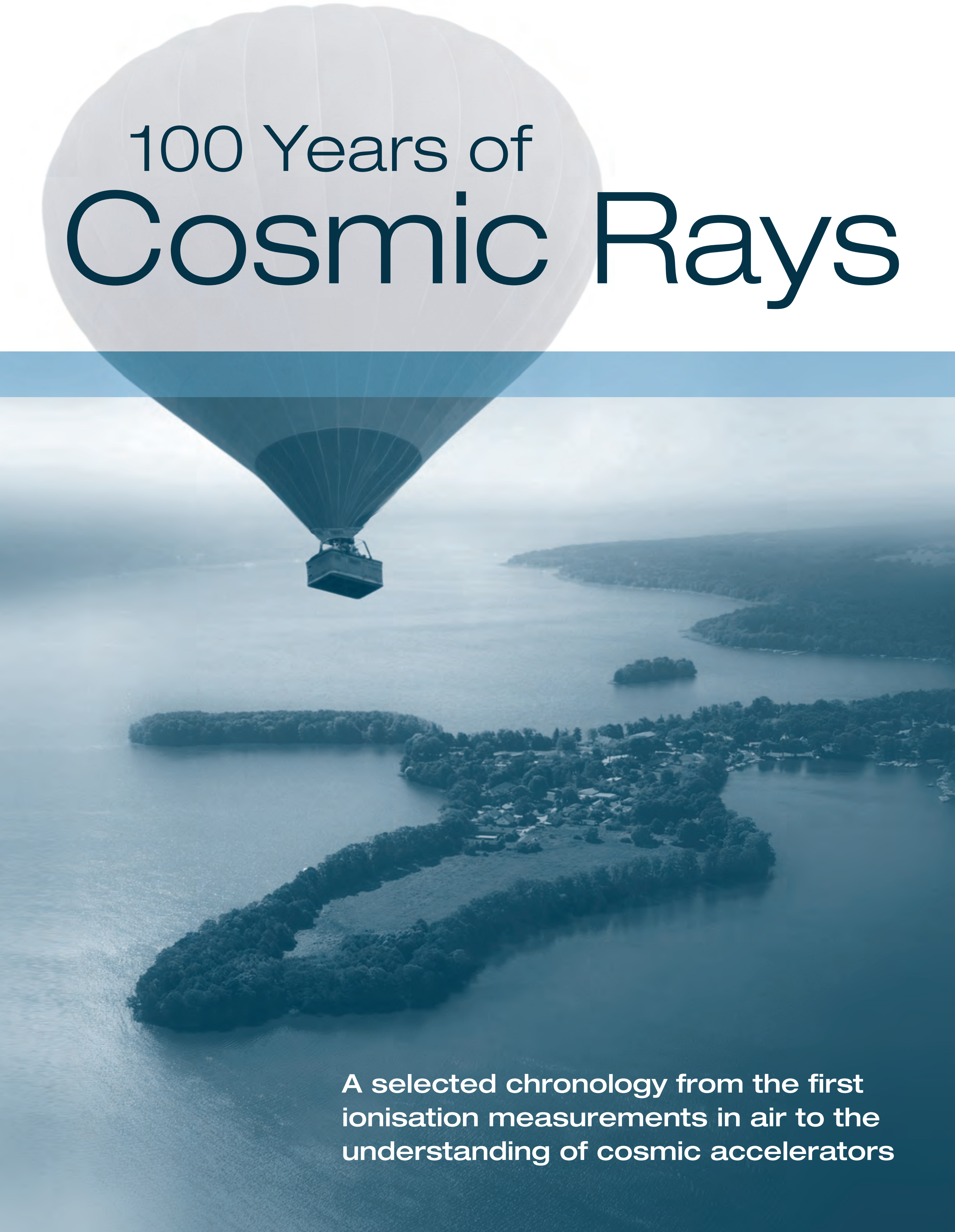
100 Years of Cosmic Rays



A selected chronology from the first ionisation measurements in air to the understanding of cosmic accelerators

100 Years of Cosmic Rays

Scientific progress is powered by questions, and the 100-year anniversary of cosmic rays is certainly a good time to pose them. Summarised below are some of those questions, which can also be seen as a guide through the chronological representation.

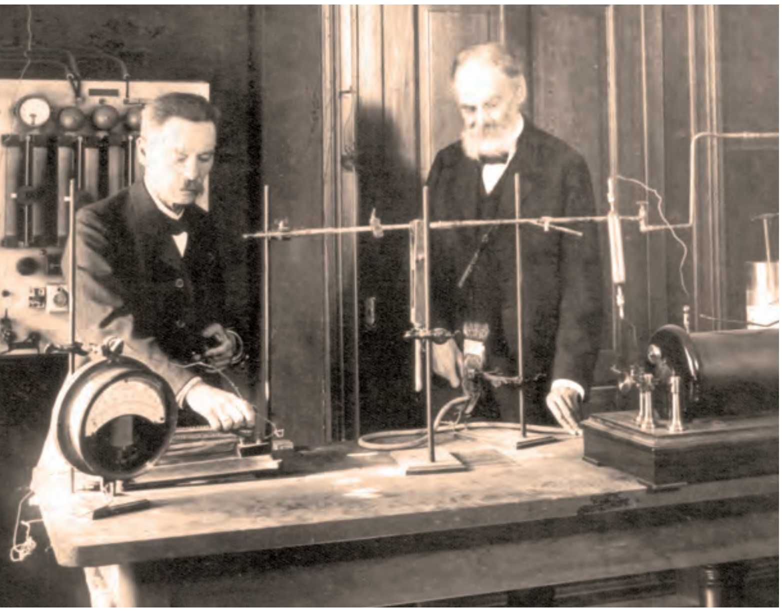
- What is the reason for the leakage of electrical charge in a well-insulated electrometer?
- What is the penetration power of ionising alpha, beta and gamma rays emitted by natural radioactive sources?
- Where is the origin of this radiation — is it near to the ground or in higher atmospheric layers?
- Was it a discovery? Does cosmic radiation really exist?
- What are the properties of cosmic rays?
- Have cosmic rays had any influence on the evolution of life on Earth?
- Is it possible that cosmic radiation influences cloud formation, weather conditions and even the climate?
- What are the sources of cosmic rays?
- What is the reason for the energy cutoff starting at energies greater than 5×10^{19} eV?
- How can cosmic accelerators produce particles with energies several orders of magnitude higher than those reached by a man-made particle accelerator, like the LHC at CERN?
- What is the fraction of antimatter in primary cosmic particles?
- Can cosmic rays give an answer about the nature of dark matter?

Those are only a few of the questions asked in the past and at present. Some of them have been answered, but many are still open, and the experience of these 100 years has shown that new results always yield new questions.
However, it is not only the right questions that have brought success. An important role has been played by the instruments developed and perfected for cosmic particle experiments and later also for accelerator experiments: electrometers, cloud chambers, Geiger-Müller counters, coincidence circuits, photographic emulsions, photomultiplier tubes, scintillation counters, Cherenkov and fluorescence light detectors, calorimeters, and tracking devices such as proportional, drift and silicon detectors. Another driving force has been the imagination of physicists in creating models and theories which then had to be proven by experiments.

The chronology presented here is based on a series of nine posters published by DESY. We sought to summarise the milestone developments, but not all important topics could be included due to limitations of space and time as well as our unavoidable subjective views.

Michael Walter, DESY

1900—1911
The Pre-Discovery Period



Elster and Geitel in their private lab

1900
J Elster and H Geitel, CTR Wilson: Explanation of why air becomes conductive

1901
CTR Wilson: Extraterrestrial radiation mentioned for the first time

Following the discovery of radioactivity and X-rays, the ionisation of gases was systematically investigated.
For these measurements, electrometers originally invented in 1789 to study electrical phenomena were used.
Julius Elster and Hans Geitel (Wolfenbüttel), and Charles Thomson Ress Wilson (Cambridge) found that ion production appears in closed and isolated detectors even in the absence of a source. The general conclusion was that this unexpected ionisation is caused by radioactive substances in the detector's walls or in its neighbourhood.
Wilson was the first to ask the question: can this penetrating radiation be extraterrestrial?

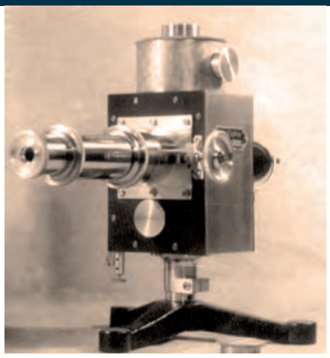
1902—1903
F Linke: First investigation of penetrating radiation with balloon flights

During six balloon flights, Franz Linke (Berlin), a meteorologist and geologist, performed ionisation measurements with an electrometer provided by Elster and Geitel. He measured the ionisation compared to on the ground. It was about the same between altitudes of 1000m to 3000m and larger by a factor of four at 5500m. His published results have obviously (and unfortunately) never been recognised.

1902—1909
General consensus that ionisation is caused by the natural radioactivity of the Earth

Over the following years, the ionisation effect was studied by many scientists in Canada, Germany, Britain and the US. The electrometers were surrounded by such different materials as water, wood, bricks and lead. The goal was to study the absorption of penetrating beta rays and gamma rays coming from radioactive elements in the ground and in the air of the environment. With increasing absorber thickness, the ionisation could be reduced, but a small fraction remained.

The Phoenix balloon (Berlin) in 1894, drawn by H Groß

From left to right: Two-string electrometer designed by Wulf; Theodor Wulf; Albert Gockel; Karl Bergwitz

1908
T Wulf: Improvement of the electrometer's design

Theodor Wulf, a German Jesuit, studied physics in Innsbruck and Göttingen. He improved the electrometer's design by replacing the thin metal foils with two thin metal fibres. This new electrometer was much easier to calibrate and became the state-of-the-art detector for outdoor measurements.

