low energy, and they decay or are absorbed in the atmosphere before they reach the surface of the Earth. The only particles that reach the ground are either very energetic or relatively stable. One such particle is the muon, which is a high-energy, heavier version of the electron. At sea level, the flow of high-energy muons from air showers is about six muons per square inch per minute.

*An air shower is a chain reaction caused by a cosmic ray entering our atmosphere. These time-lapse images are actual simulations used by physicists to model the path of an air shower one hundred microseconds at a time. Air showers last only a few hundred microseconds but can cover many square miles. For clarity, this simulation shows only one millionth of the actual number of particles in an actual air shower. To see an air shower animation, visit www.th.physik.uni-frankfurt.de/~drescher.*




*Soon after a cosmic ray enters the Earth's atmosphere, it smashes into a nitrogen or oxygen atom, producing an air shower. Cosmic ray air showers are composed of many kinds of subatomic particles, which decay at different rates.*

## MUONS

The muon is one of the many exotic particles that were first discovered in studies of cosmic radiation. The muon is a heavier version of the electron, with the same electric charge but about two hundred times more mass. Like the electron, it is a fundamental elementary particle. In contrast to electrons, muons are not stable. They decay in about two millionths of a second, turning into their lighter partners, electrons.

*Roughly six muons go through the area of this brochure every second.*

## HOW FAST DO COSMIC RAYS GO?

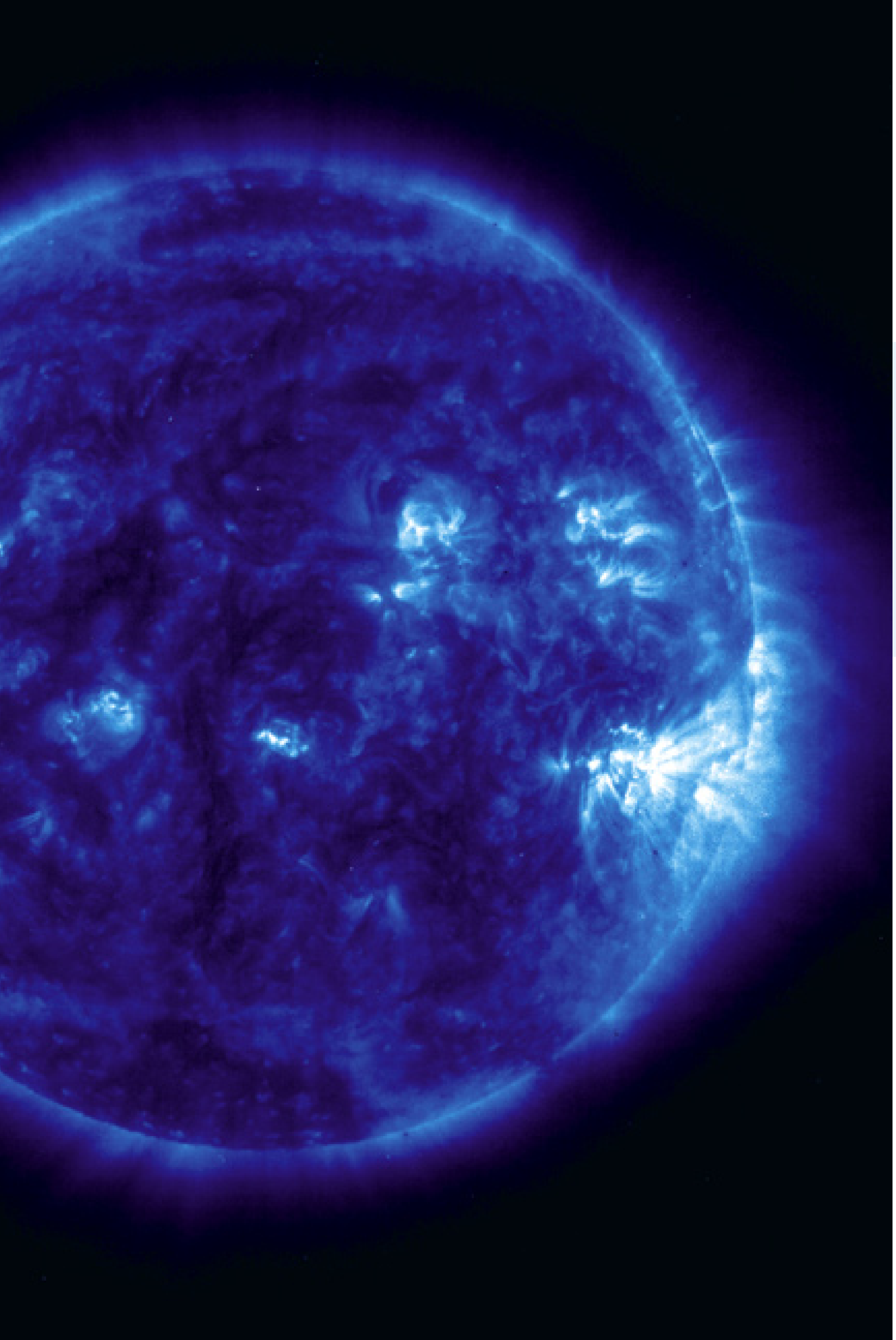
Except for particles that travel at the speed of light, the greater the energy of a particle, the greater its speed. According to Einstein's theory of relativity, only particles without mass can travel at the speed of light. However, the most energetic cosmic rays travel at 99.99999996% the speed of light, or about 186,000 miles per second.

