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Cosmos Unveiled: Cosmic Rays

The Most Energetic Particles in the Universe

Aira Astralis

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Conclusion

This free sample contains the Introduction and Chapter 1. The complete book contains the full contents above.

Introduction

Cosmic rays are high-energy particles that travel through space at nearly the speed of light. They consist of about 90 percent protons, 9 percent helium nuclei, and 1 percent heavier nuclei, with a small fraction of electrons and positrons. Despite their name, cosmic rays are not rays but particles, and they carry enormous energies, from about 10^6 to 10^20 electron volts, a range that spans 14 orders of magnitude.

The discovery of cosmic rays was made by Victor Hess in 1912, during a series of balloon flights in Austria. Hess measured the ionization of the air at different altitudes and found that the ionization increased with altitude, contrary to the expectation that it would decrease as the radiation from the Earth was absorbed. Hess concluded that the radiation was coming from outside the Earth, from the cosmos. For this discovery, he was awarded the Nobel Prize in Physics in 1936.

Cosmic rays are one of the few samples of matter from outside the solar system that can be directly studied. The composition of cosmic rays, with their mix of protons, helium, and heavier nuclei, reflects the composition of their sources, which include supernova remnants, active galactic nuclei, and other astrophysical objects. The study of cosmic rays provides information about the processes that accelerate particles to high energies and about the composition of the interstellar medium. The energy range of cosmic rays is extraordinary.

The lowest-energy cosmic rays, at about 10^6 electron volts, are produced by the Sun. The highest-energy cosmic rays, at about 10^20 electron volts, have energies comparable to a tennis ball traveling at 100 kilometers per hour, packed into a single particle. The origin of these ultra-high-energy cosmic rays is one of the great mysteries of modern astrophysics. Cosmic rays also have important effects on Earth.

They produce the ionization of the upper atmosphere, which affects the electrical properties of the atmosphere and the propagation of radio waves. They produce radioactive isotopes, such as carbon-14, which are used in radiocarbon dating. And they pose a radiation hazard for astronauts and for the electronics on spacecraft, which must be shielded and designed to withstand the cosmic ray flux.

Few forms of matter from beyond the solar system can be examined directly, and cosmic rays are among them. What they are made of reveals both the machinery that boosts particles to such energies and the makeup of the gas between the stars study of cosmic rays has led to many important discoveries in particle physics, including the positron, the muon, and the pion, and it

continues to be at the frontier of scientific research.

The cosmic ray spectrum spans an extraordinary range of energies, spanning roughly 10^6 and climbing past 10^20 electron volts, a range of 14 orders of magnitude. The spectrum follows a power law, with the number of particles decreasing as the energy to the power of about -2.7, which means that the highest-energy cosmic rays are extremely rare. The cosmic ray flux at the highest energies is about one particle per square kilometer per century, making the detection of these particles a major challenge.

The cosmic ray flux at the Earth is affected by the solar wind, which creates a magnetic bubble around the Earth called the heliosphere. The solar wind deflects the lowest-energy cosmic rays, reducing the cosmic ray flux at energies below about 10^9 electron volts. The solar modulation, as this effect is called, varies with the 11-year solar cycle, with the cosmic ray flux being lower at solar maximum and higher at solar minimum. The study of cosmic rays has also led to important technological developments.

The need to detect cosmic rays has driven the development of particle detectors, electronics, and data analysis techniques. The AMS-02 detector, with its 300,000 channels of electronics and its precision tracking, is one of the most complex scientific instruments ever built. The Pierre Auger Observatory, with its 3,000 square kilometers of detectors and its sophisticated data acquisition system, is one of the largest scientific experiments ever undertaken.

Cosmic rays are detected at the Earth after traveling through the galaxy for millions of years, deflected by the galactic magnetic field. The cosmic rays carry information about the processes that accelerate them and about the medium through which they propagate. The study of cosmic rays provides a unique window on the high-energy universe that is not accessible through electromagnetic radiation. The cosmic ray research is connected to many areas of science, including particle physics, astrophysics, cosmology, and astrobiology.

The study of cosmic rays has led to the discovery of fundamental particles, the identification of astrophysical sources, the measurement of the cosmic ray spectrum, and the search for dark matter. The interdisciplinary nature of cosmic ray research makes it one of the most exciting areas in modern science. Cosmic rays consist of about 90 percent protons and 9 percent helium nuclei. The highest-energy cosmic rays arrive at about one per square kilometer per century.