1909
K Bergwitz, A Gockel: New high-altitude measurements with balloons

Near Braunschweig, Karl Bergwitz reached an altitude of 1300m with a balloon. He measured the ionisation with an improved electrometer as designed by Wulf.
The measurements were continued by Albert Gockel (Fribourg). Neither observed a decrease of ionisation with distance from the ground, as had been expected for radiation sources in the Earth's crust. Because of problems with the detectors, it was difficult to draw definitive conclusions.

1908
A Gockel and T Wulf coin the term "cosmic radiation"

Wulf and Albert Gockel (Switzerland) were the first to study the ionisation rate on high mountains in the Alps. They did not observe strong deviations from measurements at sea level. In their publication, the term "cosmic radiation" was used for the first time.

1910
T Wulf: Ionisation measurement on the Eiffel Tower

Wulf began a series of measurements on top of the Eiffel Tower. Even at only 300m above ground, he observed a smaller reduction in radiation when compared with theoretical estimates.
He came to the same conclusion as Bergwitz and Gockel: the radioactivity of the air must contribute essentially to the measured ionisation.

Domenico Pacini with an electrometer

1910—1911
D Pacini, GC Simpson and CS Wright: Measurement of ionising radiation on and below a water surface

In Italy, Domenico Pacini (Bari) performed ionisation measurements in the bay of Livorno at a distance of 300m from the coast on the water's surface and 3m below it. Since ionising radiation from solid materials could be excluded on the sea, he concluded that the source of ionisation must be a penetrating radiation in the atmosphere.
George Simpson and Charles Wright were scientific members of RF Scott's British Antarctic Expedition. Sailing from Britain to New Zealand, they measured the ionisation and observed a dependence of the rate on the barometric air pressure, not knowing that it was connected with cosmic rays.

1912
Discovery by Victor Hess

1911
CTR Wilson: Development of the cloud chamber and publication of the first pictures

In 1895 CTR Wilson started investigating cloud formation in dust-free air. He discovered that condensed bubbles appear when air molecules are ionised by X-rays. In 1911 Wilson demonstrated with a cloud chamber that alpha and beta rays could be visualised. Two of the published pictures contained straight tracks which were probably the first photographs of cosmic particles. One year before their discovery, Wilson misinterpreted these tracks as beta rays.

Original Wilson cloud chamber (Cavendish Museum)

VF Hess in his lab in 1915

1911—1912
VF Hess: Calibration measurements with gamma rays

In 1910 Hess became an assistant at the just-founded Radium Institute of the Imperial Academy of Sciences in Vienna. He performed absorption measurements in air with the strongest gamma source available at the institute and experimentally confirmed the absorption coefficient predicted by Eve.
He improved the electrometer's construction and developed a calibration method for electrometers using gauge radium sources of different strengths.
For calibrated detectors from the company Günther & Tegetmeyer (Braunschweig), the accuracy when measuring the strength of unknown sources was about 5 per mil; uncalibrated instruments achieved 3% accuracy.

1911
VF Hess: First three balloon flights

In August and October of 1911, Hess performed three balloon flights reaching altitudes of 200m to 1000m and confirmed the findings of Wulf, Bergwitz and Gockel. To prepare for a new series of flights, Hess designed and ordered improved instruments, two for gamma-ray detection and one with thin detector walls to measure beta rays.

Victor F Hess in the balloon's basket sometime between 1911 and 1912

1912
VF Hess: Six balloon flights from the Prater in Vienna at lower altitudes

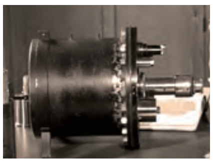
Six new flights were financed by the Imperial Academy of Sciences and supported with balloons from the Royal Imperial Austrian Aeronautical Club in Vienna. Hess measured the ionisation mainly with two or three electrometers:

1 17 April, during an eclipse of the sun at 1900m—2750m of altitude
2 26—27 April, at night for six hours at 300m—350m of altitude
3 20—21 May, at night at 150m—340m of altitude
4 3—4 June, at night at 800m—1100m of altitude
5 19 June, in the afternoon at 850m—950m of altitude
6 28 June, at night at 280m—360m of altitude

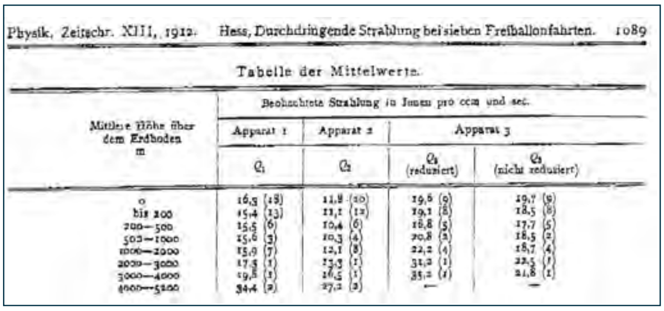
Seven flight routes of VF Hess in 1912

7 August 1912
VF Hess: Seventh balloon flight, reaching an altitude of 5350m Discovery of cosmic rays

With the hydrogen-filled balloon Bohemia, provided by the German Aero Club in Bohemia, Hess, together with W Hoffory and E Wolf, reached an altitude of 5350m and landed at noon in Bad Saarow/Pieskow in Brandenburg. All three detectors measured a strong increase in ionisation.



Electrometer used by VF Hess in 1912



Physik. Zeitschr. XIII, 1912. Hess, Durchdringende Strahlung bei sieben Freiballonfahrten. 1089

Tabelle der Mittelwerte.

Mittlere Höhe über dem Erdboden m	Beobachtete Strahlung in Jonen pro ccm und sec.			
	Apparat 1	Apparat 2	Apparat 3	
	Q_1	Q_2	Q_3 (reduziert)	Q_3 (nicht reduziert)
0	16,5 (18)	11,8 (10)	19,6 (9)	19,7 (9)
bis 200	15,4 (13)	11,1 (12)	19,1 (8)	18,5 (8)
200—500	15,5 (6)	10,4 (6)	18,8 (5)	17,7 (5)
500—1000	15,6 (3)	10,3 (4)	20,8 (2)	18,5 (2)
1000—2000	15,9 (7)	12,1 (8)	22,2 (4)	18,7 (4)
2000—3000	17,3 (1)	13,3 (1)	31,2 (1)	22,5 (1)
3000—4000	19,8 (1)	16,5 (1)	35,2 (1)	21,8 (1)
4000—5200	34,4 (2)	27,2 (2)	—	—

Mean values of all measurements during the seven flights at different altitudes (the number of ionisation values in brackets)

VF Hess summarised the results of these seven flights as follows:

- At altitudes of less than 1000m, the results are in general agreement with previous measurements.
- A radiation of high penetration power hits the atmosphere from above, which cannot be caused by radioactive emanations.
- This radiation contributes to the total amount of observed ionisation at lower altitudes as well.
- Assuming gamma radiation, the sun is not the source of the extraterrestrial radiation.
- There is no difference between ionisation measured during the day and at night.

1913—1926
Confirmation, Refusal, Confirmation

1913—1914
W Kolhörster: Confirmation of the discovery of cosmic rays

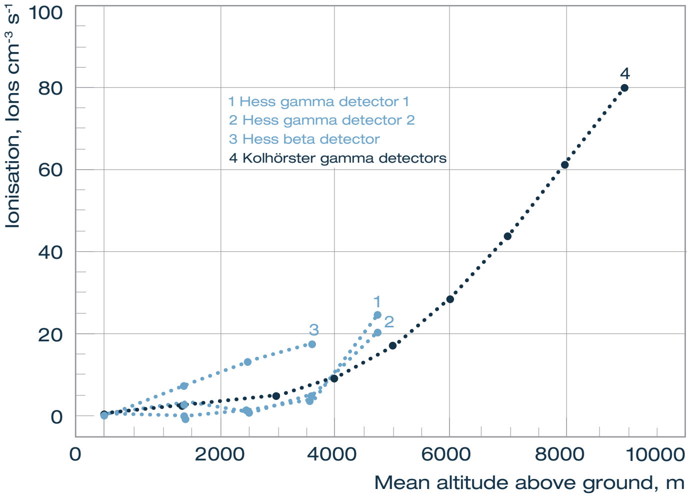
Werner Kolhörster from the University of Halle (Germany) took the important step towards very high altitudes. In 1913 he performed three flights with a hydrogen balloon up to 6000m and confirmed the results of Hess.
Kolhörster started his record flight at the end of June 1914 with improved electrometers, reaching an altitude of 9300m. The ionisation reached 80.4 ions cm^{-3} s^{-1}, and its increase (see figure) was a perfect confirmation that the high-energy radiation has an extraterrestrial origin.
He estimated the absorption coefficient of this penetrating radiation to be smaller than the value for gamma rays from radium D by a factor of at least five.

W Kolhörster (at back centre) in 1913

1914
A Gockel, VF Hess and M Kofler: High-altitude measurements in the Alps

Gockel demonstrated the hardness of the radiation with measurements 6m below the surface of Lake Constance, in the Alps at Jungfraujoch and on the Aletsch Glacier at 3400m and 2800m of altitude.

Hess and Kofler performed long-term studies of the ionisation, as dependent on time and weather conditions. Two electrometers were installed on the 2044m-high Obir in the Austrian Alps.



Ionisation measured by VF Hess and W Kolhörster, as dependent on altitude

1915
E von Schweidler: First discussion of different assumptions about the origin of cosmic rays

E von Schweidler

For the Festschrift marking the 60th birthdays of Elster and Geitel, a first theoretical investigation of possible sources of the cosmic radiation was presented by von Schweidler (Vienna).
Based on the existing knowledge of ionising radiation, he excluded the upper atmosphere, the moon, the planets, the sun and other fixed stars as sources of cosmic rays. Schweidler concluded that "the less extreme requirements prefer the hypothesis of radioactive substances distributed in outer space."

