COMMENT

A century of cosmic rays

High-energy nuclei coming from far beyond the Solar System, and the exotic particles they produce, remain our best window onto the extreme Universe. **Michael Friedlander** reflects on what we have learned.

"Coming out of space and incident on the high atmosphere, there is a thin rain of charged particles known as the primary cosmic radiation." With these words on the nature of cosmic rays, British physicist Cecil Powell began his Nobel prize lecture in 1950.

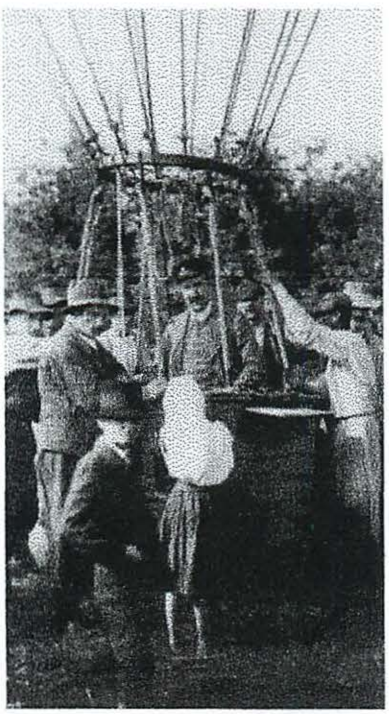
Powell's prize was awarded for his development of the photographic method of identifying high-speed and short-lived particles that were turning up unexpectedly in cosmic-ray studies as the products of high-energy collisions. At the same time, that photographic method was being used to discover new components of Powell's 'thin rain': heavy atomic nuclei. These two strands — the study of primary cosmic rays and the products of their collisions — continue to be woven into the fabric of today's research.

Although particle collisions are now studied mainly through the use of giant particle accelerators, the only window into the behaviour of the very highest-energy particles comes from examining cosmic rays. The study of the primary cosmic radiation is a part of current astrophysics: by comparing the composition of cosmic rays with that of stars, we can identify their sources and use them to investigate violent stellar processes.

This year, we celebrate the centenary of the discovery of cosmic rays by Austrian–American physicist Victor Hess. Over the decades, cosmic-ray research has spread in directions that he could never have imagined, from the discovery of antimatter to the use of carbon dating in archaeology. It has even played a crucial part in the origins of 'big science'.

RADIATION SOURCE

Hess's research was carried out in the heady days following the discovery of radioactivity and the electron. In the early 1900s, a prime research tool in the study of radioactivity was the electroscope, a sensitive device for measuring the ionization produced by radiation. It was soon found that the radioactive components of some rocks produced ionization, and most researchers believed that Earth's crust was the source of background levels of radiation. To investigate, scientists lowered electroscopes into lakes and oceans, carried them up mountains and took them to even greater heights in open baskets underneath hydrogen-filled balloons. The results were conflicting, with some showing a decrease in ionization with altitude, others an increase. It was during this confusing time that Hess, in 1911, started his own series of balloon flights.



Physicist Victor Hess on a balloon flight in 1912.

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Hess found that the ionization rate at first decreased with altitude, but then started to increase up to a height of 5.3 kilometres, the greatest height he reached. That flight took place from northern Bohemia (now part of the Czech Republic) on 17 April 1912, when a partial solar eclipse was visible from many parts of Europe. Hess detected no decrease in ionization during the eclipse, indicating that whatever the main source of the ionizing radiation coming from above, it was not the Sun.

Born in Austria in 1883 and educated at the University of Graz, Hess was a young assistant at the Radium Institute of the Austrian Academy of Sciences at the time of the flights. His discovery brought him a series of increasingly senior positions and growing professional recognition, culminating in a shared Nobel prize in 1936. With the deteriorating political situation in Europe, Hess was dismissed from his post at the University of Innsbruck in 1938 because he had a Jewish wife. He managed to escape from Austria, taking up a faculty post at Fordham University in New York.