**In other words, a cosmic ray could zip around the Earth more than seven times in one second!**

## A WRINKLE IN MUON TIME

Because a muon decays after two millionths of a second, Newton's laws of mechanics tell us that it can travel only about half a mile before it decays, even if it travels at nearly the speed of light. Therefore, we would not expect any muons to hit the Earth. However, in a single minute, even the simplest particle detector will detect about six muons per square inch. How can this be?

Einstein provided the answer. His theory of relativity says that as things move faster, their "clocks" slow down. Since muons are moving very close to the speed of light, they take five times longer to decay. This might not seem like a very long time, but it is enough time for muons to reach the Earth.

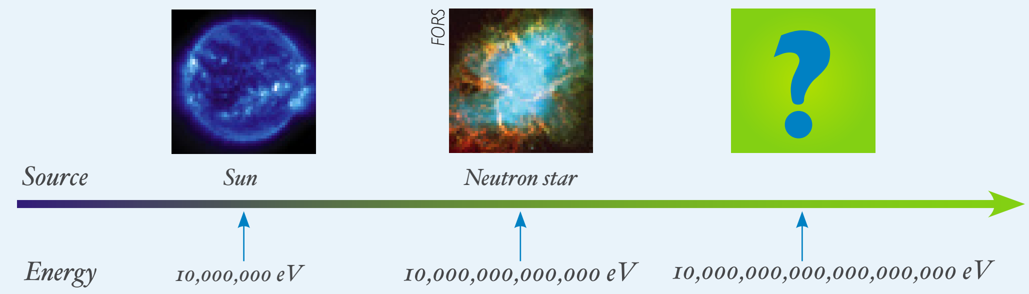


SOHO (ESA & NASA)