1918
VF Hess, W Schmidt: Estimate of the distribution of radioactive gases in the atmosphere

The model developed by Hess and Schmidt described a distribution of radioactive emanations in the atmosphere in agreement with experimental data.
As shown in the table (at right), only radium D can reach the upper atmosphere. All other radioactive emanations are concentrated near the Earth's surface because of their short lifetimes.

The altitude where the fraction of radioactive emanations is reduced to 50% compared to the Earth's surface was estimated for different radioactive products:

Radium emanations and short-lived decays:	~1200m
Radium D and decay products:	<10000m
Thorium emanations and thorium A:	2m—3m
Thorium B and decay products:	100m—150m
Actinium emanations and actinium A:	0.5m—1m
Actinium B and decay products:	10m—20m

1923
RA Millikan et al: Radiation measurements in the atmosphere

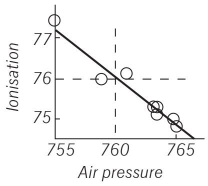
RM Otis (Pasadena), a co-worker of Millikan, observed with ionisation measurements in aeroplanes up to 5400m of altitude a dependence similar to that found by Hess and Kolhörster. However, the increase was smaller. RA Millikan and IS Bowen used an unmanned sounding balloon. A very light electrometer registered the ionisation, temperature and barometric pressure automatically on a photographic film. They measured only one averaged ionisation value between 5km and 15km of altitude, which was smaller than expected from the European results by about a factor of four.
Millikan concluded that there is no radiation of cosmic origin with the absorption coefficient estimated by Hess and Kolhörster.

RA Millikan and GH Cameron in 1925

1926
RA Millikan et al: Disproof of European results, "rediscovery" of cosmic rays

From measurements in snow-fed lakes at high altitudes, Millikan and Cameron deduced an absorption coefficient for the penetrating radiation in water supposedly smaller than found in Europe.
Claiming the discovery of cosmic rays, Millikan caused strong reactions by Hess, Kolhörster and others.

1926—1933
Investigation of Properties



The dependence of ionisation on air pressure (from Myssowski, Tuwim, Phys Zeitschrift, 39, 146 1926)

1926
L Myssowski, L Tuwim: Barometric effect

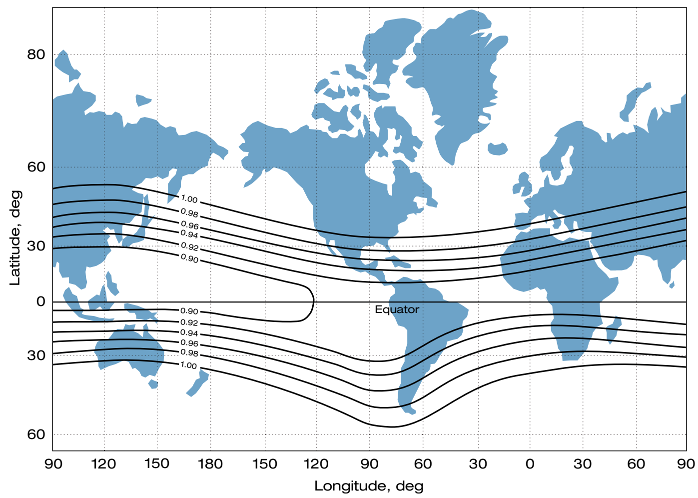
The dependence of the ionisation rate on barometric air pressure was discovered in a three-week measurement. An electrometer was installed 1m below the surface of the Neva River in Leningrad (now St Petersburg).
An explanation for the observed increase in the rate with decreasing air pressure was given many years later when muons and pions were discovered in cosmic particle interactions.

1927—1937
J Clay, AH Compton et al: Latitude effect

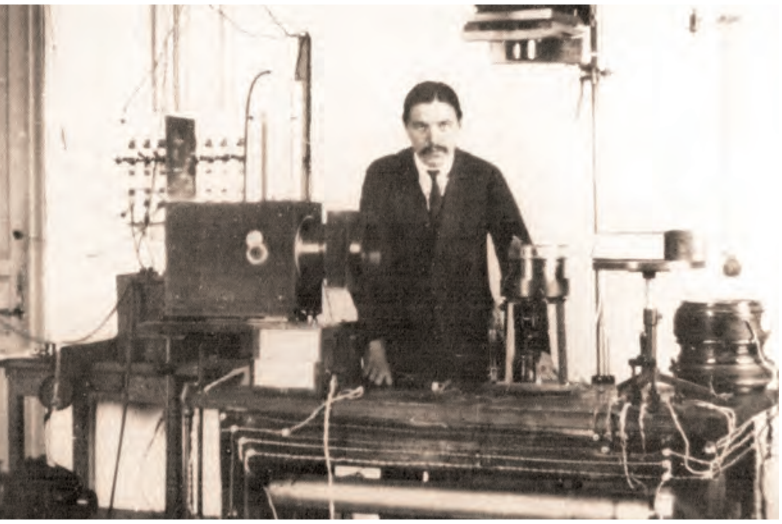
A possible dependence of the cosmic ray rate on latitude was predicted by Kolhörster in 1919. Sailing in 1926 from Amsterdam to Indonesia, J Clay used an electrometer to measure the expected decrease of the ionisation near the equator.
Through a worldwide measurement campaign initiated by Compton in the 1930s, the effect was established. This was the definitive proof that a part of the primary radiation consists of charged particles.

1927—1929
D Skobeltsyn: First cosmic ray tracks in the cloud chamber

In 1927 Skobeltsyn investigated beta rays in a cloud chamber operating in a magnetic field. By chance, he observed in two pictures straight tracks which he interpreted as being due to high-energy cosmic rays. In a dedicated experiment, he found 36 tracks in 600 photographs. This was the first visual proof for the existence of charged secondaries produced by cosmic rays.



The relative cosmic particle intensity as a function of geomagnetic latitude



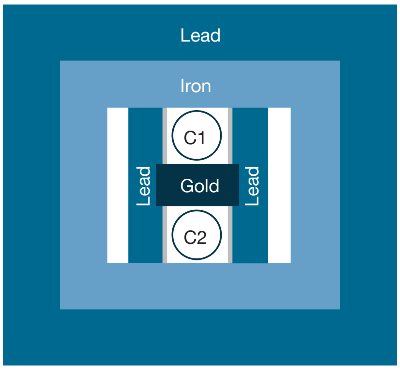
D Skobeltsyn in his laboratory in Leningrad

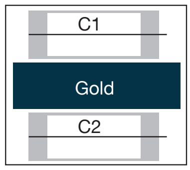
1928
H Geiger, W Müller: New cosmic particle detector

In 1928 Geiger and Müller announced the development of a new detector. The counter consists of a metal tube filled with gas, and an isolated wire at a positive high voltage in the tube centre. If a particle crosses the tube, the gas becomes ionised and the electrons move to the wire, yielding a measurable signal.

1928
W Bothe, W Kolhörster: Experiment with Geiger-Müller counters in coincidence

Bothe and Kolhörster designed a trend-setting experiment to measure the absorption of cosmic rays with two Geiger-Müller counters in coincidence. The passage of a cosmic ray through both counters could be observed using electrometers.
The absorption measurements were taken with and without a gold block between the counters. Coincidences could only be caused by particles, not by gamma rays. This was additional proof that at least a part of the secondary cosmic radiation consists of corpuscular particles.

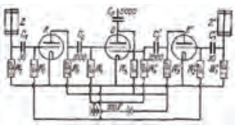




Absorber experiment with Geiger-Müller counters C1 and C2 in coincidence

1929
W Pauli: Prediction of the neutrino

The neutrino was introduced by Pauli as a neutral particle to save the momentum conservation of the beta decay, which has to be a three-body decay. He assumed that it would never be detectable.



Electronic coincidence circuit. There is a signal at C3 only if counters Z and Z' are crossed by the same particle.

1928
W Bothe: Invention of the coincidence circuit

Shortly after the absorption experiment, Bothe invented the electronic coincidence circuit. The concept was improved many times and is still an essential element in particle and astroparticle experiments.

1929—1933
J Joly: Biological impact

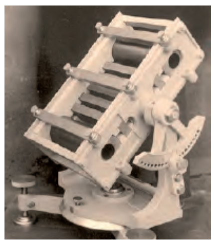
J Joly from the University of Dublin was probably the first to discuss possible biological impacts of cosmic radiation on the variation of species due to the interaction with chromosomes or on the incidence of cancer.

1930—1937
C Störmer, G Lemaitre, MS Vallarta: Trajectories in the Earth's magnetic field

A visionary explanation for the appearance of the aurora borealis was given in 1898 by K Birkeland. Electrons emitted by solar flares are guided by the Earth's magnetic field to the polar areas and excite the molecules of the atmosphere.
Based on this theory, Störmer (1930) and Lemaitre and Vallarta (1934) calculated the trajectories of cosmic particles.

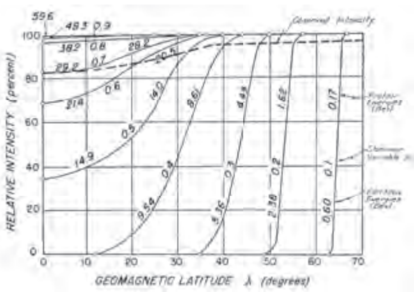
1931—1934
B Rossi, T Johnson, L Alvarez, AH Compton: East-west effect

B Rossi's prediction of an east-west effect based on Störmer's calculations of cosmic particle trajectories in the Earth's magnetic field. Particles with a positive charge should enter the atmosphere from the west, those with a negative charge from the east.
The effect was first demonstrated by Johnson and independently by Alvarez and Compton in 1932 at high altitude and low latitude in Mexico. Rossi confirmed the results in 1933 with his measurements in Eritrea.



