# A century of cosmic rays

Per Carlson

**Twenty years after puzzling atmospheric ionization led to the discovery of cosmic rays, their investigation opened up particle physics. Now they're providing a window on extragalactic astrophysics.**

**Figure 1. Victor Hess in the gondola** of his hydrogen-filled balloon some time around 1912. On 7 August of that year, he reached an altitude of 5000 m and discovered that the ionizing radiation he was investigating definitely increased with altitude. His finding is regarded as the discovery of cosmic rays. (Courtesy of the American Physical Society.)

In the Bohemian town of Aussig on 7 August 1912, Austrian physicist Victor Franz Hess made his seventh balloon flight of that year (see figure 1). The hydrogen-filled balloon would carry him, for the first time, to an altitude of about 5000 meters. To his surprise, Hess found that his carefully calibrated electroscopes showed that ionization of the atmosphere did not decrease with increasing altitude. Instead, at 4500 m, he measured an ionization about three times what it had been on the ground. By the time Hess landed six hours later near Berlin, some 200 km to the north, he had made the dramatic discovery that marks the beginning of cosmic-ray physics.

Hess and others undertook such balloon flights to investigate the mysterious invisible radiation that had already been encountered by Charles Augustin de Coulomb in 1785. Coulomb found that a charged metallic sphere, left alone in air, gradually loses its charge. A century later William Crookes observed that the rate at which an electroscope loses its charge slows with decreasing pressure.

Soon there was a steady stream of milestone discoveries at the turn of the 20th century: Joseph J. Thomson discovered the electron, Wilhelm Röntgen discovered x rays, and Henri Becquerel discovered radioactivity. The radiation from x rays and from Becquerel's uranium salts showed similar penetrating properties, and both could ionize air. Marie and Pierre Curie soon discovered new radioactive elements. The scene was now set for more general investigation of the electrical conductivity of air.

At the beginning of the 20th century, many physicists in Europe and North America made important contributions to the study of atmospheric ionization. The principal investigative instrument was the electroscope in a closed vessel. With improved insulation, the electroscope's sensitivity was increased and its discharge rate could be measured. Charles T. R. Wilson and others soon reported results of their separate observations of electroscope discharge. They concluded that the ionization must be caused by either x rays or gamma rays coming from outside the vessel. But other explanations were also considered. Wilson at one point suggested that the radiation source might even be extraterrestrial.

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Clearly, one had to investigate the effects of shielding. Ernest Rutherford and others found in 1903 that the ionization was reduced when the electroscope was shielded by metal free of radioactivity. Thus at least part of the ionization in the closed vessel had to be due to some kind of penetrating radiation. The belief generally spread that the penetrating radiation came from radioactive material in Earth's crust. So people calculated how such radiation should decrease with increasing height above the ground.

Theodor Wulf, a German scientist and Jesuit priest serving in the Netherlands, was fascinated by the penetrating radiation that discharged electroscopes. He improved the reliability and sensitivity of electroscopes by introducing two metalized silicon-glass wires in place of the traditional gold leaves (see figure 2). With that instrument in 1909, he measured ion-production rates as low as one ion pair per second.[1]

On an Easter visit to Paris the following year, Wulf brought along an electroscope and carried it to the top of the Eiffel Tower. There he measured the atmospheric ionization rate and found it to be slightly less than on the ground, 300 m below. Still, the rate he measured was much larger than one would expect if the radiation were really coming from the ground, an estimated four atmospheric absorption lengths away. So Wulf concluded that either the absorption length for gamma rays in air was bigger than the prevailing estimate or there must be another source of atmospheric radioactivity.

Between 1909 and 1911, Swiss physicist Albert Gockel carried a Wulf-type electroscope on three balloon flights. Believing that the ionization of the atmosphere was due to radiation from the ground, he sought to measure the expected decrease with altitude. On one of the flights, Gockel reached 4500 m and, like Wulf, observed a decrease of the ionization with increasing altitude—though not as much as expected. But the pressure in Gockel's instrument was changing with altitude—a source of systematic error. So it was almost impossible to draw definite conclusions. On two of his lower-altitude flights, Gockel did correct his instruments for pressure, and the measurements showed an insignificant increase of ionization with altitude. He ascribed a considerable part of the ionization to gamma rays from radioactive substances in the atmosphere.