For some years after these legendary beginnings, the nature of cosmic rays was strenuously debated by physicists. Robert Millikan (who coined the term 'cosmic rays' in 1925) continued to insist that they were electromagnetic 'rays', even after Arthur Compton had established that they were really 'particles', as revealed by the way in which they were deflected by Earth's magnetic field.

The experimental study of cosmic rays has often moved ahead of theory, yielding a host of unpredicted discoveries. One of the most dramatic was the observation of particles of antimatter. Paul Dirac's relativistic quantum theory had foretold the existence of antiparticles, and Dirac speculated that anti-atoms with anti-electrons might exist in distant anti-stars. But he made no predictions as to where to look for them on Earth: certainly not among cosmic rays.

In 1911, a tool for the study of cosmic rays had been developed by Scottish physicist C. T. R. Wilson. Wilson realized that water droplets were formed in the atmosphere by condensation of vapour on ions (an observation inspired by watching mist form on the summit of Ben Nevis in Scotland). He converted this insight into a powerful laboratory-scale device — the cloud chamber — in which the passage of charged particles was made visible by their trails of liquid droplets. In 1932, Carl Anderson was using a Wilson cloud chamber with a large magnet to study cosmic rays when he observed a particle that had the mass of an electron, but a positive charge. The discovery of the positron, as Anderson named the particle, was recognized when Anderson shared the 1936 Nobel prize with Hess.

During the period 1947–56, when cosmic-ray studies resumed after the Second World War, a host of unpredicted subatomic particles including hyperons, pions and kaons was found using photographic emulsions and Wilson cloud chambers. This complex mix of particles, called the particle zoo, forced a complete upheaval in particle theory.

Meanwhile, the study of the primary

cosmic radiation itself was advancing, and nuclei much heavier than helium were discovered. With further recent improvements to experimental techniques, the relative proportions of different cosmic-ray nuclei, and even some of their isotopes, have been precisely determined.

The proportions of the different chemical elements among cosmic rays can be compared with their abundances in the Solar System, in the atmospheres of distant stars and among the remnants of supernova explosions, to identify objects and regions where cosmic rays originate. Researchers also seek to identify the regions in which cosmic rays are accelerated to enormous energies, producing particles that travel close to the speed of light. The largest corresponding kinetic energy measured for a single cosmic-ray particle is comparable to that of a cricket ball or baseball travelling at 160 kilometres per hour. This energy is more than 100 million times larger than that of protons accelerated in the Large Hadron Collider at CERN, Europe's particle-physics laboratory near Geneva, Switzerland.

These ultra-high-energy particles are rare — only a few arrive each century over each square kilometre of Earth. Through their collisions in the atmosphere they generate billions of particles, requiring many detectors spread out over large areas. High-energy γ-rays, also produced in cosmic-ray sources, can similarly be detected by large-area arrays. Their arrival directions can point back to their sources, such as supernova remnants and active galaxies. Continued exploration of these highest-energy particles and photons might tell us about conditions in the early and very hot stages of our Universe.

Cosmic-ray studies have expanded in unanticipated directions. For example, cosmic rays have been identified as the source of the radioactive isotope carbon-14, produced by collisions with atmospheric nitrogen. The amount of carbon-14 produced in the atmosphere depends on the numbers of cosmic rays reaching Earth, which in turn depends on the 11-year cycle of solar activity. Measurement of carbon-14 has revolutionized archaeology by enabling the ages of ancient organic matter to be determined.

COSMIC CONSEQUENCES

Hess's discovery came from observing the effects of ionization produced by cosmic rays. That same effect is taking place in our bodies as cosmic rays pass through them. Over our lifetimes, we accumulate a radiation dose that causes biological damage, presumably contributing to a basic level of cancer production. Unshielded by the atmosphere, astronauts accumulate radiation doses from cosmic rays that may well exceed those considered safe. This could limit the distances to which astronauts can go as they explore the Solar System.