The solar cycle with 11 year period modulates the cosmic ray flux. Cosmic rays

carry information about the high-energy universe. The cosmic ray flux is about 100 particles per square meter per second at the surface. Cosmic rays pose a radiation hazard for astronauts and spacecraft electronics. The cosmic ray energy density is about 1 eV/cm^3 comparable to magnetic field and thermal gas. Studying these particles opens a singular view onto the universe at its most energetic..

The solar wind creates the heliosphere which deflects low-energy cosmic rays. Cosmic rays are not rays but particles traveling at nearly the speed of light. Cosmic rays include a small fraction of electrons and positrons. The cosmic ray spectrum spans 14 orders of magnitude in energy. Cosmic rays are detected after traveling millions of years through the galaxy. The solar wind creates the heliosphere modulating cosmic rays. The interdisciplinary nature makes it exciting. This is cosmic ray physics. This is the introduction to cosmic rays.

Truly extraordinary. Cosmic rays are amazing.

Cosmic rays or astroparticles are high-energy particles or clusters of particles (primarily represented by protons or atomic nuclei) that move through space at nearly the speed of light. They originate from outside the Solar System - from the Milky Way, from distant galaxies, and from the Sun. Upon impact with Earth's atmosphere, cosmic rays produce showers of secondary particles, some of which reach the surface, although the bulk are deflected into space by Earth's magnetic field (the magnetosphere) or by the heliosphere.

Cosmic rays were discovered by Victor Hess in 1912 in balloon experiments, for which he was awarded the 1936 Nobel Prize in Physics. Direct measurement of cosmic rays, especially at lower energies, has been possible since the first satellites in the late 1950s. Particle detectors similar to those used in nuclear and high-energy physics are used on satellites and space probes for research into cosmic rays.

Data from the Fermi Space Telescope (2013) have been interpreted as evidence that a significant fraction of primary cosmic rays originate from the supernova explosions of stars. Based on observations of neutrinos and gamma rays from blazar TXS 0506+056 in 2018, active galactic nuclei also appear to produce cosmic rays. The term ray (as in optical ray) seems to have arisen from an initial belief, due to their penetrating power, that cosmic rays were mostly electromagnetic radiation.

Chapter 01: The Discovery of Cosmic Rays

The discovery of cosmic rays is a story that spans several decades and involves some of the most famous physicists of the early 20th century. The story begins with the discovery of radioactivity by Henri Becquerel in 1896, which led to the study of ionizing radiation and the development of instruments for detecting it.

In the early 1900s, physicists noticed that electroscopes, which are instruments for measuring electric charge, would gradually lose their charge, even in the absence of any radioactive source. This suggested that there was a source of ionizing radiation in the environment. The question was whether this radiation came from the Earth or from the sky.

The first serious investigation was by Theodor Wulf, who in 1909 measured the ionization at the top of the Eiffel Tower and found that it was higher than at the ground, suggesting that the radiation was coming from the sky. However, the result was ambiguous, because the Eiffel Tower was not high enough to give a clear result. The decisive experiments were made by Victor Hess in 1912.

Hess, an Austrian physicist, made a series of balloon flights in which he measured the ionization of the air at altitudes up to 5,300 meters. He found that the ionization initially decreased with altitude, as expected from the absorption of radiation from the Earth, but then increased at higher altitudes. He also observed that the radiation was constant day and night, ruling out the Sun as the source.

The confirmation of Hess's discovery was made by Werner Kolhorster in 1913 and 1914, who made balloon flights to even higher altitudes, up to 9,000 meters, and found that the ionization continued to increase. Kolhorster's measurements confirmed that the radiation was extraterrestrial in origin. The name "cosmic rays" was coined by Robert Millikan in 1925, who extensively studied the radiation and confirmed its extraterrestrial origin. The discovery of cosmic rays was important not only for astrophysics but also for particle physics.

Before the development of particle accelerators, cosmic rays were the only source of high-energy particles, and many of the fundamental particles were discovered in cosmic ray experiments, including the positron (discovered by Carl Anderson in 1932), the muon (discovered by Anderson and Neddermeyer in 1936), and the pion (discovered by Cecil Powell in 1947). These discoveries established cosmic rays as a window into the high-energy universe and on the fundamental particles.