# WHERE DO COSMIC RAYS COME FROM?

WHERE DO COSMIC RAYS WHERE DO COME FROM? COME

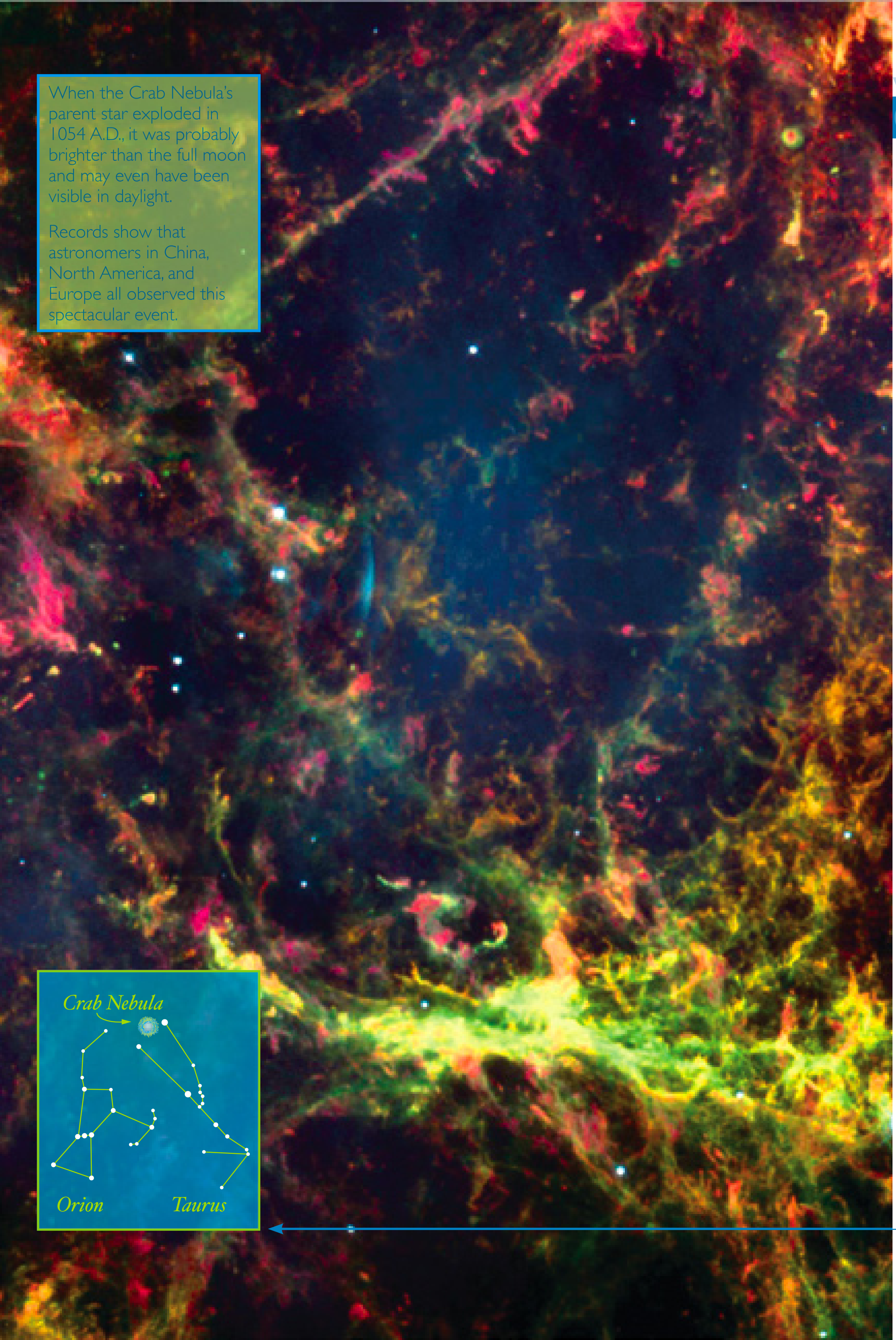
Ever since cosmic rays were discovered one hundred years ago, scientists have tried to determine their origin. We know now that low-energy cosmic rays come from stars like our own Sun. Higher-energy cosmic rays come from neutron stars, which are the remains of exploded stars.




A mystery surrounds the most energetic cosmic rays. Physicists cannot explain how cosmic rays achieve such great energy. For instance, even the highest-energy rays that the Sun emits have only one *trillionth* the energy of the ultrahigh energy rays that we observe. Something in the Universe is speeding up those ultrahigh energy rays. The question is *what?*

A big problem in answering this question lies in the fact that most cosmic particles have electric charges. Magnetic fields, which exist between stars and galaxies, change the direction of charged objects and therefore prevent cosmic particles from traveling to Earth in a straight line. The unpredictable paths of cosmic rays make it very hard for scientists to determine the rays' exact origins, since the paths do not point back to their sources.