Today, the scale of physics research has expanded to the point at which it is not unusual for a single scientific paper to have hundreds of authors, crossing international boundaries and using internationally funded equipment. The origin of this revolution can be traced to cosmic rays. The cost and manpower demands of cosmic-ray research in the 1950s, although modest by today's standards, were beyond the capacity of any single group. The 'G-stack' collaboration, for example, of which I was a part (in Powell's research group at the University of Bristol, UK), was created to undertake the flight of a 'giant' stack of photographic detectors beneath a balloon. The special photographic emulsions, made by the photo company Ilford, were processed in Bristol; the balloon was flown in northern Italy; and the measurements and analysis were carried out by groups in Bristol, Brussels, Copenhagen, Dublin, Genoa, Milan and Padua. Our results, including many examples of new and very short-lived particles, were reported in a 1955 paper (J. H. Davies *et al. Il Nuovo Ciménto* **2,** 1063–1103; 1955) that carried the names of 36 scientists, by far the largest number of co-authors up to that time.

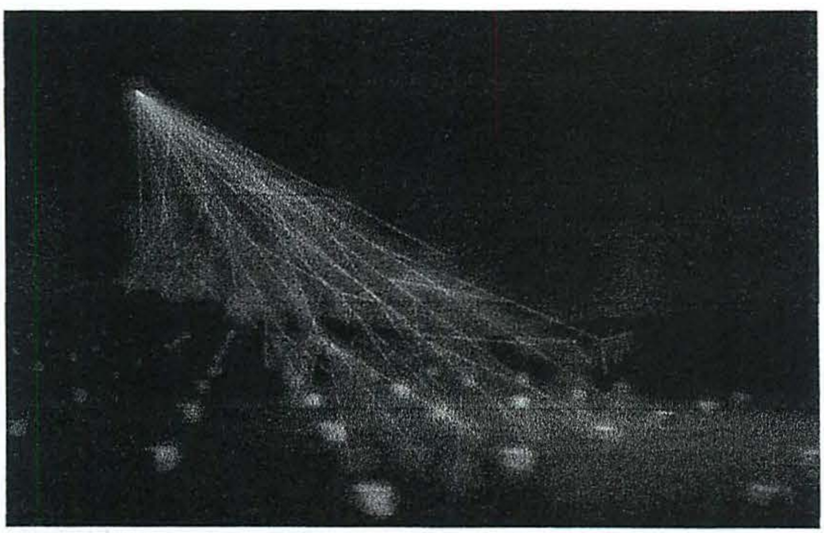
This style of large international collaborations is today exemplified by CERN, which was founded in 1954 and houses the largest particle accelerator ever built. Prominent among CERN's founders were many cosmic-ray scientists, including Powell and Edoardo Amaldi, its first director of research.

"After 100 years, cosmic-ray research is mature but still open to producing surprises."

One lesson to be learned from cosmic-ray research is the need to examine carefully any rare but apparently strange observations, and not to discard them as part of the background noise that many particle-physics experiments accumulate. The discovery of antimatter rested on the detection of a single track of a lone positron. Similarly, the discovery of some kaons was based on observations of single events. Although some discoveries may emerge from the statistical analysis of large quantities of data, we should remember that important discoveries can still be established by a single observation.

After 100 years, cosmic-ray research is mature but still open to producing surprises. Cosmic rays continue to be studied from balloons, Earth-orbiting satellites and long-range space probes as well as ground-based detectors that cover enormous areas, seeking the sources of the highest-energy cosmic rays. Antiparticles might also be identified. Longer flights and larger areas are permitting the accumulation of more data on particles and cosmic γ-rays, thus increasing the detection of yet more of the rarest events.

There are already suggestions that some of the highest-energy particles and γ-rays come from well-known objects such as some supernova remnants. More data might locate, more firmly, the directions in which their sources are located and should define the acceleration processes. Perhaps the physical conditions are even more exotic than we can imagine at present. This field of astroparticle physics seems sure to produce future Nobel prizewinners. ■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Cosmic-ray collisions create showers of particles, requiring detectors spread out over a vast area.

