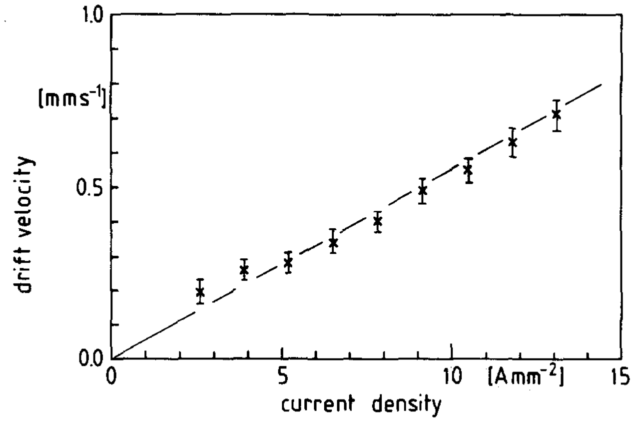

Fig. 2. Drift velocity versus current density in copper.

minals is zero. While turning the magnetic field on, the amplifier must be protected from damage by the large induced emf by closing switch *S*.

With the gear motor moving the Hall specimen in the correct direction, the voltage will decrease and reach zero at about 0.7 mm/s, the drift velocity in copper.

The drift velocity depends upon the strength of the electric field inside the metal. Figure 2 shows the change in drift velocity from 0.3 to 0.6 mm/s$^{-1}$ with a change in current from 5 to 10 A while the carrier mobility remains constant. With a current density of 10 A/mm$^{-2}$ in Sb a drift velocity of $-0.5$ mm/s$^{-1}$ could be observed. Here the drift motion is opposite to that in copper due to the fact that in Sb the majority carriers are "holes."

## DISCUSSION OF RESULTS

The experiment can be explained from two different points of view leading to the same quantitative description according to the principle of relativity in electromagnetic induction.

Let us consider the case where the Hall voltage is exactly compensated, e.g., zero.

In a frame of reference attached to the Hall specimen the magnetic field flux through the circuit formed by specimen, Hall contacts and leads to the voltmeter changes. This gives rise to an induced voltage and hence a Coulomb force which is equal and exactly opposite to the Lorentz force acting on the drifting electrons. The induced voltage thus compensates the Hall voltage.

In a frame of reference attached to the magnet, no Hall voltage will be generated as the electrons are on average at rest with respect to the magnetic field and the mean Lorentz force is zero.

## ACKNOWLEDGMENTS

I am greatly indepted to Professor H. Happ who while reading through old notes on demonstration experiments came across this convincing demonstration, to Professor G. Dietz and Dr. T. Pauls for helpful discussions and for reading the manuscript, to Mrs. T. Becker for the reproductions and to Mrs. R. Küpper for the drawings and her help during the measurements.

[1] J. Jaumann died on 15 June 1971 at the age of 69.

---

# The early history of cosmic ray research

Qiaozhen Xu[a] and Laurie M. Brown
*Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60201*

(Received 22 May 1985; accepted for publication 11 February 1986)

We review the prehistory and early history of cosmic ray studies, concentrating on the period 1900–1927. Following the discoveries of the electron and radioactivity just before the turn of the century, the old problem of leakage of charge from a conductor in air was investigated in terms of the new concept of ionization and ionizing radiation, part of which was found to be highly penetrating and to be of extraterrestrial origin. At first supposed to consist only of ultrahigh energy gamma rays, the cosmic ray primaries are now known to be mainly charged particles. The modern period of cosmic ray research began in 1927, when individual particles were studied by cloud-chamber and coincidence counting techniques.

## I. INTRODUCTION

The discovery and exploration of the cosmic rays are heroic chapters in the history of modern physics. The exploration sometimes required adventurous journeys and arduous exertions, involving descents into caves and mines, sea voyages, mountain ascents, balloon flights, etc. The results were no less heroic, yielding profound geophysical and astrophysical insights and initiating such fields as elementary particle physics and high-energy nuclear physics. Begun as a study of the distribution in land, sea, and atmosphere of the sources of the mysterious invisible radiations that seemed inescapable, cosmic ray research gradually revealed the wealth of particles that populate the tiniest portions of space as well as providing a window on the most remote regions of space and time.