Top: B Rossi (middle) in Eritrea; bottom: Geiger-Müller counter telescope

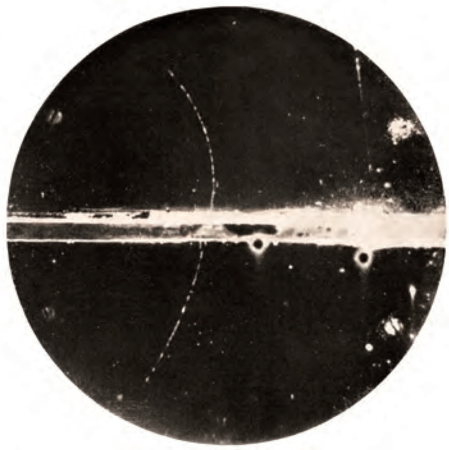
The relative cosmic particle intensity as a function of geomagnetic latitude for minimum energies of electrons and protons



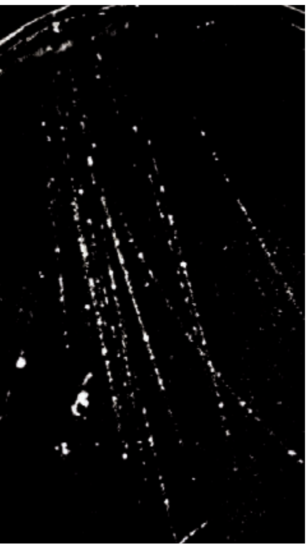
1933—1947
Birth of Particle Physics

1932
CD Anderson: Discovery of the positron

In 1931, with a cloud chamber operating in a strong magnetic field, Anderson observed cosmic ray tracks with negative and positive charges, which were interpreted as electrons and protons. Since many positive tracks had the same ionisation as the electrons, Anderson introduced a 6mm-thick lead plate into the chamber. In photographs from 1932, he found tracks with the ionisation and track length observed for electrons, but with a positive charge. This anti-electron (positron) had been predicted two years earlier by PAM Dirac.



A positron with an energy of 63MeV entering the lead plate from below and leaving the plate with an energy of 23MeV. For a proton, the track length would be ten times shorter.



Cloud chamber photograph of a particle shower with about 16 tracks. The divergence of the tracks points to an interaction in the magnet coil.

1933—1935
B Rossi, PMS Blackett, G Occhialini: Particle showers

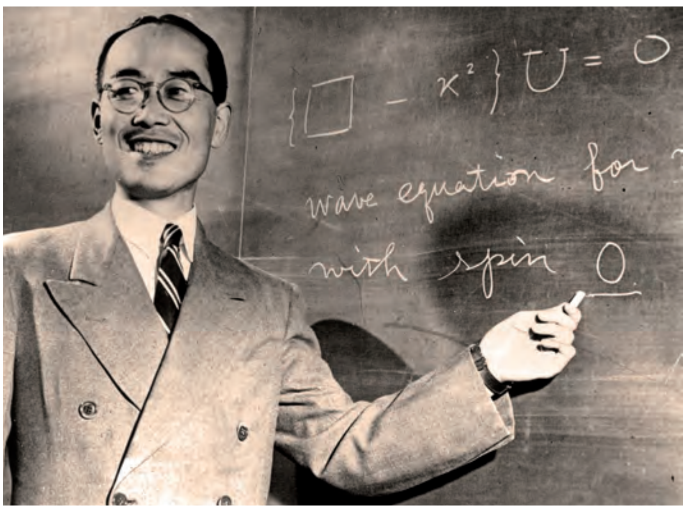
Rossi performed measurements with three Geiger-Müller counters in coincidence with and without lead shielding on top. The coincidence rate increased with the shielding, even though the opposite had been expected. The explanation was the shower production by an incoming cosmic particle.
Blackett and Occhialini demonstrated the shower production visually with cloud chamber photographs.

1934
W Baade, F Zwicky: Supernovae as possible sources of cosmic rays

By investigating photographic plates taken over the past 30 years, about 13 short flaring, extremely bright objects were identified. Zwicky and Baade called them supernovae. Based on the estimated energy release, they concluded that supernovae are sources of cosmic rays. This hypothesis is still valid, but not completely confirmed.

1935
H Yukawa: Prediction of the pion

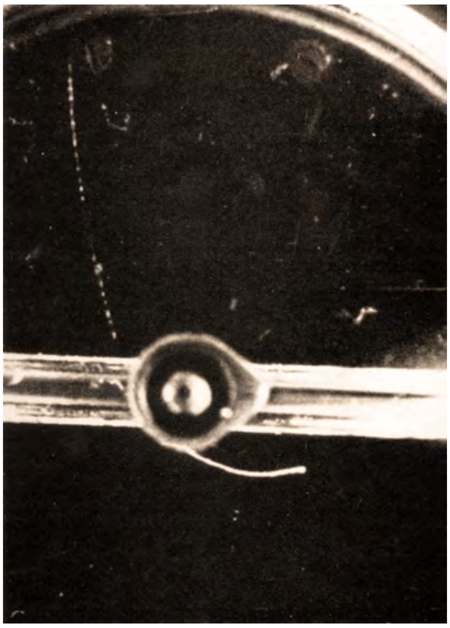
Yukawa formulated a theory to explain the dense packing of protons and neutrons in the nucleus of an atom. The short-ranged field needed a carrier with a mass inversely proportional to the range. He estimated a particle mass of about 100MeV and predicted that these particles could be produced in cosmic particle interactions.



H Yukawa, 1949

1936
SH Neddermeyer, CD Anderson: Discovery of the muon

In a cloud chamber exposure with a 1cm-thick platinum plate in the centre, 6000 photographs were taken. Anderson and Neddermeyer found about 25 events where the energy loss in the platinum absorber was much smaller than measured for electrons or positrons. Since the mass should be between the electron and proton masses, they first called it the mesotron.
For several years, it was assumed that this particle was the predicted Yukawa particle.



Stereographic photograph of a cloud chamber exposure. A muon enters the chamber from above and comes to rest below.

1937
M Blau, H Wambacher: First cosmic ray nuclear interaction in a photo emulsion

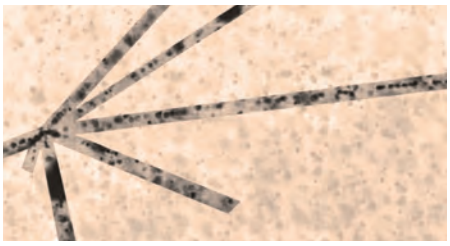
The photo-emulsion technique was developed by M Blau. In 1937 a five-month exposure to cosmic particles was performed at Hess's Hafelekar cosmic ray station at an altitude of 2300m.
The discovery of a so-called star was a breakthrough of this detection technique. A cosmic particle interacted with an atom of the emulsion, producing eight tracks.

1937
DH Perkins, GPS Occhialini, CF Powell: Discovery of the pion

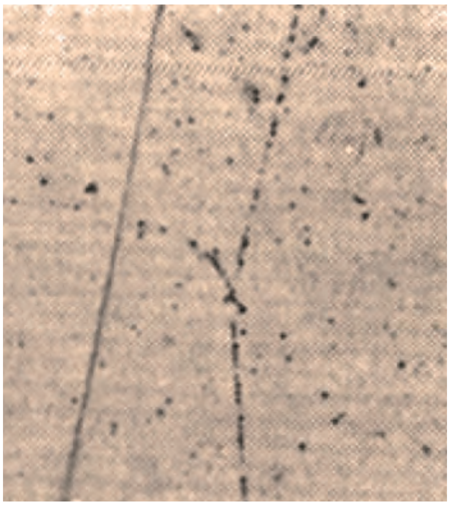
In 1938 Yukawa and Sakata predicted the lifetime of the Yukawa particle to be about 10^{-8} seconds, which was 100 times shorter than the measured lifetime of the muon.
The problem was solved with the discovery of the pion in photographic emulsions in 1947. Perkins found one event, and two months later Occhialini and Powell identified 25 pion interactions.
In Britain, the emulsion technique was improved by Powell, Perkins and others, in cooperation with the Ilford company.

1938
I Lange, SE Forbush: Solar cosmic particles

In February 1942, a large solar flare appeared. Lange and Forbush measured an increase in the cosmic particle rate of about 15%. They concluded that this additional fraction is caused by charged particles emitted by the solar flare.



A "star" produced in a photo emulsion by a cosmic particle



The pion event identified by Perkins. Tracks B and C are protons; D is a tritium nucleus. The short track E is a recoil nucleus. The grain density and scattering of track A correspond to a particle with a mass of about 100MeV.

1938
P Auger: Extensive air showers

With two Geiger-Müller counters in coincidence, Auger and his colleagues, Maze and Robley, detected extensive air showers. They measured the rate at up to 300m of counter distance and estimated the energy of the primary cosmic particles to be about 10^{15}eV.

1947—1959
Extensive Air Showers

1947
First International Cosmic Ray Conference in Krakow

The first edition of the biennial International Cosmic Ray Conference was held in Krakow, Poland.
In the front row of the photo stand P Blackett, J Blaton, A Wheeler and W Heitler. Other prominent participants included P Auger, G Bernardini, J Clay, M Cosyns, L Janossy, L Leprince-Ringuet and CF Powell.

1947
D Skobeltsyn et al: Start of air shower experiments in the Pamirs

After WWII, a broad cosmic ray research programme began in the Soviet Union. At 3860m of altitude, an experiment using Geiger counters was installed over an area of 1000m in diameter. For the first time a reduction of random signals was achieved by forming coincidences of local counters, followed by the requirement of coincidences of counters at a greater distance.