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Cosmic Rays: 1912–2012

One hundred years ago, using balloon flights up to 5 kilometers altitude, Victor Hess demonstrated that the intensity of penetrating ionizing radiation increased with altitude, indicating that Earth is exposed to high-energy radiation from space [*Hess*, 1912]. Since that observation, these "cosmic rays" have enabled discoveries basic to elementary particle physics and astrophysics. This discovery earned Hess the 1936 Nobel Prize in Physics, shared with Carl Anderson, who discovered the positron among the secondary cosmic rays near the ground [*Anderson*, 1933].

Then, the only known ionizing radiation with range in air more than about 30 centimeters was the γ ray (electromagnetic radiation with energy above about 100 kiloelectron volts), so the radiation from space was assumed to be γ rays and was called "cosmic rays." That name has stuck, although the "cosmic rays" studied today are not actually rays but particles. Indeed, γ rays do impinge on Earth, and γ ray astronomy is a burgeoning area of astrophysics, but the term "cosmic rays" continues to apply to the charged particles that make up the bulk of the incident ionizing radiation.

What Are Cosmic Rays? Geomagnetism Helps Find the Answer

Jacob Clay, a Dutch physicist, measuring the penetrating radiation during travels between the Netherlands and Java, demonstrated that the intensity was lower near the equator and initially attributed the variation to atmospheric effects dependent on geographic latitude [*Clay*, 1927, 1928, 1930]. Later he and American physicist Arthur Compton recognized the variation as a geomagnetic effect, giving evidence that the radiation consisted of charged particles [*Clay and Berlage*, 1932; *Compton*, 1932]. Convincing support for this conclusion came from measurements at 69 locations that demonstrated variation of intensity with geomagnetic latitude [*Compton*, 1933].

Theoretical studies of the motion of charged particles in the geomagnetic field [*Störmer*, 1930] led to quantitative understanding of Compton's latitude effect and to prediction of east-west asymmetry in cosmic ray intensity, the direction depending on the sign of the charge [*Rossi*, 1930a; *Lemaitre and Vallarta*, 1933]. The first demonstration of excess from the west, implying positive charge, was made in Mexico City with a Geiger counter coincidence telescope (two Geiger counters connected to an electronic circuit that registers a signal when both register simultaneous signals, indicating that a particle has penetrated both) [*Alvarez and Compton*, 1933].

Measurements on high-altitude balloons by counter telescopes interspersed with lead demonstrated the penetrating nature of the primaries and led to the conclusion "that the incoming cosmic radiation consists of protons" [*Schein et al.*, 1941]. Evidence for nuclei as heavy as iron came from balloon flights of cloud chambers and photographic emulsions [*Freier et al.*, 1948a, 1948b]. Evidence of electrons in cosmic rays came from balloon flights of a cloud chamber [*Earl*, 1961] and a scintillator telescope [*Meyer and Vogt*, 1961].

Elements heavier than iron are much less abundant in cosmic rays; initial evidence for them came from certain crystals in meteorites, which revealed tracks produced by heavily ionizing particles. A small fraction of these tracks could be caused only by nuclei with charge greater than that of iron [*Fleischer et al.*, 1967]. Subsequently, balloon flights of several square meters of photographic emulsions detected extremely rare heavy nuclei, including two identified as having an atomic number near 90 [*Fowler et al.*, 1967].

Elementary Particle Physics Without (Man-Made) Accelerators

The earliest discoveries of elementary particles beyond protons, electrons, and neutrons came from particles produced by cosmic rays colliding with nuclei in the atmosphere. Anderson discovered the positron when a photograph of a cosmic ray traveling through a cloud chamber in the field of a large laboratory magnet displayed the track of a particle of mass similar to an electron bending in the direction that a positive particle would move [*Anderson*, 1933].