*As a byproduct of the nuclear fusion that causes it to shine, the Sun constantly produces cosmic rays. These cosmic rays propagate to Earth in "solar wind," rivers of particles that carry into space one million tons of matter every second. The Sun's churning surface is visible in this false-color ultraviolet image taken by the SOHO satellite.*



When the Crab Nebula's parent star exploded in 1054 A.D., it was probably brighter than the full moon and may even have been visible in daylight.

Records show that astronomers in China, North America, and Europe all observed this spectacular event.



NASA

*The Crab Nebula is in the Taurus constellation, which is next to Orion. Thanks to the three bright stars that form Orion's Belt, Orion and Taurus are easy to locate on clear winter nights.*

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## How do cosmic rays reach the Earth?

The Universe is not completely empty. Among other things, it is filled with radiation left over from the Big Bang, the creation of the Universe thirteen billion years ago. This so-called *microwave background radiation* acts like a fog. It interferes with cosmic rays from distant sources, preventing them from reaching Earth. In other words, a high-energy cosmic ray traveling toward Earth from the other end of the Universe is likely to collide with the microwave background radiation. In the collision, the cosmic rays lose energy and can even completely disappear.

Therefore, high-energy cosmic rays cannot travel far without losing some energy to this radiation. As a result, physicists do not expect to see many cosmic rays above a certain energy, provided that their sources are very far away. This energy is called the GZK cutoff, after the physicists who first predicted it in 1966: Kenneth Greisen, Georgi Zatsepin, and Vadim Kuzmin.

However, if cosmic rays are coming from a much smaller distance (less than 1/100 the diameter of the Universe, about 700 million trillion miles), they do not have as much opportunity to interact with the cosmic microwave background. Therefore, they reach our atmosphere intact, having lost little of their tremendous energies.

Two experiments, the Akeno Giant Air Shower Array (AGASA) and High Resolution Fly's Eye (HiRes), have measured these high-energy particles. Surprisingly, AGASA has observed enough high-energy particles *above* the GZK cutoff to suggest that the cutoff does not exist—which in turn suggests that a source of ultrahigh energy cosmic rays is very close to the Earth.

Only with future experiments will we know for sure.

## THE BIG BANG

Current evidence suggests that the Universe is about thirteen billion years old. It began as a very hot and dense soup of subatomic particles that expanded and cooled very quickly. When everything in the Universe cooled, it allowed stars and planets to congeal, and all that was left in the empty space between them was the leftover light. Today, outer space, which is the vacuum between stars and planets, is about -454 degrees Fahrenheit. That is, the energy of the particles of light is equivalent to that temperature.

In contrast, the Universe began with a temperature of about one trillion degrees Fahrenheit, or about one billion times the temperature of the Sun's surface.

*Some cosmic particles come from neutron stars, which are the remains of exploded stars. A neutron star lies at the center of the Crab Nebula (left). This neutron star contains more matter than our Sun yet it is only ten miles across—less than the length of Manhattan. Neutron stars are extremely dense: one teaspoon of a neutron star weighs as much as one billion elephants!*

# HOW ARE COSMIC RAYS DETECTED?

When a cosmic ray enters the Earth's atmosphere, it smashes into an atom, which breaks into subatomic particles that then move on to break apart other atoms. Therefore, on Earth, we see not the cosmic ray itself, but rather the shower of particles that it creates. Physicists seek to learn about individual cosmic rays by measuring the air showers that they produce.

## The Air Shower Array Method

Air showers are typically quite large: they can be several miles wide by the time they hit the ground, with tracks that are tens of miles long. One way of observing air showers is to observe the particles that eventually hit the surface of the Earth, such as muons and other very energetic particles. An experiment that measures air shower particles relies on many detectors positioned across hundreds of square miles of the Earth's surface. Such a group of detectors is called an *air shower array.*

*AGASA consists of 111 particle detectors over forty square miles of a river valley in Akeno, Japan. An AGASA detector appears in the inset.*

AGASA, Institute of Cosmic Ray Research (ICRR), Tokyo

### Akeno Giant Air Shower Array

The world's largest air shower array is the Akeno Giant Air Shower Array (AGASA), an experiment in Akeno, Japan, composed of 111 cosmic ray detectors spread over forty square miles.