1949
E Fermi: Model of cosmic particle acceleration

The basic idea behind Fermi's model was that particles reach a higher energy when they enter the front of a plasma cloud which is moving with the very high velocity *v*. Such plasma clouds are produced, for instance, in supernova explosions. But the model cannot explain acceleration to very high energies.

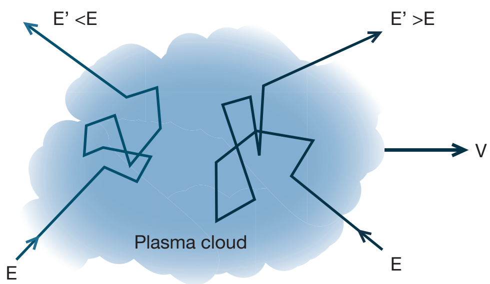
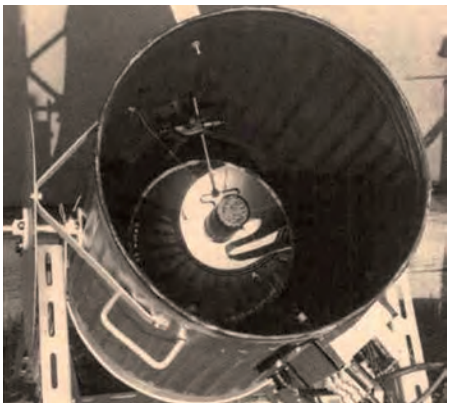


Illustration of Fermi's acceleration model

1953
W Galbraith and JV Jelley: First air Cherenkov counter



First air shower Cherenkov counter

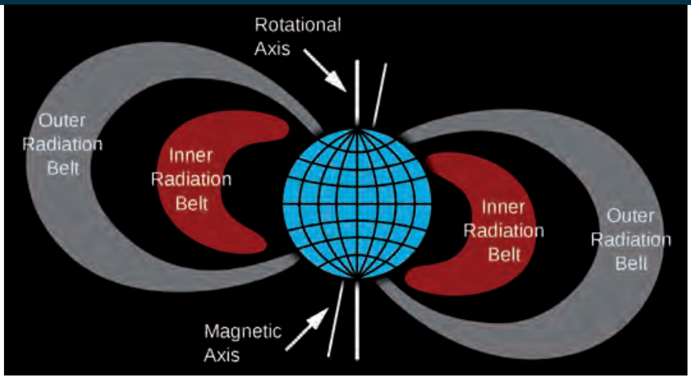
The availability of very sensitive photon detectors (photomultipliers, or PMTs) allowed for proving PMS Blackett's hypothesis that cosmic air showers produce Cherenkov light.
The British physicists W Galbraith and JV Jelley built the first very simple air Cherenkov counter using a rubbish bin. Working on cloudless nights, a mirror on the bottom of the bin focussed the incoming light on a PMT in front of the mirror.
But it would take 36 years before the Cherenkov telescope detected high-energy gamma rays from the Crab Nebula.

1954—1961
First generation of extensive air shower (EAS) arrays

In Britain an EAS array of 91 Geiger-Müller counters was built by TE Cranshaw and W Galbraith, covering an area of about 0.6km^2. It operated from 1954 to 1957 and measured primary energies of up to 10^{17}eV. At MIT, a group led by B Rossi developed a pioneering detector type. The fast timing of scintillation counters and PMTs allowed for the determination of shower direction and core position. Also the analysis techniques were the basis of future EAS experiments. Other strong activities were taking place in Japan and the Soviet Union.

1958
J Van Allen: Discovery of belts of radiation

Van Allen discovered with Geiger counters installed on the Explorer 1 and the Pioneer satellites that the Earth is surrounded by "clouds" of cosmic particles which are trapped by the Earth's magnetic field.



Van Allen belts surrounding the Earth

1957
Launch of Sputnik 2, with Geiger counter for cosmic particle detection

The era of space experiments started with Sputnik 2. With a Geiger-Müller counter built by Vernov's group (Moscow State University), the intensity of cosmic rays was measured from 3—9 Nov. A strong increase in radiation was measured at a latitude of 60°. Later, it would be interpreted as the outer radiation belt.

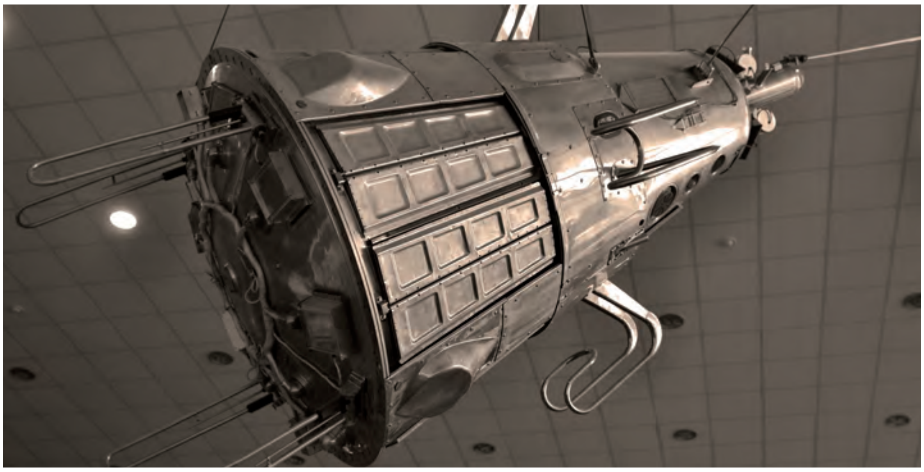
1958
E Parker: Theory of the solar wind

The solar wind was originally discovered by L Biermann in 1951. Parker was the first to develop a theory of how electrons and protons can escape from the surface of the sun to follow the field lines of the sun's magnetic field. The solar wind was first measured by the Luna 1 satellite on its way to the lunar fly-by.

1958
Launch of Sputnik 3

This was the first mission with several novel scientific instruments which collected data over a period of two years. Cosmic rays were measured with a scintillation counter and their nuclear components with a Cherenkov counter.

Sputnik 3



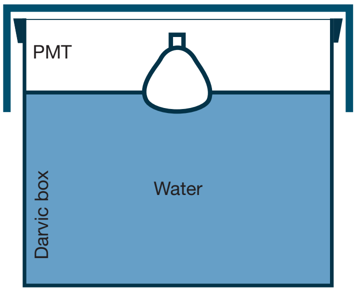


Illustration of the first water Cherenkov counter

1958
NA Porter: Prototype of a water Cherenkov detector

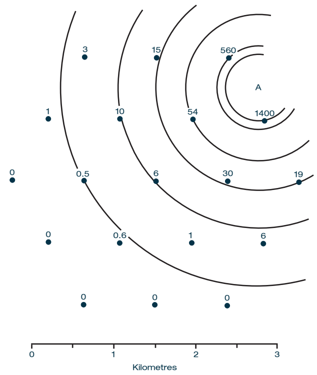
Not only was the air Cherenkov detector built in Britain, but so was the first water Cherenkov detector. NA Porter used a water-filled steel tank with a photomultiplier looking from the top into the water. Relativistic charged particles produce Cherenkov light in the water, which is measured by the PMT. The construction from 1958 is not so different from the design of modern water Cherenkov detectors at IceTop and the Pierre Auger Observatory.

1959
GV Kulikov/ GB Khristiansen: Discovery of the "knee" of the cosmic ray spectrum

With data from the Pamirs EAS and an earlier experiment, Kulikov and Khristiansen demonstrated that there is a change in the slope of the distribution of the number of particles per shower. They interpreted this discovery to mean that particles with energies greater than 10^{16}eV (corresponding to more than 10^{7} particles per shower) are probably of metagalactic origin, now known not to be true.

1959—1970 Discoveries





Left: Air Cherenkov light stereo telescope array; middle: J Linsley searching for snakes in a detector station; right: hexagon structure of the array with the position of the UHE event

1959—1964 Chudakov et al: First stereo Cherenkov telescope

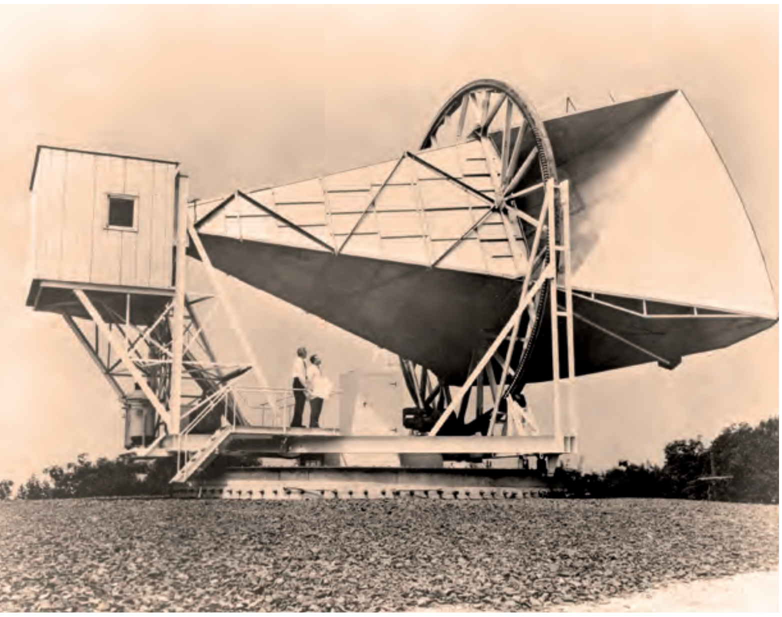
A stereoscopic Cherenkov telescope system was installed on the Crimean Peninsula to improve the sensitivity to and the reconstruction of the shower as well as the direction of the primary high-energy gamma. Twelve telescopes, each consisting of a container with a mirror and one photomultiplier, were installed on rails to vary the stereoscopic view. The sensitivity was low, but had they measured over several years, they might have been able to see the Crab Nebula.