## A neglected contribution

Many contributions that led to the discovery and early understanding of cosmic rays have largely been forgotten. In the work that culminated with high-altitude balloon flights in 1910–14, the experiments by Italian physicist Domenico Pacini were important but little noticed. After investigating electrical conductivity in gaseous media, Pacini began making ionization measurements with an electroscope on land, at sea, and underwater in the Gulf of Genoa. Several hundred meters offshore in the shallow gulf, Pacini found the ionization rate slightly lower 3 m underwater than at the surface. He concluded, therefore, that there is penetrating radiation in the atmosphere, independent of radioactive material in the crust.[2]

Why wasn't Pacini's work properly recognized? He carried out his experiments alone and under conditions made difficult by lack of resources. He was, for instance, unable to attend international conferences. And the fact that most of his articles were written in Italian probably contributed to their neglect.

Hess did call attention to Pacini's prescient contribution in a book published in 1940, two years after Hess left Nazi-annexed Austria for the US.[3] Recalling the situation some 30 years earlier, when the general view was that radioactive substances in the soil and in the air could account for the observations, Hess wrote:

> The first who expressed some doubts as to the correctness of this view was D. Pacini, who, in 1910, from measurements at sea and on shore at Livorno concluded that part of the observed ionization might be due to sources other than the known radioactive substances.

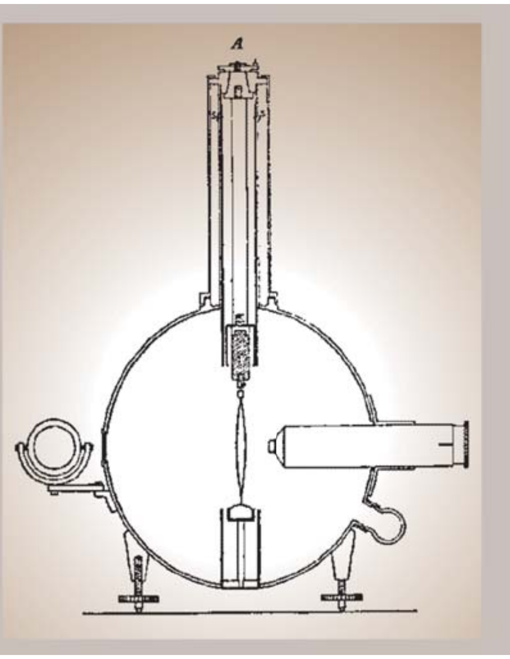


**Figure 2. Theodor Wulf's 1909 electroscope**. Shown in cross section is the instrument's 17-cm-diameter zinc cylinder with its pair of flexible wires below the access tower *A*. The wires are pushed apart by static electricity, and the microscope peering in from the right measures their separation, illuminated by light from the mirror at left. The air in the cylinder was kept dry by sodium in the small recess below the microscope. (Adapted from ref. 1.)

## Victor Hess

Hess was born in 1883 in a castle in the Austrian province of Styria. The castle was the residence of the prince whom Hess's father served as forester. Hess earned his PhD in 1906 at the University of Graz. Being familiar with the existing data on the absorption length of radioactivity in air, he was intrigued by Wulf's results and wanted to clarify them. Seeking first to improve the absorption data, he made careful measurements of the absorption of radiation from radium. His new measurements, however, were consistent with existing data. So the Wulf and Gockel results remained puzzling.