Each detector is housed in a small hut of about fifty square feet and contains four layers of scintillators, special plastics that emit a pulse of weak light when penetrated by a charged particle. As a result, AGASA is sensitive to the muons and other charged particles in cosmic ray air showers. By detecting these particles as they reach the Earth's surface, physicists can calculate the direction and timing of the air shower, and thereby learn about the cosmic ray that initiated the shower.

## The Air Fluorescence Method

Charged particles are not the only observable parts of a cosmic ray air shower. When the movement of the air shower through the atmosphere excites air molecules, some of this excitation energy is emitted in the form of ultraviolet (or UV) light. This process is called *air fluorescence*. Observing air fluorescence light is yet another way to detect cosmic rays, but this method is not as easy as it sounds. Because the air fluorescence light of an air shower is very dim, it can be seen only by very sensitive light detectors on clear, moonless nights in desert climates, far away from city lights.

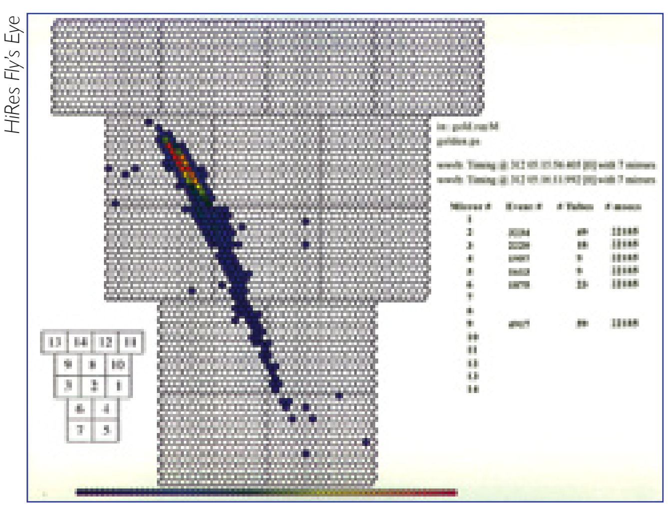
### The High Resolution Fly's Eye Observatory

Since May 1997, the High Resolution Fly's Eye Observatory (HiRes) has been detecting cosmic rays with the air fluorescence method. At the HiRes site in the Utah desert, mirrors are positioned to reflect the UV light of an air shower into a box full of light-detecting photomultiplier tubes. The UV light collected by the tubes allows physicists to calculate the shower's position and energy.

David J. Bird

*This figure shows the kind of detector at HiRes Fly's Eye. UV light caused by an air shower's excitation of atoms is reflected by mirrors into a box containing hundreds of photomultiplier tubes. A picture of the air shower can be reconstructed from the time of the light's arrival and the amount of light collected by each tube. This technique works on clear, moonless nights, using very fast camera elements to record light flashes just few microseconds in duration.*

HiRes Fly's Eye



*This is an actual readout from the HiRes detector. Each hexagon represents a photomultiplier tube. Colored hexagons represent photomultiplier tubes that have detected UV light. The elongated image represents the actual shape of the air shower.*

Photonis

*Light-detecting photomultiplier tubes come in all shapes and sizes. Today, they are used for such things as medical imaging, nuclear waste management, radiation detection, and high-energy physics experiments.*

David J. Bird

*This photograph was taken by a person standing between a HiRes mirror (seen behind him, reflecting him and the sky) and a box of photomultiplier tubes (seen above the reflection). Note that the tightly packed tubes resemble the eye of a fly.*

## PHOTOMULTIPLIER TUBES

Photomultiplier tubes are the standard tools that physicists use to detect weak light.