1960 MA Markov: Proposal of high-energy cosmic neutrino detection

Markov proposed installing arrays of photomultipliers in deep lakes or in the sea to search for rare neutrino interactions. In about two-thirds of the interactions, a muon is produced which carries most of the energy and direction of the neutrino.
Relativistic muons produce in water Cherenkov light which is detected by PMTs.

1960—1963 Volcano Ranch EAS experiment

An array of 19 scintillation detectors ($3.26m^2$ each) operated in the configuration above (black dots in the schematic drawing) for three years at 1770m of altitude in New Mexico. It was the first experiment to measure air showers with energies greater than 10^{20}eV. The cosmic particle with the highest energy of 1.4×10^{20}eV (out of 5×10^{10} particles in the shower) was measured in February 1962. The experiment gave the earliest hint of a flattening of the energy spectrum at around 10^{20}eV.



1965 A Penzias and R Wilson: Discovery of the cosmic microwave background radiation (CMB)

The CMB radiation was detected by chance as Penzias and Wilson measured the background noise temperate of the Bell Labs horn-reflector antenna between July 1964 and April 1965. They found an excess temperature of 3.5°K which was isotropic, unpolarised and independent of seasonal variations. Dicke, Peebles, Roll and Wilkinson interpreted this effect as the cosmic microwave background radiation. The CMB is a relict of the early universe, which was a hot, dense plasma of photons and elementary particles. At that time, the temperature was about 3000°K, which cooled down due to the expansion of the universe.

Horn-reflector antenna

1965
Kolar Gold Field and Case-Witwatersrand-Irvine: Detection of atmospheric neutrinos

The first atmospheric neutrinos, decay products of pions or kaons produced in interactions of cosmic particles in the atmosphere, were detected by two groups. The Bombay-Osaka-Durham collaboration operated a visual detector in the Kolar Gold Field of India at a depth of 7500m water equivalent.
The Case-Witwatersrand-Irvine group worked in a South African gold mine at a depth of 8800m water equivalent. To reduce background muons, the detectors were set up to be triggered by horizontal muons.

1967—1987
Haverah Park: EAS cosmic particle array

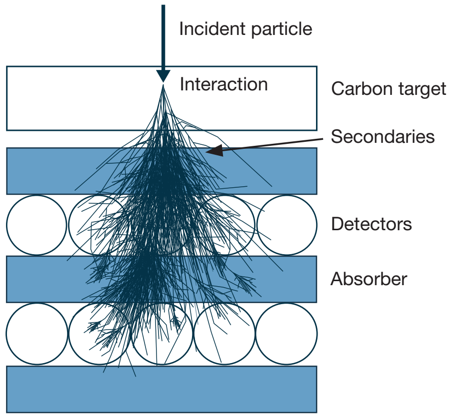
To study EAS showers with energies from 10^{15}eV to 10^{20}eV, a 12km^2 array of water Cherenkov counters was built and operated by the University of Leeds. For the first time, water Cherenkov counters were used. Together with Akeno in Japan, they found the “ankle” of the cosmic ray spectrum. The event with the highest energy was measured at 8.28×10^{19}eV.

1966
K Greisen and G Zatsepin, V Kuzmin: GZK cutoff energy for cosmic particles

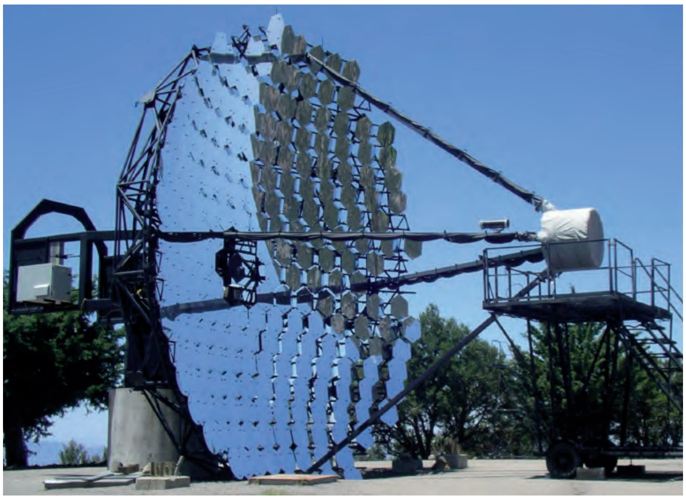
The prediction that the energy of cosmic particles from distant sources is limited to 5×10^{19}eV was made independently by Greisen and by Zatsepin and Kuzmin. Cosmic particles with higher energies interact with photons of the cosmic microwave background radiation before they reach the Earth.

1965—1968
Launches of Proton 1—4: Cosmic ray spectrum at 10^{11}—10^{15}eV

For the first time an ionisation calorimeter built by Moscow State University was installed in satellites. This allowed a direct measurement of cosmic particle spectra in the energy range of 10^{11}eV to 10^{15}eV below the “knee”.



Ionisation calorimeter



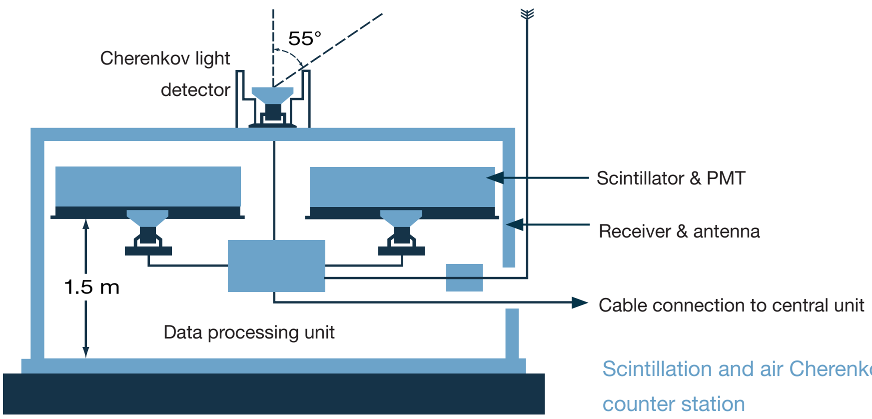
Whipple telescope

1968
Whipple collaboration: First 10m diameter Cherenkov telescope

The 10m mirror of the Whipple telescope was a new level of quality in the design of air Cherenkov detectors which is still state of the art. In the first years of operation, a single PMT measured the Cherenkov light.

1970
Yakutsk: EAS array in Siberia

Data-taking started in 1970 with a prototype array of 13 scintillation counter stations. The array was extended in the following years. In addition to scintillation counters, air Cherenkov and muon detectors were added. At 18km^2 it was at the time the largest, most complex array to measure the energy spectrum, the direction of primary particles and their mass composition in the energy range of 10^{17}eV to 10^{20}eV.

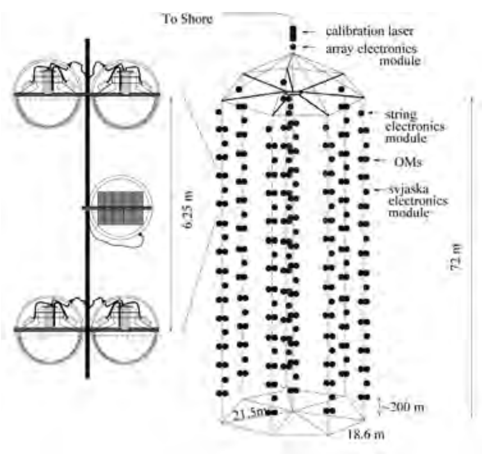


Scintillation and air Cherenkov counter station

1971—1995
New Technologies

1973—1991
Fly's Eye: First fluorescence detector array

Fluorescence light is produced when cosmic particle showers excite air molecules. The pioneering work was done by a group under K Greisen in the 1960s. Initial prototype detectors measuring air fluorescence light were built and tested by the University of Utah at the beginning of the 1970s. The Fly's Eye detector array was located in the desert of Utah at an altitude of about 1370m. With 67 detector units, each consisting of a container with a 1.5m mirror and a light collection system, the array was able to register on moonless nights fluorescence light over an area of about 1000km^2. In 1991 an event was detected with $(3.2 \pm 0.9) \times 10^{20}$eV, the highest energy ever measured.



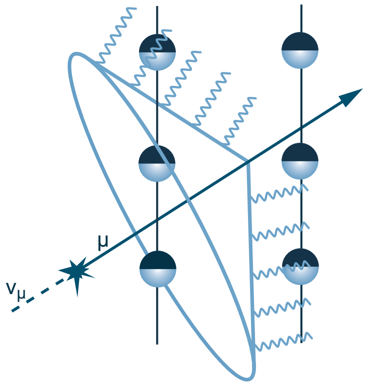
Baikal NT-200 detector

1978—1996
DUMAND project: Deep Underwater Muon and Neutrino Detector

Discussions about building DUMAND began in 1973. According to the 1978 proposal, one cubic kilometre of ocean was to be instrumented at a depth of 5km near the coast of Hawaii by about 23000 photomultiplier detectors. Neutrinos produce a muon in two-thirds of their very rare interactions. Relativistic muons produce in water Cherenkov light which is measured by PMTs. The arrival time allows for reconstructing the muon track. To disentangle the large amount of high-energy atmospheric muons from the muons produced in the few neutrino interactions, one looks for upward-going muons, as only neutrinos can traverse the Earth. The giant project failed for several reasons, but the almost 25 years of R&D were a very helpful basis for subsequent projects.