The cosmic rays are responsible for a fraction of the small electrical conductivity of the atmosphere observed during fine weather, even at low altitudes. The conductivity of the air, as measured by the rate of discharge of an electroscope, was studied as a part of atmospheric physics (meteorology) from about 1900. At that time, only a few years after the discovery of radioactivity, it was believed that the air's conductivity was due to ions produced by radioactivity in the Earth's crust, and that the "residual ionization" found later at heights above the ground (e.g., on the Eiffel Tower), or above glaciers or on the sea, was due to radioactive emanations mixed with the air. However, balloon flights carried out between 1909 and 1914 showed a large systematic increase in ionization with altitude (on the scale of kilometers), which strongly suggested that an ionizing radiation came down from above and was gradually absorbed by the atmosphere. Beginning about 1926, this radiation was considered well established (even by the most skeptical scientists) and was called by the name "cosmic rays." The present article deals with the history of the cosmic rays up to that date.

## II. THE DISCOVERY OF IONS IN THE ATMOSPHERE

In 1785, Charles Coulomb showed that a charged metallic conducting body, placed in the air, gradually loses its charge. That was probably the first reported observation of electrical conduction in the atmosphere in fine weather. After the passage of more than a century, the cause of the air's conductivity was still regarded as an unsolved mystery. We should emphasize that we are concerned with extremely delicate effects, involving only a few ion pairs in a macroscopic volume of air, and that the techniques of observation (which will not be discussed in detail) were being developed at the same time as the observations themselves were being made. Therefore, it is not surprising that there was a considerable measure of disagreement in the pioneering investigations.

Joseph John Thomson, the discoverer of the electron, began to investigate the electrical conductivity of gases at Cambridge University in the early 1880s, applying high voltage from a spark coil to a gas discharge tube. Between 1886 and 1896 he published about ten articles in the *Proceedings of the Royal Society of London*. In his papers, he introduced new terminology: a "polarized molecule" splits into a "positive atom" and a "negative atom."[1] In an 1895 paper entitled "On the Electrolysis of Gases," he began to speak of "ions" in the gas.[2] Beginning in 1896, thus soon after the discovery of x rays, Thomson was using the new radiation to create ions in the air in his apparatus. In 1906, Thomson received the Nobel Prize in Physics "in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases." That was how the citation described his pathbreaking discovery of the electron![3]

Between 1896 and 1899, Thomson's student, Charles Thomson Rees Wilson published four articles on the effects of x rays on the nucleation of small "clouds" in the laboratory. In his paper "On the Condensation Nuclei Produced in Gases by the Action of Roentgen Rays, Uranium Rays, Ultra-violet Light, and other Agents," Wilson emphasized the difference "between 'ions' and nuclei which carry no charge of electricity."[4] One of his findings was that negative ions have a greater efficiency than positives in nucleating cloud formation.[5] During those years, he studied meteorological effects, and to continue those studies he invented the "cloud chamber," which was later used to observe the tracks of fast charged particles, including those of the cosmic rays.

The German scientists Julius Elster and Hans Geitel formed an interesting research team. Having been friends already in high school, they both became teachers at the Gymnasium in Wolfenbüttel. According to Abraham Pais, "When Elster married and had a house built, Geitel moved in with the young couple and together the two friends built a laboratory in the new home. Here they started their research (often financed from their own pockets) which were to make them internationally renowned. They experimented on photoelectric effects, on spectroscopy, on the conduction of electricity through gases, and especially on atmospheric electricity. These last experiments led to their classic work on the radioactivity of the atmosphere."[6] Pais's article describes their efforts to find an external source for the energy of radioactive substances.

In Thomson's book of 1906 on gas conduction, he wrote:

> In May of 1900, Elster and Geitel...noticed that an electrified body gradually lost its charge...They found that the rate of leak varied,...that it was very much smaller in mist or fog than when the weather was bright and clear, that it was greater at high altitudes than at low ones, and that on the tops of mountains the rate of escape of negative electricity was much greater than that of positive. In plains, they found the rate of leak to be the same for plus and minus charges. They concluded that free ions existed in the atmosphere.[7]

The results of Elster and Geitel were in agreement with some earlier experiments of F. Linss.[8] They did not speculate on a possible origin of the atmospheric ions.