The discovery of cosmic rays by Victor Hess in 1912 was one of the most important discoveries in the history of physics. Hess's balloon flights, made at a time when the nature of ionizing radiation was not well understood, showed decisively that this radiation was arriving from outside the Earth, from the cosmos. The discovery opened a new field of research that has produced many important discoveries and that continues to be at the frontier of science.

The discovery of cosmic rays also had important consequences for particle physics. The positron was discovered by Carl Anderson in 1932, the muon by Anderson and Neddermeyer in 1936, and the pion by Cecil Powell in 1947. The story of the discovery of cosmic rays is a story of ingenuity and perseverance. Hess made his balloon flights in 1912, at a time when ballooning was dangerous and the instruments were primitive.

He measured the ionization at altitudes up to 5,300 meters, enduring the cold and the low oxygen at high altitudes. His measurements showed the ionization growing stronger rather than weaker as the balloon climbed, defying the expectation of a decrease, and he concluded that the radiation was coming from outside the Earth. The confirmation of Hess's discovery was made by Kolhorster, whose balloon ascents of 1913 and 1914 reached still greater heights.

Millikan, who had previously been skeptical of Hess's results, became one of the most prominent advocates of cosmic ray research. The discovery of cosmic rays by Hess in 1912 was a landmark in the history of physics, and it was recognized with the Nobel Prize in 1936. Hess made his balloon flights during a total solar eclipse in 1912 to rule out the Sun as the source of the radiation.

His measurements showed that the ionization increased with altitude, demonstrating that the radiation was coming from outside the Earth. The discovery of cosmic rays opened up a new field of research that has produced many important discoveries. The positron was discovered by the muon came from Anderson and Neddermeyer in 1936, and Powell found the pion in 1947 Powell in 1947. Hess received the Nobel Prize in Physics in 1936 for his discovery. Millikan coined the term cosmic rays in 1925.

Anderson discovered the positron in 1932 and the muon in 1936. Kolhorster confirmed Hess results in 1913 and 1914. Hess made balloon flights during a total solar eclipse to rule out the Sun. The positron was discovered by Carl Anderson in 1932 in Physical Review. Powell discovered the pion in 1947 using photographic emulsions. Wulf measured ionization at the Eiffel Tower in 1909. Hess concluded the radiation was from outside the Earth from the cosmos.

Becquerel discovered radioactivity in 1896 leading to the study of ionizing

radiation. Hess measured ionization at altitudes up to 5300 meters. Anderson discovered the muon with Neddermeyer in 1936. The name cosmic rays was coined by Robert Millikan in 1925. Hess made balloon flights during a solar eclipse in 1912. Kolhorster flew to 9000 meters. This is the discovery. Truly remarkable science. Hess was brave.

Nevertheless, following wider recognition of cosmic rays as being various high-energy particles with intrinsic mass, the term "rays" is consistent with known particles such as cathode rays, canal rays, alpha rays, and beta rays. Meanwhile "cosmic" ray photons, which are quanta of electromagnetic radiation (and so have no intrinsic mass) are known by their common names, such as gamma rays or X-rays, depending on their photon energy.

Of primary cosmic rays, which originate outside of Earth's atmosphere, about 99% are the bare nuclei of common atoms (stripped of their electron shells), and about 1% are solitary electrons (that is, one type of beta particle). Of the nuclei, about 90% are simple protons (i.e., hydrogen nuclei); 9% are alpha particles, identical to helium nuclei; and 1% are the nuclei of heavier elements, called HZE ions. These fractions vary highly over the energy range of cosmic rays.

A very small fraction are stable particles of antimatter, such as positrons or antiprotons. The precise nature of this remaining fraction is an area of active research. An active search from Earth orbit for anti-alpha particles as of 2019 had found no unequivocal evidence. Upon striking the atmosphere, cosmic rays violently burst atoms into other bits of matter, producing large amounts of pions and muons (produced from the decay of charged pions, which have a short half-life) as well as neutrinos.

One discovery chapter footnote deserves recovery from the older literature: the electroscope itself. Hess's instrument was a crude ionization chamber in which the leakage of charge, measured by the drift of a quartz fiber, stood in for the invisible rain; the electroscope had been invented for physics on the ground, and its unexpected sensitivity at altitude was what made the whole discovery possible. The balloon-borne electroscope is accordingly the field's founding instrument, the device that turned an unexplained leakage of charge into evidence for a universe full of rays, and the modern descendant of that first quiet fiber is the silicon heart of every detector the later chapters describe.

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ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.