1984
Baikal neutrino project: First stationary string

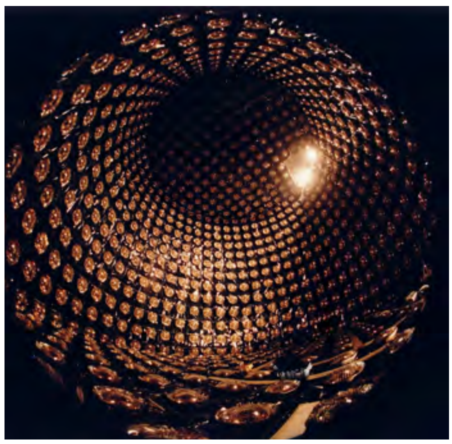
Lake Baikal in Siberia, with its clean water and stable ice in wintertime, was chosen for the installation of a water Cherenkov neutrino detector. The first string of PMT detectors, deployed at a depth of 1200m in 1984, measured atmospheric muons. Construction of the present NT-200 detector started at the end of the 1980s. An array of eight strings with 24 floors and 48 PMTs per string was planned. After several installation steps, NT-200 was completed in 1998. One of the first neutrino events with an upward-moving muon was detected in 1996.



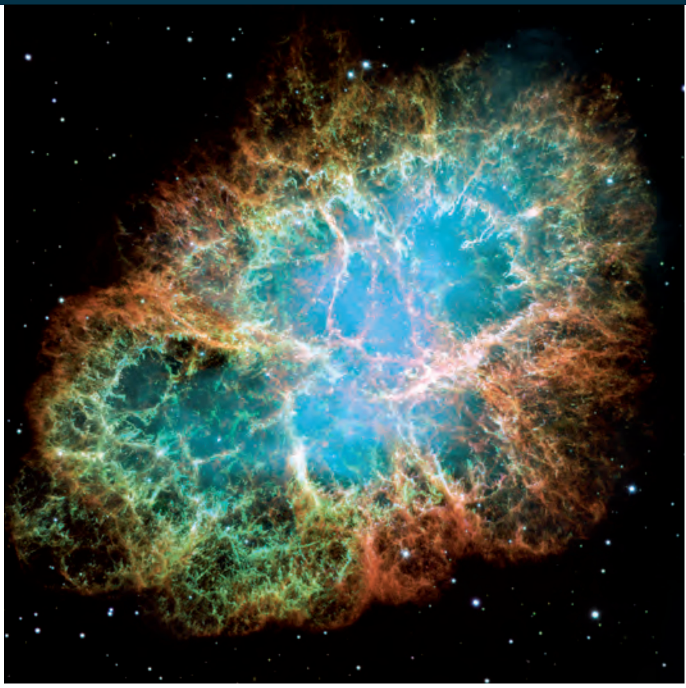
Muon detection through Cherenkov light

1987
Supernova 1987A: First detection of low-energy neutrinos

The neutrino window on the universe was opened by chance on 23 February 1987, when a supernova explosion in the Small Magellanic Cloud was discovered by optical telescopes. At the time several underground detectors were looking for proton decays in large volumes of water and in liquid scintillators. The data showed that three detectors observed an excess of events at the same time: the Japanese Kamiokande II detected 11 events within 13 seconds, the US IMB eight events within 6 seconds and the Soviet Union Baksan five events within 9 seconds from SN1987A.



Photomultipliers on the inner wall of Kamiokande II



1989
Whipple collaboration: Gamma rays from Crab Nebula

A telescope camera with 37 PMTs and an efficient analysis algorithm allowed a considerable reduction of hadronic background events. In 1989, more than 20 years after the Whipple telescope started to look for Cherenkov light flashes, the discovery of gamma rays from the Crab Nebula opened a new window into the sky: high-energy gamma astronomy.

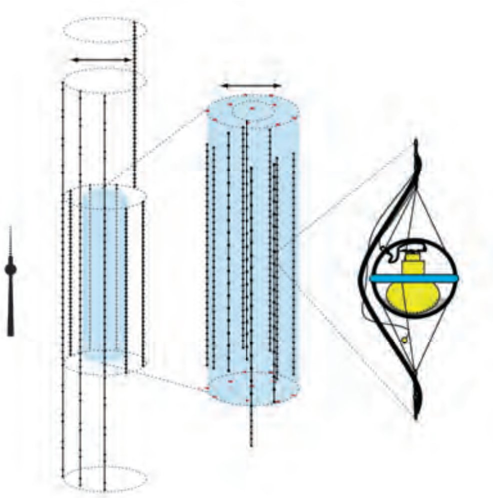
Crab Nebula

1993
AGASA: Highest-energy event

The Akeno Giant Air Shower Array (AGASA) operated in Japan from 1990—2004. It consisted of 111 scintillation and 27 muon detectors distributed over an area of $100 km^2$. The event with the highest energy of 2×10^{20}eV was measured in December 1993.
The particle shower was distributed over an area of $6 \times 6 km^2$. In total, 11 events with an energy greater than 10^{20}eV were detected; this did not show the decrease expected for the GZK effect observed in other experiments.

1993—2009
AMANDA neutrino detector

The first string of photomultiplier modules was installed in the ice at the South Pole in the austral summer of 1993—1994. The AMANDA detector collected data in the final configuration of 19 strings from 2000—2009. About 1000 muon-neutrino interactions per year were measured. However, the neutrinos were produced in pion decays in the atmosphere of the northern sky. No significant neutrino signal from a galactic or extragalactic point source was found.



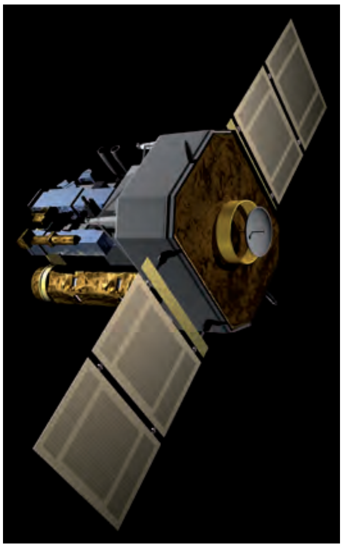
Schematic view of the 19-string AMANDA detector mostly installed at a depth of 1400m—2000m

1995
Detection of antiprotons in primary cosmic rays

In the 1970s, NASA began the exploration of primary cosmic rays with balloon experiments at very high altitudes. Particle detectors weighing more than 1000kg measured particle energies and the composition of the primaries, and searched for antimatter.
Three experiments launched in the early 1990s, IMAX, BESS and CAPRICE, published the discovery of antiprotons.

1995
Start of SOHO: Solar and Heliopheric Observatory

SOHO is a joint project of NASA and ESA to study the sun and the solar wind. Originally designed to operate for two years, it still provides important information about the structure of sunspots and the temperature profile and gas flow in the corona over a complete sun cycle of 11 years.
SOHO is also a very important detector for space weather, providing alerts in the case of sun bursts directed at the Earth.



SOHO satellite

1996—2012
Gamma-Ray Astronomy

H.E.S.S.: 4 telescopes in 2003, 5 in 2012

MAGIC: 1 telescope in 2004, 2 in 2009

VERITAS: 2 telescopes in 2006, 4 in 2008

1996—2010
KASCADE & KASCADE-Grande

With the KArlsruhe Shower Core and Array DEtector, a new generation of modern shower arrays came into operation. Some 252 stations, each consisting of four electron/gamma liquid scintillation counters and a muon counter, were arranged in an array of $200 \times 200 m^2$. In the centre a hadron and muon detector system with an active area of $320 m^2$ was installed. KASCADE was extended in 2003 by 37 scintillation counter stations to become KASCADE-Grande. This allowed the study of the composition of primary cosmic particles from 10^{15}eV to 10^{18}eV, covering the “knee” and the so-called “second knee”. An important contribution of the Karlsruhe group is the development of the CORSIKA simulation programme for cosmic air showers, which is used worldwide by all experimental astroparticle physics groups.

KASCADE detector array

1997—2006
HiRes

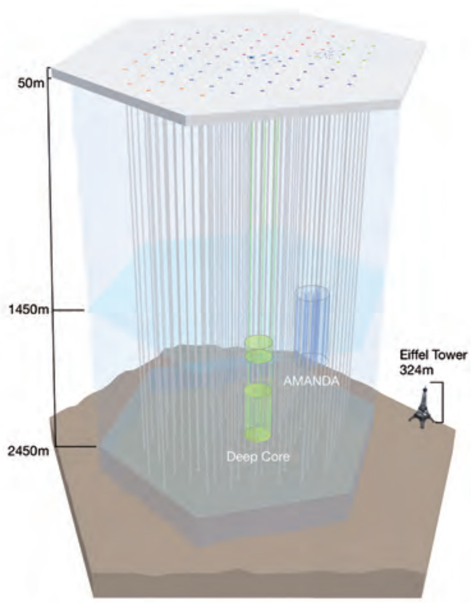
The High Resolution air fluorescence experiment, known as HiRes, replaced the first-generation Fly’s Eye detectors in Utah. With smaller photomultipliers and an improved data acquisition system, a higher sensitivity could be reached in order to determine the energy, direction and chemical composition of the highest-energy cosmic rays. At energies greater than 5×10^{19}eV, the decrease in the measured particle flux is in agreement with the expectations of the GZK effect.

2002
Third generation of Cherenkov telescopes

The success story of high-energy gamma astronomy began with the operation of the new generation of air Cherenkov telescopes: H.E.S.S. in Namibia, MAGIC in La Palma and VERITAS in Arizona.

2004
IceCube & IceTop

From 2004—2010, the giant IceCube Neutrino Observatory was built at the South Pole. Some 86 strings with digital optical modules were installed to survey one cubic kilometre of ice to depths of 1450m to 2450m. Every hour about 10 up-going muons from neutrino interactions near the detector and about 7 million down-going atmospheric muons are reconstructed by measuring the Cherenkov light.
In addition, 81 pairs of IceTop tanks are installed on the surface to investigate air showers in the “knee” energy region.
In the data analysed so far, no neutrinos have been observed from point sources. All the neutrinos measured since 2005 were produced in the northern atmosphere.