Six months after Elster and Geitel, Wilson reported on experiments done "in a small closed vessel containing dust-free air not exposed to any known ionizing agents," and concluded that the air was a conductor of electricity, the rate of leakage of charge being independent of the sign and proportional to the pressure. A saturation current was produced when the potential was either 120 or 210 V. Its value was taken to measure the ionization, and in this way he estimated that at atmospheric pressure 10 ion pairs were produced per second per cc of air (later revised by him to 14).[9]

In 1903, Canadian physicists John Cunningham McLennan and Eli Franklin Burton tried to relate the conductivity of the air to the thorium emanation that Ernest Rutherford had recently observed. They argued that air is continually ionized, as shown by its weak electrical conductivity, and so "one is forced to conclude there is present in the air an emanation possessing properties similar to that emitted by the thorium compounds."[10]

Wilson also speculated that "some radioactive substance in the atmosphere ...is carried down in the rain."[11] These physicists, then, discovered and named the "ions" in the atmosphere, introduced the term "ionization," and tried to relate it to the radioactivity of the Earth.[12]

## III. EXPERIMENTS ON THE CONDUCTIVITY OF THE ATMOSPHERE

After the discovery of ions in the atmosphere, physicists carried out numerous experiments on aspects of this phenomenon, some out of mere curiosity without any apparent aim, but most of them trying to explore the unknown origin of the ions.

### A. Experiments with vessels of various materials

In 1902, McLennan and Burton made a series of observations on atmospheric air confined in air-tight vessels of different metals, concluding that, "the effects observed would seem to indicate that all metals in varying degree are the sources of a marked though feeble radioactive emanation."[13] Robert John Strutt also reported, "...there are very marked differences in the rate of the leak, when different materials constitute the walls of the vessel." As a result, he said: "There can therefore, be little doubt that the greater part–if not the whole–of the observed ionization of air is not spontaneous at all, but due to Becquerel rays from the vessel."[14]

### B. Experiments with different temperatures and pressures

J. Patterson wrote in 1902 that at constant atmospheric pressure, the conductivity of the air was constant over temperatures ranging from room temperature to 500 °C, and for pressures down to 1/3 atmosphere; for lower pressures it was proportional to the pressure.[15] Wilson found a similar pressure dependence, and wrote that "The falling off from this law at the higher pressures might be taken as indicating that the ionization is due to radiation from the walls of only moderate penetrating power."[16] G. Jaffe, however, found not a simple proportionality of conductivity with pressure, but the linear relation $y = ap + b$, arguing, "This fact seems to indicate that the ionization is (at least partly) due to a radiation from the walls which is not of uniform-type. On this supposition the term $b$ would correspond to a very weak radiation, which is perfectly absorbed by as little as 3 cm of air at 1/5 of an atmosphere pressure."[17] These authors therefore attributed the air's conductivity to local sources.

### C. Experiments concerning periodicity

From 1903 to 1904, George C. Simpson made a very complete series of observations on the diurnal and annual variations of the potential gradient, ionization, and dissipation within the Arctic Circle, at Karasjok in Norway at latitude 69° North, on which he wrote a summary in 1905. In his report entitled "Atmospheric electricity in high latitudes," he wrote, "The daily period of the ionization is not so pronounced as that of the dissipation, but the ionization is slightly lower in the evening than in the morning or at midday during the whole year...temperature has a great effect on the ionization while no effect of temperature on the ratio $[I_+/I_-]$ is apparent." And he also pointed out, "The value of the ratio $I_+/I_-$ shows a very distinct yearly period with a maximum in the winter and a minimum during the summer." About the ionization, he wrote "during the summer we have six months' fall from August to February followed by a similar six months' linear rise from Feb. to Aug..."[18]

In 1906 and 1907 Alexander Wood, working with Norman R. Campbell also claimed to have detected a diurnal periodicity in the ionization of gases in closed vessels, having two maxima and two minima per day,[19] a result confirmed by T. Frederick McKeon.[20]