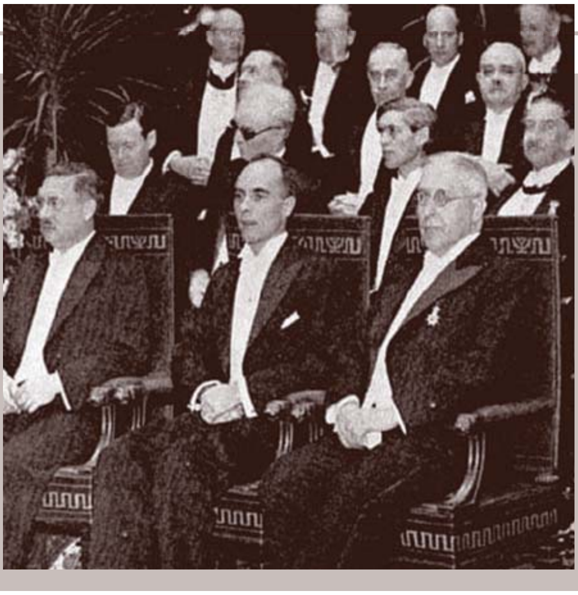
Hess designed Wulf-type electroscopes with 3-mm-thick brass walls that would withstand the high-altitude conditions. With them, he made 10 balloon flights during 1911–13. He would carry three electroscopes on board, one with a thinner window for measuring beta radiation. A month

## Hess's Nobel Prize

The 1936 Nobel Prize in Physics was shared by Victor Hess, for the discovery of cosmic rays, and Carl Anderson, for the discovery of the positron. Arthur Compton, in his letter nominating Hess for the prize, wrote, "The time has now arrived, it seems to me, when we can say that the so-called cosmic rays definitely have their origin at such remote distances from the Earth, that they may properly be called cosmic, and that the use of the rays has by now led to results of such importance that they may be considered a discovery of the first magnitude."

The Nobel Committee for Physics pointed out that Hess's discovery opened new vistas for the understanding of the structure and origin of matter. "It is clear," the committee wrote, "that Hess, with his skillful experiments, has proven the existence of an extraterrestrial penetrating radiation, a discovery more fundamental than that of the radiation's corpuscular nature and the latitude variation of its intensity."

At the ceremony, Hess (right) and Anderson (middle) are seated beside chemistry laureate Peter Debye.



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after the decisive 7 August 1912 flight that revealed a very significant increase of the ionization at high altitude, Hess reported his results at a meeting in Münster, Germany:

> The results of the present observations seem to be most readily explained by assuming that radiation of very high penetrating power enters the atmosphere from above, and can still produce a part of the ionization observed in closed vessels at the lowest altitudes.[4]

For his discovery, Hess was awarded the 1936 Nobel Prize in Physics (see the box above).

Important new results require independent confirmation. Werner Kolhörster, having improved the Wulf electroscope, made five balloon ascents before the outbreak of World War I in the summer of 1914. His last ascent reached 9300 m, and at that altitude he measured an ionization six times larger than at ground level, clearly confirming Hess's result.[5] (See figure 3.)

Moreover Kolhörster determined the absorption length of the radiation to about 1300 m, an order of magnitude larger than the value measured for gamma radiation from radioactive sources. So an unknown radiation with extreme penetrating power was causing the ionization measured independently by Hess and Kolhörster. The intensity of the radiation was found to be quite constant, with no day–night or weather-dependent variations.

### What could it be?

With World War I came a four-year hiatus in cosmic-ray research. The war years and those immediately following were characterized by nationalist feelings that slowed the progress of many branches of pure science.

Although most physicists outside of Germany and Austria believed the prewar conclusions of Hess and Kolhörster, some did not. In particular, Robert Millikan in the US was skeptical. With Ira Sprague Bowen, he introduced an ingenious technique using unmanned sounding balloons with recording instruments. In a balloon flight over Texas that reached an altitude of 15 000 m, they measured a radiation intensity not more than one-fourth of what Hess and Kolhörster had reported. Unaware that a geomagnetic difference between Texas and Central Europe was responsible, they attributed the discrepancy to a turnover in the intensity curve at high altitude. Millikan believed there was no extraterrestrial ionizing radiation. At the American Physical Society's April 1924 meeting, he asserted that "the whole of the penetrating radiation is of local origin."[6]

Millikan had changed his mind when he and Harvey Cameron reported in 1926 on experiments in high-altitude California lakes. The ionization rate was measured with electroscopes at various depths in two lakes—one at altitude 1500 m and the other at 3600 m. The underwater rate in the lower lake corresponded to the rate about 2 m deeper in the higher lake. That is, two meters of water absorbed about as much of the radiation as two kilometers of air.