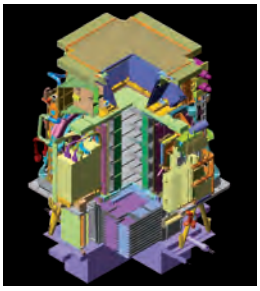


IceCube detector

2004
Pierre Auger Observatory

The largest extensive air shower array was constructed as the first true hybrid observatory. It comprises 1600 water Cherenkov detectors distributed on a grid of 1.5km over an area of 3000km^2, and 27 air fluorescence telescopes erected at four stations on the periphery of the observatory. Important results include the exploration of the ultra-high-energy area with a cut-off as expected from the GZK effect; the particle composition; and a first hint of the extragalactic origin of the highest-energy cosmic particles.

One of the air fluorescence light detector stations on the hill and a water Cherenkov tank on the right



Schematic view of the PAMELA detector

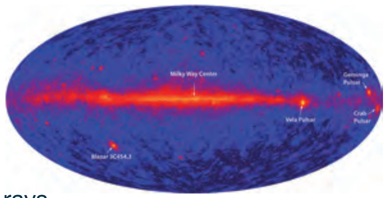
2006 PAMELA mission

The Italian-Russian satellite was launched with the goal of antimatter-matter exploration in primary cosmic rays. PAMELA measured an unexpected increase in the positron fraction at energies between 10^{10}eV and 10^{11}eV which was later established by Fermi LAT at even higher energies. Further investigations will answer whether this effect opens a window on a “new physics”.

2008
Telescope Array

The Telescope Array project in Utah combines the successful tradition of Fly’s Eye and HiRes air fluorescence shower detection with a ground array of scintillator counters distributed over an area of about 500km^2. The experiment is complemented by a low-energy extension. Both the particle flux and composition can be studied for primary particle energies above 3×10^{16}eV.

2008
Fermi Large Area Telescope and Burst Monitor

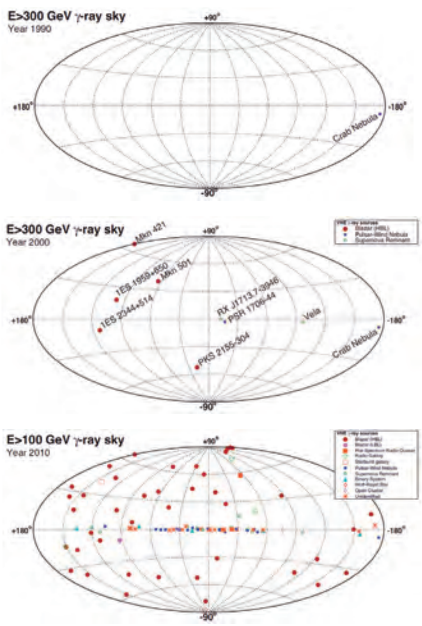


Fermi LAT all-sky view

The Fermi satellite carries two experiments, the Large Area Telescope (LAT) to measure high-energy gamma rays up to energies of 10^{11}eV and the GLAST Monitor for the detection of gamma-ray bursts. The high sensitivity of both instruments allowed the detection of many new galactic and extragalactic gamma-ray sources (with LAT) and gamma-ray bursts (with GLAST). With the LAT electromagnetic calorimeter, the electron flux was measured up to energies of 10^{12}eV. For positrons, the energy range from 2×10^{10}eV to 2×10^{11}eV was investigated and an increase in the positron fraction observed.

2010
Evolution of the gamma-ray sky

The progress of very high-energy gamma-ray astronomy with ground-based air Cherenkov telescopes over the last two decades can be seen in the sky plots of detected sources. With the second-generation Whipple telescope, one source, the Crab Nebula, was observed until 1990. Ten years later, Whipple and HEGRA had seen nine sources. And from 2003—2010, the third-generation telescopes H.E.S.S., MAGIC and VERITAS detected about 110 gamma sources.



2011
Launch of the Antimatter-Matter Spectrometer

The AMS cosmic particle spectrometer installed at the International Space Station was designed to search for cosmic particles and antiparticles up to energies of 10^{12}eV. A further goal is the indirect search for dark matter.

To search for possible anti-matter concentrations in the universe predicted by some theories, the sensitivity for measuring the anti-helium/helium fraction was improved by a factor of 1000.

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1900 Elster and Geitel in their private lab
Archive R Fricke, Wolfenbüttel
1902 The Phoenix balloon (Berlin) in 1894, drawn by H Groß
R Assmann et al, editors, Wissenschaftliche Luftfahrten, Vieweg Verlag, Braunschweig 1899
1908 Theodor Wulf
Archiv der Deutschen Provinz der Jesuiten, Kaulbachstrasse 31a, 80539 Munich
1908 Two-string electrometer designed by Wulf
Archive R Fricke, Wolfenbüttel
1909 Albert Gockel
Archive University of Fribourg, Switzerland
1909 Karl Bergwitz
Archive R Fricke, Wolfenbüttel
1910 Domenico Pacini with an electrometer
A De Angelis, University of Udine, Italy
1911 Original Wilson cloud chamber
Cavendish Museum of the Department of Physics, Cavendish Laboratory
1911 VF Hess in his lab in 1915
VF Hess Society, Schloss Pöllau/Austria
1911 Victor F Hess in the balloon's basket sometime between 1911 and 1912
VF Hess Society, Schloss Pöllau/Austria
1912 Seven flight routes of VF Hess in 1912
DESY*
1912 Electrometer used by VF Hess in 1912
VF Hess Society, Schloss Pöllau/Austria
1912 Mean values of all measurements during the seven flights at different altitudes
VF Hess, Physikalische Zeitschrift 13, 1084 1912
1913 W Kolhörster (at back centre) in 1913
Archive R Fricke, Wolfenbüttel
1914 Ionisation measured by VF Hess and W Kolhörster, as dependent on altitude
DESY*
1915 E von Schweidler
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1926 RA Millikan and GH Cameron in 1925
Sekido, Yataro and H Elliot, editors. 1985. Early History of Cosmic Ray Studies. D Reidel Publishing Company, Dordrecht
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Original: Myssowski, Tuwim, Phys Zeitschrift 39, 146 1926*
1927 D Skobeltsyn in his laboratory in Leningrad
Skobeltsyn Institute of Nuclear Physics, Moscow State University
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1928 Absorber experiment with Geiger-Müller counters C1 and C2 in coincidence
Original: W Bothe, W Kolhörster, Naturwissenschaften 16, 1045 1928*
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1930 The relative cosmic particle intensity as a function of geomagnetic latitude
D Montgomery, Cosmic Ray Physics, Princeton University Press, Princeton, New Jersey 1949
1931 B Rossi (middle) in Eritrea
Archive INFN Padua
1931 Geiger-Müller counter telescope
Archive INFN Padua
1932 A positron with an energy of 63MeV entering the lead plate from below
W Gentner, H Maier-Leibnitz and W Bothe, An atlas of typical expansion chamber photographs, Pergamon Press, London 1954
1933 Cloud chamber photograph of a particle shower with about 16 tracks
W Gentner, H Maier-Leibnitz and W Bothe, An atlas of typical expansion chamber photographs, Pergamon Press, London 1954
1935 H Yukawa, 1949
Yukawa Hall Archival Library of YITP, Kyoto University
1936 Photograph of a cloud chamber exposure
W Gentner, H Maier-Leibnitz and W Bothe, An atlas of typical expansion chamber photographs, Pergamon Press, London 1954
1937 A "star" produced in a photo emulsion by a cosmic particle
M Blau, H Wambacher, Nature 140, 585 1937
1947 The pion event identified by Perkins
DH Perkins, Nature 159, 126 1947
1947 The first edition of the biennial International Cosmic Ray Conference
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DESY*
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Archive Harwell Atomic Energy Research Establishment
1958 Van Allen belts surrounding the Earth
http://en.wikipedia.org/wiki/ File: Van_Allen_radiation_belt.svg
1958 Sputnik 3
Skobeltsyn Institute of Nuclear Physics, Moscow State University
1958 Illustration of the first water Cherenkov counter*
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1959 Air Cherenkov light stereo telescope array
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1984 Baikal NT-200 detector
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1987 Photomultipliers on the inner wall of Kamiokande II
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1989 Crab Nebula
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1993 Schematic view of the 19-string AMANDA detector
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1995 SOHO satellite
NASA
1996 KASCADE detector array
KIT
2002 H.E.S.S.: 4 telescopes in 2003, 5 in 2012
H.E.S.S. collaboration
2002 MAGIC: 1 telescope in 2004, 2 in 2009
MAGIC collaboration
2002 VERITAS: 2 telescopes in 2006, 4 in 2008
VERITAS collaboration
2004 IceCube detector
IceCube collaboration
2004 One of the air fluorescence light detector stations
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2006 Schematic view of the PAMELA detector
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2008 Fermi LAT all-sky view
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2010 The progress of very high-energy gamma-ray astronomy
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*Recreated by Susann Niedworok/Christine Iezzi, DESY

DESY

ASPERA

Durham University

NETZWERK TEILCHENWELT

Milestones:
100 Years of Cosmic Rays

1900 — 1911
Period of pre-discovery and the search for the origin of penetrating radiation

1912
Discovery of cosmic rays by Victor F Hess

1913 — 1926
Time of uncertainty: confirmation, refusal and confirmation of cosmic radiation

1926 — 1933
Investigation of the properties: from cosmic rays to cosmic particles

1933 — 1947
Birth of particle physics

1947 — 1959
First ground-based extensive air shower and space experiments

1959 — 1970
Discovery of the cosmic microwave background, atmospheric neutrinos and ultra-high-energy events

1971 — 1995
Development of new technologies to search for ultra-high-energy events, cosmic neutrinos and high-energy gamma rays

1996 — 2012
Successful exploration of the high-energy gamma-ray sky as well as the building of giant extensive air shower and neutrino observatories