### D. Experiments with shielding

Some of the earliest and most significant experiments on shielding were done by Rutherford and H. Lester Cooke, who motivated their experiments with these comments: "Since the excited activity obtained from the atmosphere is very similar in character to the excited radiations from thorium and radium, it was thought possible that some penetrating rays might be given off from the surface of the earth and walls and rooms on which excited activity from the air is distributed. In order to test this point, the amount of ionization was observed in testing vessels of about 1 liter capacity.... The effect of placing metal screens outside the testing vessel was observed." They found little effect on the rate of discharge from a 2 mm thickness of lead placed around their apparatus, but 5 cm of lead cut down the discharge rate by 30%. Beyond 5 cm of lead, they found no effect, although 5 tons of pig lead was placed around the apparatus. On removing the screens, the discharge returned to the original value. They concluded that their results showed that "about 30% of the ionization inside a closed vessel is due to an external radiation of great penetrating power." They claimed that "these effects could not be due to the presence of thorium or radium in the laboratory, for similar results were observed in the library which was free from all possible contamination by radioactive substances."[21]

In order to determine whether the radioactive emanation was given off by the walls of the containing vessel, McLennan and Burton also did a screening experiment. They reported, "The heavy cylinder was filled with air to a pressure of about 400 cm Hg, and allowed to stand until its conductivity had become steady. It was then placed in an insulated galvanized iron tank which was gradually filled with water so as to surround the cylinder with a layer 25 cm in thickness. The initial conductivity before the water was admitted was 21.1. As the water rose, the conductivity decreased and fell to 13.3, when the tank had been filled. The values for the conductivity...show that the loss was almost directly proportional to the rise of the water. The total fall in conductivity was about 37%." "From these results," they arrived at the conclusion that "it is evident that the ordinary air of a room is traversed by an exceedingly penetrating radiation."[22] They made that important observation as early as 1902.

### E. Experiments at different localities

Aside from experiments carried out in laboratories, physicists made experiments at different kinds of localities such as in caves, on the sea, on lakes, etc. In 1903, Elster and Geitel, experimenting in caves, observed the interesting phenomenon that the rate of leak in caves and cellars, where the air was stagnant and only renewed slowly, was much greater than in the open air. They found that in a cave, the electric charge leaked off at seven times the rate it did in the outside air, even when it was clear and free of mist. They also found that in a cellar whose windows had been shut for eight days, the rate of leak was considerably greater than it was in the outside air.[23]

Arthur S. Eve had speculated in 1907 that the ionization over the ocean should be less than that over land, for "experimental evidence...indicates that radium is present in seawater to a markedly less degree than in the sedimentary rocks on land. And, since radium emanation decays to half value in four days, the wind is unable to transport the emanation from land to places in mid-ocean before the activity is decreased." Eve did not obtain the result he expected, so he suggested that "The ionization observed is larger than would be anticipated from such a cause (wind carrying radium emanation from land to sea), but it is possible that the rate of recombination of ions over the sea may be less than over the land."[24]

C. S. Wright considered lake water to be a very efficient shield for the Earth's radiation, stating, "that the water of Lake Ontario acts as a perfect screen both for the earth's radiation and, if a sufficient depth be taken, for the gamma rays from radium. On this account and owing to the fact that the water of Lake Ontario contains no active impurity, it has been possible to determine what portion of the ionization in the receivers used in this investigation was due to residual active impurities and to intrinsic activity in the metals of the receivers." By this method, he determined that the ionization due to radioactive impurities in clay soil was about 1 ion per cc per s.[25]

### F. Conclusions

During the first years of the present century, physicists primarily working on radioactivity, as well as those engaged in atmospheric science, became aware that the electrical conductivity of the air in fine weather (or alternatively, of gases in closed vessels) was an indicator of the presence of invisible high-energy radiation and they did numerous experiments to study its properties and determine its sources. In summarizing those experiments, Rutherford concluded in 1905, "It is now certain that a large part of the ionization observed in a clean metal vessel results from the emission of ionizing radiations from its walls. A part is due to a very penetrating radiation of the gamma ray type which is everywhere present on the surface of the earth." He noted further that "In most cases the ionization falls off nearly proportionally with the pressure, and is approximately proportional to the density of the gas. Both of these results are to be expected if the ionization observed is due to radiations from the walls or to a penetrating type of radiation passing from the outside through the material of the vessel."[26]