The result convinced Millikan and much of the scientific community "that the rays do definitely come from above." Now convinced that penetrating radiation entering the atmosphere was electromagnetic, he coined the name "cosmic rays." In Central Europe, the names *Höhenstrahlung* (high-altitude radiation) and *Ultra-Gammastrahlung* became current.

It took a long time before the nature and composition of cosmic rays were understood. The general opinion that they were gamma rays was tenacious. But if they were, they would be unaffected by Earth's magnetic field. In 1927, however, Jacob Clay used an ionization chamber on a sea voyage from Java to the Netherlands to demonstrate a significant latitude effect in cosmic-ray intensity, which showed that at least part of the radiation is corpuscular.

Millikan at first argued that there was no latitude effect, but Arthur Holly Compton supported the corpuscular view. The debate between the two giants went on for some time. Compton undertook several expeditions in 1932 to measure the latitude effect. He showed clearly that the effect exists and that it's larger for lower-energy cosmic rays. Millikan finally accepted the latitude effect after making measurements from airplanes in 1933.

## They must be corpuscular!

Already in 1927, Dmitri Skobeltsyn in the Soviet Union had obtained a cloud-chamber photo that showed a cosmic-ray track. The following year saw a breakthrough in cosmic-ray research: the advent of the Geiger–Müller counter, a gas-filled ionization-detector tube developed by Hans Geiger and Walther Müller. Individual charged particles could now be registered. In 1929 Kolhörster and Walther Bothe placed two GM tubes one above the other and registered coincidences.[7] Interposing a 4-cm thickness of gold between the tubes reduced the coincidence rate only slightly, proving that cosmic rays contain charged particles of much higher energy than the Compton electrons that would be produced by gamma rays.

The development of the electronic coincidence circuit in 1930 by Bruno Rossi greatly improved the resolution of coincidence timing. Rossi found in 1932 that 60% of the cosmic rays that traversed 25 cm of lead could also traverse a full meter of lead. Clearly, the cosmic-ray flux contained not only a soft component easily absorbed in a few millimeters of lead but also a hard component of charged particles with energies above 1 GeV!

Earth's magnetic field would bend incident charged particles so that if they were negative, more would come from the east than from the west, and vice versa. In 1930 Rossi suggested a way to measure that effect with GM tubes.[8] In effect, one could build cosmic-ray telescopes with such tubes. In 1933 he and others demonstrated an east–west effect that showed most cosmic rays to be positive. The following years saw a lot of new experimental data on the east–west and latitude effects.

Given that the particles incident on the atmosphere have positive charge, one had to ask whether they are protons, nuclei, or perhaps even the recently discovered positrons. The answer came from a balloon flight with GM tubes and lead absorbers in 1940 by Marcel Schein and collaborators at the University of Chicago.[9] At an altitude of 20 km, where primary cosmic rays—those originating outside the atmosphere—dominate, Schein found that the high-energy particles passed through lead absorbers without generating the showers of low-energy electrons one would expect from a high-energy electron or positron. So the incident flux of primary cosmic rays was shown to be dominated by protons.

## New particles: 1932–53

Wilson's cloud chamber, first demonstrated in 1911 but much improved over the next two decades, made it possible to record tracks of individual charged particles in the showers of secondaries initiated by cosmic-ray primaries. Two principal improvements made it so useful by the 1930s: triggering its sensitivity cycle to coincide with the passage of charged particles, and placing the chamber in a magnetic field to measure particle charges and momenta. The cloud chamber's role in the exploration of the particle world started in 1932 when Carl Anderson at Caltech discovered the positron, presumably from a cosmic-ray shower, by means of a cloud chamber in a magnetic field[10] (see figure 4). For that first glimpse into the world of antimatter, Anderson shared the 1936 Nobel Prize with Hess.