Soon cloud chamber pictures of cosmic rays revealed a particle "of unit charge, but with a mass larger than that of an electron and smaller than that of a proton…since no evidence for their existence in ordinary matter obtains, it seems likely that there must exist some very effective process for removing them" [*Neddermeyer and Anderson*, 1937]. This was the first evidence for an unstable elementary particle, the muon.

Later, specialized photographic emulsions of cosmic ray tracks showed "slow charged particles of small mass…which, at the end of their range, produce secondary mesons" [*Lattes et al.*, 1947]. For this discovery of the particle known as the pion and for development of the nuclear emulsion technique, Cecil Frank Powell received the 1950 Nobel Prize in Physics. Soon after, evidence was produced for particles that are now known as the neutral kaon and charged kaon

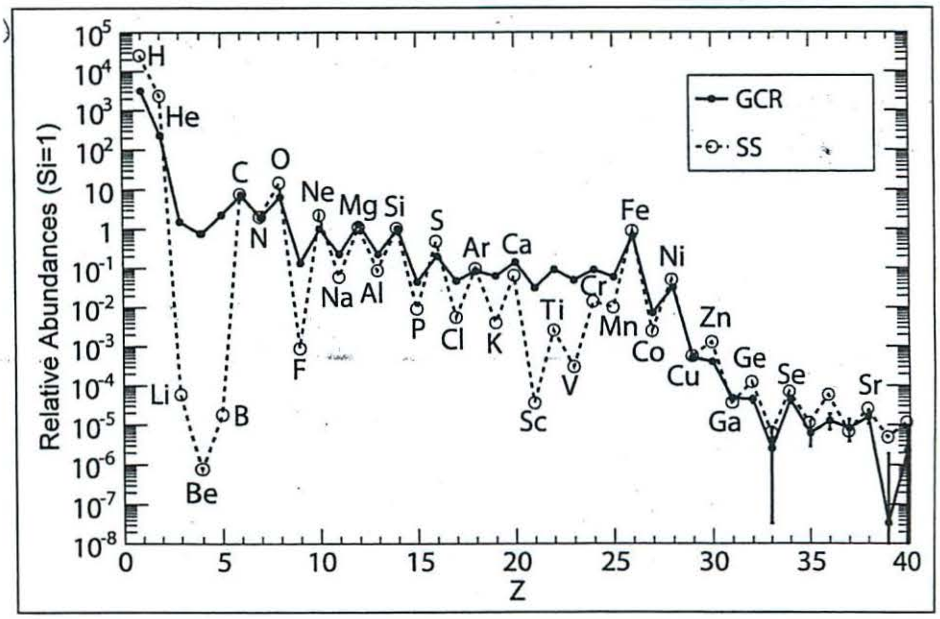

Fig. 1. Abundances of elements in galactic cosmic rays (GCR) and the solar system (SS) [Lodders, 2003] (adapted from George et al. *[2009] and* Rauch et al. *[2009]). Reproduced by permission of the American Astronomical Society.*

By M. H. Israel

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[*Rochester and Butler*, 1947]. The first evidence for an elementary particle more massive than a proton came from cloud chamber photos showing decay of a neutral particle (the Λ) into a proton and a pion [*Armenteros et al.*, 1951].

In the early 1950s the focus of elementary particle physics moved from cosmic rays to particle accelerator laboratories, and cosmic ray studies turned to astrophysics. Nonetheless, the highest-energy cosmic rays far exceed energies available at any man-made accelerator.

Cosmic Ray Composition Measurements Today

Electronic instruments on balloons and spacecraft have made precise measurements of the cosmic ray elemental composition over energy ranges from tens of megaelectron volts per nucleon to a few teraelectron volts per nucleon. Figure 1 shows abundances of elements in cosmic rays and in the solar system [*Lodders*, 2003]. That elements such as lithium, beryllium, and boron, which are rare in the Sun and solid bodies of the solar system as well as in the atmospheres of other stars, are much more abundant in cosmic rays is evidence of nuclear fragmentation by heavier cosmic rays in collisions with nuclei of interstellar gas, which produces these secondary cosmic rays.