In the same year, Eve wrote that "the natural ionization of the air at the surface of the earth" has obvious causes; namely, "the only ionizing agents under such conditions are (1) radiation due to radioactive matter contained in the air, (2) radiations due to active matter on the surface, or in the material of the sides of the vessel, (3) penetrating radiation through the sides of the vessel, due to radioactive matter in the surrounding bodies."[27]

## IV. TENTATIVE SUGGESTIONS OF AN EXTRATERRESTRIAL SOURCE

Robert Andrews Millikan, in a popular book of 1935 surveying particle and cosmic ray physics, stated that "Apart from a passing suggestion of Richardson in 1906,.... I can find no record of the existence anywhere up to 1910 of any ideas even remotely related to those that are now associated with the term 'cosmic rays'."[28] Millikan's statement is not really accurate, for an extraterrestrial source was considered by several scientists, in the early years of the century, as the cause of atmospheric ionization and the Earth's negative electrical potential.

In 1901 Wilson tried "to test whether the continuous production of ions in dust-free air could be explained as being due to radiation from sources outside our atmosphere, possibly radiation like Röntgen rays or like cathode rays, but of enormously greater penetrating power." He carried out experiments in tunnels, but finding no evidence of any decrease in the rate of ionization, no matter how much solid rock was overhead, he concluded: "It is unlikely, therefore, that the ionization is due to radiation which has traversed our atmosphere; it seems to be, as Geitel concludes, a property of the air itself."[29] In 1902, he boiled down freshly collected rainwater and found the dry residue to be radioactive. He also found that "The radioactivity obtained by the evaporation of rain disappears in the course of a few hours, falling to half its initial value in one hour."[30] The same results were obtained from the evaporation of freshly fallen snow.[31] These experiments did not, however, suggest the origin of the radioactivity, and the possibility of an extraterrestrial source remained in his mind.

In 1903, in discussing experiments of Philipp von Lenard, Wilson suggested that sunlight ionizes the air, "especially in the upper atmosphere, while it is still strong in ultraviolet rays."[32] And considering ionized layers of the atmosphere nearer the ground, he wrote, "It is quite conceivable that we may be driven to seek an extraterrestrial source for the negative charge of the earth's surface."[33]

The connection between the source of the air's conductivity and the Earth's electric charge was also considered by Simpson, who stated in 1904: "If we take for granted that the sun continually emits Becquerel rays consisting of positive and negative electrons, one would expect the following to be the consequence. Some of the electrons which reach the earth's atmosphere will be absorbed–probably mainly by the water vapour and dust in the lower atmosphere–but according to Rutherford's experiments more positive than negative; thus we may expect a greater number of negative electrons to reach the surface, a corresponding number of positive electrons being held back by the air. We at once see a cause for the positive charge of the air and the corresponding negative charge on the surface."[34] (The reference here to "positive electrons" is not prescience; it merely refers to the positive unit charge.)

Pursuing the same issue in 1906, Wilson said: "If the existence of a penetrating radiation from cosmical sources were established it would be of the greatest importance in connection with atmospheric electricity. For it would open the question as to whether the negative charge of the earth might not be supplied by these rays. At present I think it is much more likely that precipitation will prove to be a sufficient source."[35] As Millikan acknowledged, Owen W. Richardson also considered the possibility of an external radiation source. He said it could account for a reported diurnal variation in both the Earth's electric field and the conductivity of enclosed air, and he speculated, "In the case of the earth the ionizing rays presumably come from extraterrestrial sources, and will be absorbed to some extent by the earth's atmosphere. They will therefore be more intense further away from the earth's surface,..."[36]

In 1909, a review by Karl Kurz also ruled out radioactive matter in the Earth's crust as an effective ionizing agent at high altitudes because of the absorption of the air, and noting that the conductivity of the air at high altitude is of the same order of magnitude as at the Earth's surface, asked, "What ionizing agent compensates the lack of penetrating radiation from below? Is there perhaps, after all, an ionizing radiation from outside the atmosphere? It could be of such strength and absorbability that it would be without effect in the lower atmosphere... ."[37]

He mentioned preparations at Munich for studies on balloon flights during the forthcoming International Balloon Week in December 1909.