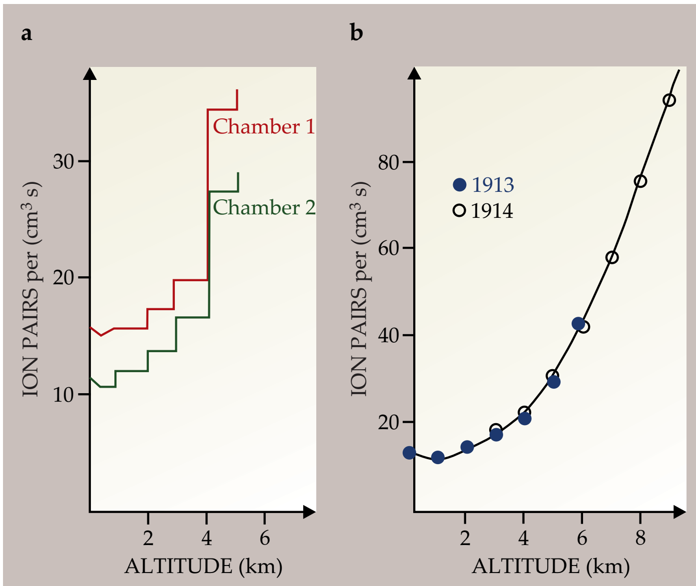

**Figure 3. The rate of atmospheric ionization** as a function of altitude, as measured **(a)** by Victor Hess on 7 August 1912, and **(b)** by Werner Kolhörster in 1913. (Adapted from ref. 2.)

Also in 1936 Anderson and his student Seth Neddermeyer made another monumental discovery with a cloud chamber, this time with a 1-cm-thick platinum plate inserted to manifest energy loss.[11] The setup revealed a new type of charged particle that suffered much less energy loss in the plate than an electron would. They estimated its mass as intermediate between those of the electron and the proton. A few years earlier, Hideki Yukawa had postulated the existence of a new particle in that mass regime to mediate the strong interaction in nuclei. Its predicted mass, of order 100 MeV, was related to the short range of the nuclear force. Hearing of the new discovery, Yukawa thought it corresponded to his prediction. But the particle's lifetime, about 2 μs, was a hundred times too long for the strongly interacting Yukawa particle. Also, traversing meter-thick lead blocks, it showed far too weak an interaction with matter. The new particle was not Yukawa's meson, but rather the muon, a weakly interacting charged lepton much like the electron—only more than 200 times heavier.

Toward the end of World War II, the nuclear-emulsion technique, using stacked plates of photographic emulsion, reached a high degree of sensitivity. Many results of fundamental importance were then obtained by exposing such stacks to cosmic-ray showers at high altitudes. In 1947, emulsion stacks exposed at 5.5 km in the Bolivian Andes by Cecil Powell and coworkers finally revealed the Yukawa meson—which we now call the pion. What the emulsions actually recorded were 11 cases of a positively charged pion decaying into a muon plus an invisible neutrino.[12] If the pion comes to rest before it decays, the two-body decay produces a telltale