Photomultipliers make use of a process called photoelectric emission, which was explained by Albert Einstein in 1905. According to Einstein, light can have enough energy to knock electrons out of certain materials when it strikes the surfaces of those materials. The glass windows of photomultiplier tubes are coated with such a material, so that light entering the tube knocks out electrons. (A single light particle, called a photon, frees a single electron.) In the tube, strong electric fields accelerate the freed electrons toward a metal surface, where the electrons knock out even more electrons. Repeated a few times (typically eight to ten times), this process creates more than a million electrons, which form a current that is easy to detect. In this way, the photomultiplier converts very weak light into a strong and easily measured electrical signal.

Photomultipliers come in many shapes and sizes, depending on their use. They are often used in high-energy physics experiments and are the main part of the HiRes air fluorescence camera.

A photomultiplier and a piece of scintillator are all that is needed to build a simple muon detector. Today, high schools around the world perform experiments with muon detectors and, in joint projects, form large arrays many times bigger than AGASA. These detectors teach students and teachers alike how to build, operate, and understand the results of a real experiment—and may one day help solve one of the biggest mysteries in physics.

For more information on detector projects at high schools around the world, visit http://quarknet.fnal.gov.

### Combination Method: Pierre Auger Observatory

The best cosmic particle detector would be a combination of HiRes and AGASA—in other words, one that exploits both the shower array and air fluorescence methods. Exactly this kind of detector is currently being built in Pampa Amarilla, Argentina. It is named the Pierre Auger Observatory, after the French physicist who discovered air showers in 1936.

The observatory consists of two types of detectors. Some of the detectors are similar to those of HiRes, which detect the UV light created by air showers. The second set of detectors observes the muons that are part of the air showers themselves. As the muons pass through water tanks at a speed faster than the speed of light in water, they create a burst of light (similar to the sonic boom created by an object moving faster than the speed of sound in air). This burst of light is called *Cherenkov light*, and so these detectors use what is called the *water Cherenkov* method.

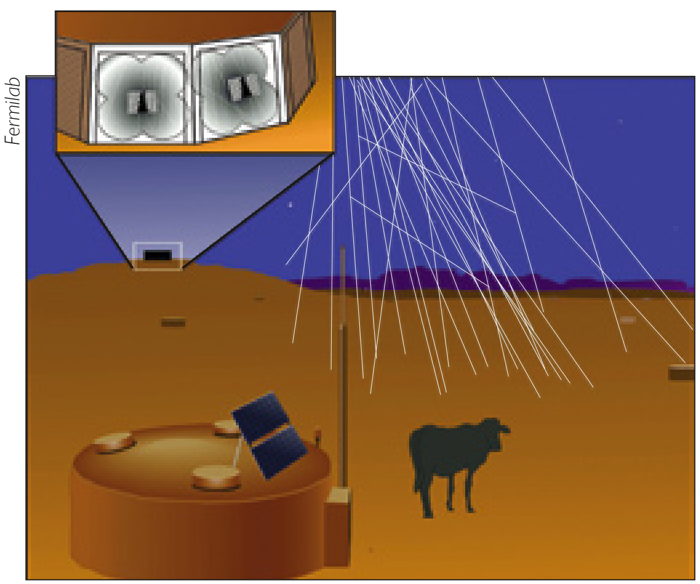
Using both kinds of detectors simultaneously will allow physicists to make more precise measurements of the energy, composition, and direction of cosmic rays.

CERN

*Pierre Auger*

This speed does not violate Einstein's theory of relativity, which states that nothing can travel faster than the speed of light in a vacuum (empty space), because a particle can be moving faster than the speed of light in water but still slower than the speed of light in a vacuum.