## V. FIRST OBSERVATIONS ON IONS IN THE ATMOSPHERE AT DIFFERENT ALTITUDES

Typical experiments on atmospheric ionization studied the rate of discharge of a charged object at different heights above the ground. If the penetrating radiation present at the surface of the Earth were entirely of terrestrial origin, one should detect a diminution in the intensity of this radiation even at moderate distances above the Earth's surface. The altitude dependence was studied, more or less simultaneously, by carrying apparatus to towers and mountain tops or aloft in balloons.

### A. Observations on mountains and towers

In May of 1900, Elster and Geitel found that the rate of leak of electrical charge was greater at high altitudes than at low ones. They compared the effect at sea level and up to 3000 m on the tops of mountains; they reported their observations, but drew no conclusions.[38]

In 1909, Theodor Wulf, of Ignatius College in Valkenburg, Holland, greatly improved the electroscope, replacing the gold leaves with two slender metal wires held, under tension by a light quartz fiber. When charged, the two wires repelled each other and the separation was measured by means of a microscope.[39] This kind of sensitive electroscope was used in later experiments, including those of Hess and Millikan. (See Fig. 1.)

Karl Bergwitz had reported a large decrease of ionization with height, but observations by Albert Gockel contradicted this (see below).[40] On the basis of these balloon results, Wulf decided to make measurements at the top of a tower, since he was skeptical about getting accurate readings in a balloon. The balloon was moving, changed location, and could be influenced by clouds and rain.

In March and April of 1910, Wulf made four measurements with his new sensitive electroscope on the Eiffel Tower in Paris. After substracting the chamber background, he found that six ions were produced per cc per second by the radiation at the surface of the Earth, while at 300 m on top of the tower the number was 3.5. The intensity of ionization was thus reduced to 60% at the top, not what he had expected. According to Wulf's calculation, at 80 m the gamma rays should already reduce to half their value on the ground, and at 300 m it should be only a few percent of the value on the ground. Therefore, Wulf concluded, "either another source of gamma-rays exists in the upper layers of the atmosphere, or the absorption coefficent of gamma-rays in air is apparently smaller than has been assumed."[41]

In 1911, McLennan and E. N. Macallum of Toronto tried to check values calculated by Eve on the effect of altitude in the intensity of the gamma rays from RaC present in the Earth,[42] measuring the ionization on the ground and on buildings at different heights. They found that the ionization at the top of a tower "was only about 48% of the effect produced by similar radiations on the university lawn," in agreement with Eve's calculations.[43]

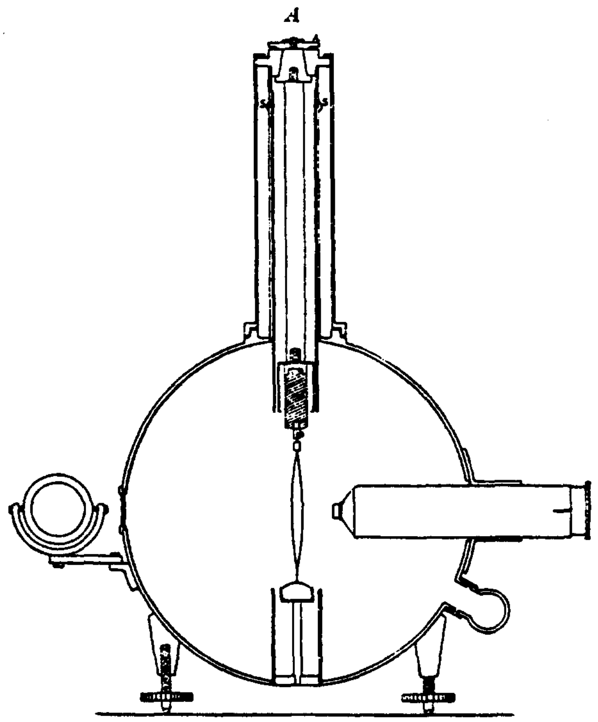

Fig. 1. Electroscope developed by Wulf in 1909.

### B. Balloon flight observations

Hermann Ebert made three balloon flights in June and November of 1900, and January 1901 and reached a maximum height of 3770 m. He tried to repeat the Elster–Geitel experiments in "free air," because in mountain-top observations there was always a distortion of the electrical potential levels of the Earth; the effect might also be seasonal. On his first trip up to 2920 m, a negatively charged body discharged faster than a positive one, showing that positive ions were in excess in that layer of the atmosphere. At higher altitude, the discharge rates of both signs of charges became equal. On the second ascent, there was definite evidence of a variation of ionization with height.