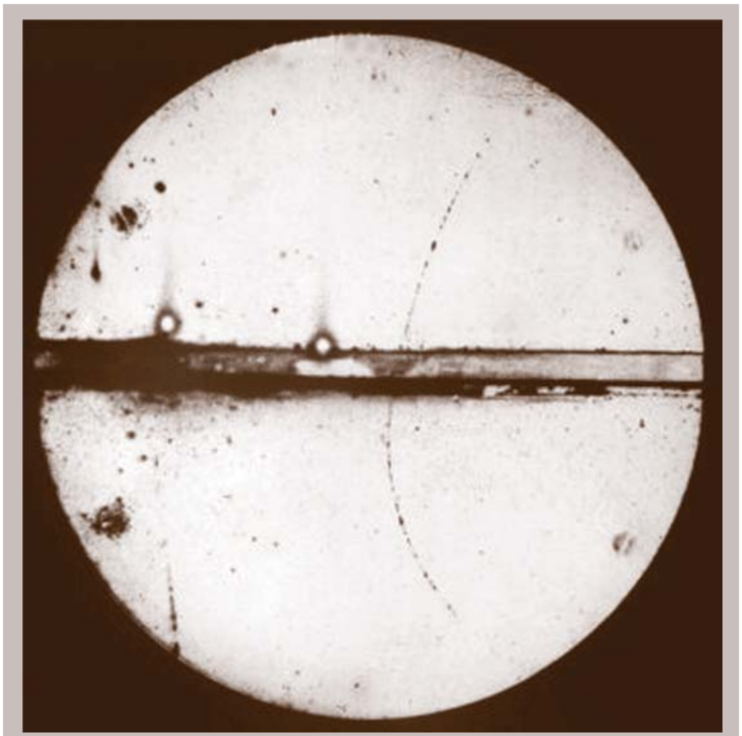

**Figure 4. A historic cloud-chamber photograph** taken by Carl Anderson in 1932 shows a positive particle, presumably from a cosmic-ray shower, entering from the top, curving in the chamber's transverse magnetic field, and losing energy in the lead plate. After traversing the plate, the track is much too long for a proton of that curvature. Also, the weak ionization density along the track indicated a particle much lighter than the proton. This was the first sighting of the positron proposed by Paul Dirac in 1928. (Adapted from ref. 10.)

monoenergetic muon spectrum. And indeed Powell and company found that each of the 11 decay events produced a 0.6-mm-long track in the emulsion.

Powell received the 1950 Nobel Prize in Physics for "his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method." Underscoring the centrality of cosmic rays in the discovery of the pion, the muon, and the positron, he chose the title "The Cosmic Radiation" for his Nobel lecture. The charged pion's lifetime was later determined to be about 10 ns. Yukawa's quantum of the strong nuclear field had clearly been found, to be displaced only much later by the gluons of quantum chromodynamics.

In 1947, magnetized cloud chambers exposed to cosmic-ray showers revealed the first of the so-called V-particles, neutral particles decaying into two charged particles. In 1947 George Rochester and Clifford Butler at the University of Manchester reported the decay of the neutral K meson into two charged pions.[13] Soon a cloud chamber on the Pic du Midi in the French Pyrenees recorded a neutral particle decaying into a proton and a negative pion—the $\Lambda$ hyperon, the first of the nucleon's "strange" relatives. In 1948 Powell found in emulsion an example of a decay into three charged pions. That was the $K^+$ meson. Like the pions and the muons, all these new particles were products of cosmic-ray showers initiated by primary protons interacting in the atmosphere.

After two decades of such fundamental discoveries in cosmic-ray showers, the 1953 Cosmic Ray Conference at Bagnères-de-Bigorre in the French Pyrenees marked the transition to accelerator-based particle physics.[14] High-energy accelerators were built at large laboratories in the US and Europe. With particle physics moving to accelerators, the main focus of cosmic-ray research shifted to astrophysics and cosmology, with investigations on their composition, sources, and the acceleration mechanisms that produced them.

## Heavier nuclei

A balloon experiment at 30 km revealed in 1947 that in addition to protons, cosmic rays also contain completely stripped heavier nuclei. Today we know that the primary cosmic-ray flux comprises about 87% protons, 11% helium nuclei, and 2% heavier elements. The nuclear abundances are very similar to the composition of the solar system, but with a striking difference. The weakly bound light nuclei lithium, beryllium, and boron—almost absent in the solar system—are several orders of magnitude more abundant in cosmic rays. That's because carbon and oxygen nuclei in collisions with interstellar hydrogen produce those light nuclei. A few percent of the Be nuclei in the cosmic-ray flux are the long-lived unstable isotope $^{10}$Be, with a half-life of 1.5 million years. From the $^{10}$Be abundance in the flux and an estimate of the interstellar H density, one can conclude that the average travel time of an arriving $^{10}$Be was about 5 million years.

## Antimatter and antiworlds

Following the discovery of the antiproton in 1955 at the Berkeley Bevatron, Luis Alvarez initiated a search for cosmic antimatter. Could there be antiworlds that are sending us antiparticles? Positrons and antiprotons are, of course, produced in our own galaxy in high-energy collisions of cosmic-ray nuclei with interstellar hydrogen and helium. But the production rate from such prosaic processes is very small; searches for cosmic-ray antiprotons found none until 1979. Today a total of about 10 000 cosmic-ray antiprotons have been detected by balloon- and satellite-borne detectors. However, the measured energy spectrum up to 200 GeV shows no sign of any exotic antiworld source. No heavier antinuclei have been found, and the upper limit for the antihelium-to-helium flux ratio is of order $10^{-7}$.