Measurements of the isotopic composition of cosmic rays have led to understanding of the sources of galactic cosmic rays. Radioactive secondaries (e.g., beryllium-10) demonstrate that the nuclei scientists now observe were accelerated about 15 million years ago [*Yanasak et al.*, 2001]. The lack of nickel-59, which is unstable to capture of atomic electrons, with a half-life of 70,000 years, but stable as a bare nucleus, proves that these heavy nuclei spent at least 10^5 years as ambient interstellar material after they were synthesized in a supernova before a blast wave from another supernova accelerated them to cosmic ray energies, where they are stripped of their atomic electrons [*Wiedenbeck et al.*, 1999]. The detailed isotopic and elemental composition of the primary cosmic rays gives evidence of their origin in regions of the galaxy where there are collections of massive stars [*Binns et al.*, 2005; *Rauch et al.*, 2009].

Measurements of the composition of cosmic rays up to teraelectron volt energies demonstrate subtle differences in the spectra of different elements and deviations of spectra from simple power laws [*Ahn et al.*, 2010], leading to constraints on theories of the mechanism of cosmic ray acceleration. Spectra of electrons have shown features suggestive of unusual sources [*Chang et al.*, 2008; *Abdo et al.*, 2009], and measurements of the positron/electron ratio also suggest exotic sources of cosmic ray positrons, possibly the decay of particles constituting "dark matter," which has never been directly detected but is known by its gravitational effects to be about 5 times as abundant as normal matter in the universe [*Adriani et al.*, 2009].

Cosmic Rays at Extremely High Energies

In 1930 a circuit for use with Geiger counters capable of registering "triple simultaneous impulses or even more" [*Rossi*, 1930b] led to the discovery of cosmic ray air showers, events where widely separated particle detectors on the ground registered simultaneous signals. Air showers were investigated by Pierre Auger, who demonstrated that as many as a million particles could be present at the ground, each with an estimated energy of about 100 megaelectron volts. Estimating a factor of 10 to account for the energy lost in the atmosphere, he concluded "that 10^{15} [electron volts] is likely to be the energy of the primary particle" [*Auger et al.*, 1939].

The flux of cosmic rays falls steeply with energy and as a result, the highest-energy cosmic rays are quite rare, and their detection requires very large arrays of detectors and long exposure times. A milestone in the study of ultrahigh-energy cosmic rays was the detection in the array at Volcano Ranch, in New Mexico, of an air shower for which the energy of the primary particle was shown to be 10^{20} electron volts [*Linsley*, 1963]. The source of these ultrahigh-energy cosmic rays is one of the most interesting puzzles in modern astrophysics.

Today, even with much larger detector arrays in Argentina [*Abraham et al.*, 2010] and Utah [*Sokolsky et al.*, 2011], no cosmic ray with energy greater than a few $\times 10^{20}$ electron volts has been detected. Indeed, the spectrum falls steeply above about 4×10^{19} electron volts, as predicted by *Greisen* [1966] and by *Zatsepin and Kuz'min* [1966], due to resonant interaction of protons of this energy with photons of the cosmic microwave background, the radiation left over from the Big Bang that pervades the universe. Measurements above 10^{19} electron volts give promise of seeing cosmic rays from specific extragalactic sources, because at these energies the deflection of the cosmic rays by galactic magnetic fields is relatively small. These high-energy cosmic rays also offer the possibility of studying elementary particle interactions at energies unattainable in the laboratory.

Also important to the history of cosmic rays are many related observations, including work in the decade before 1912 that suggested but left doubtful the possibility of extraterrestrial radiation, as well as the controversies involving Robert Millikan, who was unconvinced by the balloon measurements of Hess and others, resisting the idea of extraterrestrial origin until 1925, and who remained unconvinced that the radiation was charged particles for several years after their latitude dependence was established. For further historical reviews, see *Carlson* [2012], *Friedlander* [2012], *Rossi* [1964], and *Friedlander* [2000].

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