From these observations, Ebert concluded: The discharge rate of charged bodies grows appreciably with height, for both positive and negative charges; the unipolarity observed at sea level extends at most to 2000–3000 m; that is, the excess of the leak of charge from a negatively over that from a positively electrified body reaches a maximum at a height between 2000 and 3000 m; at the highest altitudes there is but little difference between the two leaks. However, the leak depends to some extent upon meteorological factors.[44] Those were the first balloon observations on the discharge rate that we have been able to find.

In 1909, Bergwitz made balloon ascents, in which he found a marked decrease of the total ionization, which at 1300 m was only about 25% of the value on the ground.

That was considered to be in better accord with expectation, if the ground were the source of a gamma radiation responsible for the residual ionization. However, there was some question about the validity of Bergwitz's measurements, because his electrometer was damaged during the flight by deformation of its pressure vessel.[45]

Between 1909 and 1911, the Swiss physicist Gockel undertook several balloon ascents, his first flight being carried out to mark a special occasion. *The Society of German Natural Scientists and Physicians,* which met each year in a different German-speaking city, convened in Salzburg, Austria in September 1909. Such famous physicists as Planck, Wien, Sommerfeld, Elster, Stark, Born, Laue, Hahn, Meitner, and Einstein were in attendance.[46] It was at this meeting that Kurz presented his review on the penetrating radiation. He and Wulf had made observations in Zermatt and its surroundings which persuaded them that the source of the radiation was the ground, but they were planning balloon flights to study the variation of the radiation with altitude. In Braunschweig, Germany, balloon flights were also being prepared, and an *International Balloon Week* was to take place.[47]

Gockel played an important part in this activity. As he reported, "For the *International Balloon Week* in December 1909, the Swiss Aeroclub had the kindness to place the Balloon 'Gotthard' at the disposal of Dr. de Quervain and the author. Unfavorable weather had the effect that the ascent had to be put off to the last day of the week, the 11th of the month." The balloon carried three persons (de Quervain for meteorology, Lieutenant Muller to guide the balloon, Gockel to make electric measurements) to a height of 4500 m. Gockel's conclusion was: "The result of the measurement is that in the free atmosphere, there is in fact a lessening of the penetrating radiation, but by far not to the extent that one could expect if the radiation arises mainly from the ground."[48] He made several additional balloon ascents in which he found a slight decrease in gamma radiation with height, but later he realized that his experimental procedure was not free of objection. Gockel's last flight, made on 2 April 1911, was an "Aeroclub Excursion" and carried five persons. Comparing the ionization rate at 2500 m with an earlier result he had obtained at 2800 m, and correcting for barometric pressure, he found a weak *increase* in ionization with increasing height.[49]

## VI. DECISIVE EXPERIMENTS BY HESS AND BY KOLHORSTER

From Wulf's Eiffel Tower experiments and Bergwitz's and Gockel's balloon observations, Victor Franz Hess, an Austrian physicist, decided that the accumulated evidence suggested the presence of a previously unknown source of ionization and he initiated an experimental program to check this possibility. He first measured outdoors the absorption in air of gamma rays from an intense radium source, varying the distance between a closed ionization chamber and the source from 10 to 90 m, establishing that gamma rays from the Earth should be almost completely absorbed at a height of 500 m.

Hess was an active amateur balloonist, and he planned a series of manned-balloon ascents. He was aware that during Gockel's ascents, the pressure of the gas in his instrument varied with altitude, which invalidated the measurement. To avoid this problem, he designed an instrument that could survive the rigors of an open balloon gondola–an air-tight ionization chamber with walls sufficiently thick to withstand a pressure differential of one atmosphere, containing a temperature-compensated Wulf fiber electroscope.