The existence of antimatter islands in the cosmos is no longer seriously considered. But there are other, somewhat less exotic scenarios for the appearance of more antiparticles in cosmic rays than can be explained by ordinary interstellar collisions. Such an antimatter surprise came in 2009, when the orbiting PAMELA spectrometer recorded data on the flux of cosmic-ray positrons.[15] If cosmic-ray positrons are produced in interstellar collisions of known particle species, the positron-to-electron ratio should decrease slowly with increasing positron energy. Instead, the ratio observed by PAMELA increased with energy from 5 GeV to

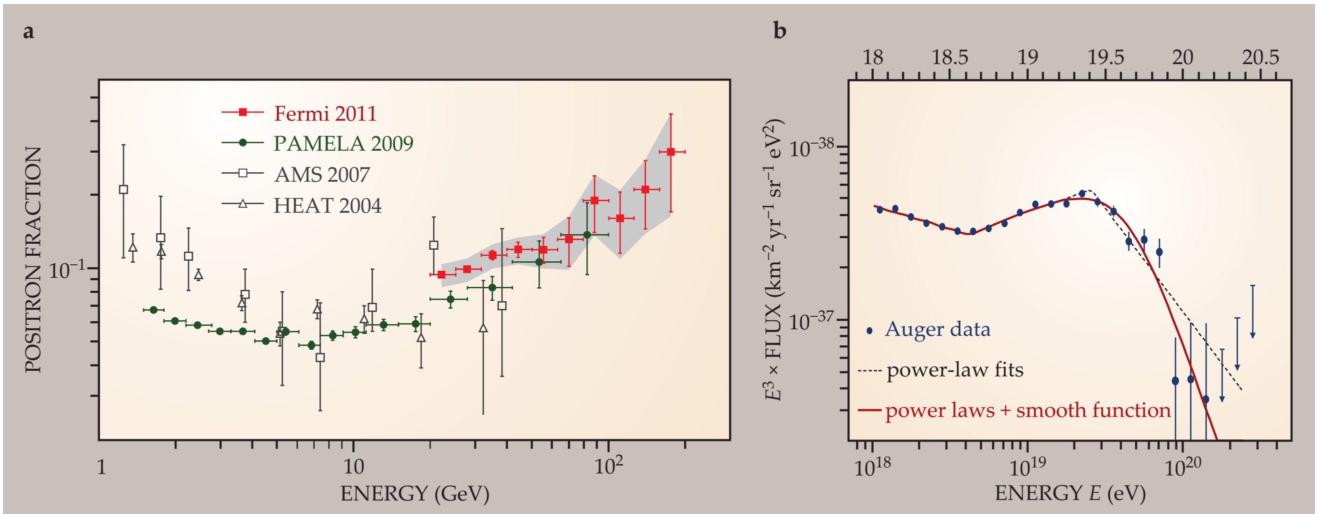

**Figure 5. Cosmic-ray results in the new century. (a)** Recent PAMELA[15] and *Fermi*[16] orbiting-spectrometer measurements of the positron fraction of the combined cosmic-ray flux of electrons and positrons, plotted as a function of the charged lepton's energy, reveal a surprisingly persistent rise from 10 to 200 GeV. Open data points are from earlier experiments. (Adapted from ref. 16.) **(b)** The cosmic-ray spectrum at energies $E$ above $10^{18}$ eV measured at the Pierre Auger Observatory is here multiplied by $E^3$, making it appear flatter. The steepening near $3 \times 10^{19}$ eV may be the Greisen-Zatsepin-Kuzmin cutoff expected if the ultrahigh-energy particles are, as generally thought, mostly protons. The curves and straight lines are different fits to the data. (Adapted from ref. 17.)

100 GeV. That unanticipated rise has now been confirmed and extended up to 200 GeV by NASA's *Fermi* orbiter,[16] as shown in figure 5a. The growing positron excess may come from high-energy stellar sources such as pulsars or from annihilations of still-unidentified dark-matter particles.