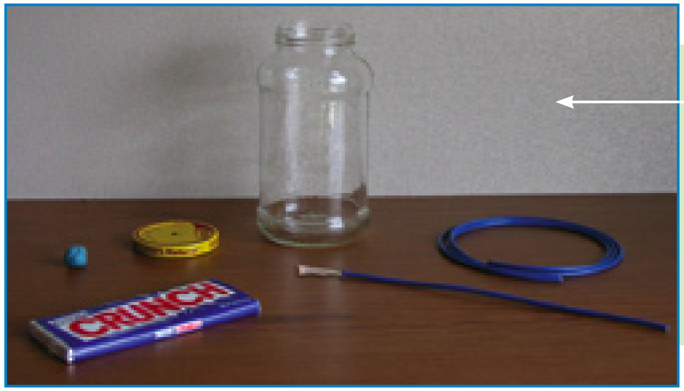
Fermilab



*This illustration represents the two kinds of detectors at the Auger Observatory. One is a mirror array much like that of the HiRes experiment. The other is a ground array, which is similar to that of AGASA.*

BUILD YOUR OWN BUILD YOUR OWN BUILD YOUR OWN BUILD YO

# ELECTROSCOPE! ELECTROSCOPE!




## COMPONENTS

1 spaghetti jar with lid
Small ball of clay or putty
Very thin foil from a candy bar
8 inches of insulated, threaded wire (e.g., speaker wire)

## DIRECTIONS

1. Punch a hole in the lid of the spaghetti jar.
2. Cut two 1- by 2-inch rectangles of foil from the candy wrapper.
3. Make a small hole near the top of each piece of aluminum foil.
4. Thread the wire through the hole of the jar lid.
5. Strip about 1 inch of insulation from the wire on each end.
6. Press clay or putty around hole to keep the wire in place.
7. Above the lid, roll the stripped wire into a ball.
8. Under the lid, shape the stripped wire into two hooks.
9. Thread one piece of foil onto each hook.
10. Be sure the foil pieces hang side by side, very close to each other.
11. Carefully twist the lid onto the jar.

*Electroscopes are instruments that measure electric charge.*

Victor Hess (see page 4) and others noticed that the metal in electroscopes lost their charge after time, and that this loss of charge was due to charged subatomic particles from outer space—cosmic rays—bombarding the metal.

## TEST YOUR ELECTROSCOPE

Run a comb through your hair or rub a balloon on your head or shirt. Place the comb or balloon near the balled-up wire. The electric charge will transfer equally to the two rectangles of foil, causing them to repel each other and fly apart. The greater the distance between the pieces of foil, the greater the charge.



HOW DO COSMIC RAYS

# AFFECT US?

Cosmic rays are literally everywhere. They may influence our lives in a number of ways.

*About six hundred particles from cosmic ray air showers bombard your body every minute.*

Cosmic rays are thought to influence everything from our climate to our genes. For instance, when a charged particle from a cosmic ray air shower travels through a cloud, water droplets are left in its wake. Such particles may also cause genetic mutations in organisms and even accelerate their evolution. Although these effects are subtle, scientists still attempt to uncover how cosmic rays have influenced the Earth's history and even our existence.

Cosmic rays are also known to have unwelcome effects on computers. A cosmic ray that passes through a computer can swap a single digit in the computer's memory. These so-called *soft fails* are fairly insignificant on Earth, but in space, satellites on long flights are exposed to large numbers of cosmic rays and therefore may experience problems due to soft fails.

Cosmic rays are part of the natural radiation we are exposed to here on Earth. However, at flight altitudes, radiation exposure due to cosmic rays is fifteen to thirty times greater than at sea level. Consequently, the Federal Aviation Administration has studied radiation doses in aircraft.

But no matter how cosmic rays may affect our lives, we are still left with the curiosity that leads us to ask where cosmic rays come from and why they exist. These tiny particles, moving at nearly the speed of light, may help us better understand the laws of physics and discover unknown objects both in our own Galaxy and in distant regions of the Universe.

# CREDITS

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This booklet may be read online and downloaded in PDF format at www.nevis.columbia.edu/cosmic_rays.

*On the cover: HiRes camera by David J. Bird; Victor Hess from Y. Sekido and H. Elliot, Eds., Early History of Cosmic Ray Studies, (Dordrecht: D. Reidel Publishing Co., 1985)*