## Measuring the spectrum

Starting in 1932 Patrick Blackett and Giuseppi Occhialini at Manchester managed to study cosmic rays with a cloud chamber triggered by GM tubes above and below it. With the triggered chamber in a magnetic field, they were able to measure the cosmic-ray energy spectrum up to 20 GeV and, for the first time, show that it has an $E^{-2}$ power-law falloff above 1 GeV.

When a sufficiently energetic high-energy cosmic ray enters the atmosphere, the resulting shower of secondary particles can be detected over an extended area on the ground. Such "extensive air showers" were first observed by Rossi in 1933. Their systematic investigation by Pierre Auger and collaborators later in the decade yielded very important results. With GM tubes, they recorded coincidences on the ground over separations up to 300 m. From the showers' areas and particle densities on the ground, they estimated that a single shower could comprise more than a million secondary particles, corresponding to energies as high as $10^{15}$ eV for the instigating primary particle.

The showers were first thought to be electromagnetic—that is, a cascade of gammas and electron–positron pairs. But the observed shower spread was seen to be wider than one expects for an electromagnetic shower. The extensive lateral spread was eventually understood to be mainly due to nuclear collisions that created pions.

When cosmic-ray research resumed after World War II, it became clear that new detectors were needed to study the very rare occurrence of the highest-energy showers. Fast photomultiplier tubes and organic scintillators with nanosecond response times made their entry into research around 1950, and many shower-detection arrays with hundreds of scintillators spread over square-kilometer areas eventually came into use. The primary cosmic-ray spectrum at very high energies was found to fall like $E^{-2.7}$.

Primary cosmic-ray energies have now been seen up to a few times $10^{20}$ eV. But such events are extremely rare. At $10^{20}$ eV, one can expect to see only one shower per century per square kilometer of detector array. The Pierre Auger Cosmic Ray Observatory in Argentina, completed in 2008, is a 1600-detector array covering an area of 3000 km². Its goal is to study in detail the composition, sources, and spectrum of the highest-energy cosmic rays. Figure 5b shows a recent Auger determination of the ultra-high-energy cosmic-ray spectrum.[17]

In 1966 Kenneth Greisen and, independently, Georgiy Zatsepin and Vadim Kuzmin realized that cosmic-ray protons above a threshold energy of about $3 \times 10^{19}$ eV would lose energy by interacting with low-energy photons of the cosmic microwave background to produce pions. Therefore, they predicted, the energy spectrum should exhibit an abrupt downturn at that threshold—the so-called GZK cutoff.

## Open questions and prospects

Figure 5b shows a falloff near $3 \times 10^{19}$ eV that looks a lot like the anticipated GZK cutoff. But a possible alternative offered in 2010 by the Auger collaboration remains in play.[18] The collaboration reported evidence that the cosmic-ray flux at the highest energies might be dominated by iron nuclei rather than protons (see PHYSICS TODAY, May 2010, page 15). In that case, what looks like the GZK cutoff might be a nuclear-photofragmentation threshold. It's also possible that the abrupt steepening manifests the acceleration limit of some class of extragalactic sources.

The 100 years since Hess's discovery have seen remarkable developments. The flux of high-energy particles arriving at Earth from beyond the solar system includes not only charged particles but also neutrals likes gammas and neutrinos. Cosmic-ray research today benefits from new detector technologies originally developed for particle physics. Large detectors nowadays fly on satellites as well as on balloons.

Last May the PAMELA and *Fermi* instruments were joined in space by the AMS-02 cosmic-ray spectrometer installed on the International Space Station. On the ground, the Auger Observatory has been joined by, among others, the Telescope Array of air-shower fluorescence detectors in Utah, the IceCube neutrino detector deep in the ice at the South Pole (see the article by Francis Halzen and Spencer Klein in PHYSICS TODAY, May 2008, page 29), and the Antares neutrino telescope underwater off the French Riviera.

All those facilities, and many more, seek to answer questions like the following: What are the extragalactic sources of the highest-energy cosmic rays? What mechanism fuels the gamma-ray bursts we see halfway across the cosmos? What can cosmic rays tell us about the particle makeup of nonbaryonic dark matter?

Over the next decades, cosmic-ray research will very likely bring us important new discoveries relating the microcosmos of particle physics to the universe.

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