### A. Flights in 1911 and 1912

In 1911, on the first of a series of ten balloon flights, Hess reached 1070 m. He found that the ionization varied very little and concluded , "Since the radiation of that height was not remarkably different from that at sea level, there must be another source of the penetrating radiation in addition to the gamma-radiation from the radioactive substances in the earth's crust."[50] In the same year he made two other balloon flights, and in 1912 seven more, among which two were of special importance. The first flight in 1912 took place on the occasion of a considerable partial eclipse of the sun in lower Austria on 17 April, from 11 am to 1 pm, up to an altitude of 2750 m. During the eclipse, the balloon descended as a result of the cooling of the gas. Hess found that the radiation at around 2000 m was greater than at ground level, and that the eclipse had no effect on the penetrating radiation. Therefore, he came to the conclusion that "if a part of the radiation is of cosmic origin, it can hardly come from the sun, at least so long as one thinks of a gamma-radiation propagated in straight lines."[51]

### B. Decisive flight

The seventh flight of Hess, in a hydrogen-filled balloon was intended to reach a very high altitude. At 6:12 on the morning of 7 August 1912, the balloon ascended from a field near the town of Aussig, in Austria. In its gondola were three persons: a navigator, a meteorologist, and Hess. The flight lasted six hours, reaching the height of 5350 m. At noon, the balloon touched down near the German town

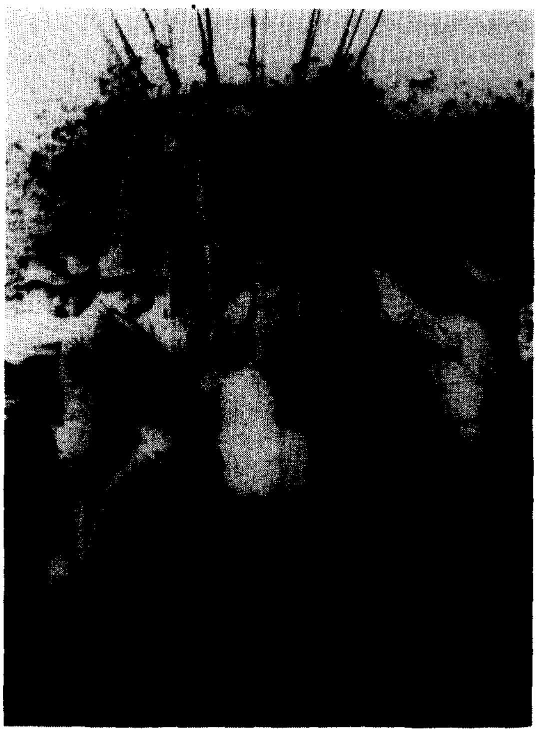

Fig. 2. Photograph of Professor V. F. Hess taken after an important balloon flight in 1912.

Table I. Data taken during Hess's 7th flight in 1912.

| Balloon "Böhmen" (1680 cbm hydrogen)<br>Meteorological observer: E. Wolf. | Leader: Captain W. Hoffory.<br>Electr. observer: V. F. Hess |
|---|---|

| No. | Time | Mean height abs. $m$ | Mean height rel. $m$ | Observed radiation Inst. 1 $q_1$ | Inst. 2 $q_2$ | Inst. 3 $q_3$ | Inst. 3 red. $q_3$ | Temp. | Rel. humidity % |
|---|---|---|---|---|---|---|---|---|---|
| 1 | $15^h 15$–$16^h 15$ | 156 | 0 | 17.3 | 12.9 | ⋯ | ⋯ | $1\frac{1}{2}$ days before the ascent (in Vienna) | |
| 2 | $16^h 15$–$17^h 15$ | 156 | 0 | 15.9 | 11.0 | 18.4 | 18.4 | | |
| 3 | $17^h 15$–$18^h 15$ | 156 | 0 | 15.8 | 11.2 | 17.5 | 17.5 | | |
| 4 | $6^h 45$– $7^h 45$ | 1700 | 1400 | 15.8 | 14.4 | 21.1 | 25.3 | + 6.4° | 60 |
| 5 | $7^h 45$– $8^h 45$ | 2750 | 2500 | 17.3 | 12.3 | 22.5 | 31.2 | + 1.4° | 41 |
| 6 | $8^h 45$– $9^h 45$ | 3850 | 3600 | 19.8 | 16.5 | 21.8 | 35.2 | − 6.8° | 64 |
| 7 | $9^h 45$–$10^h 45$ | 4800 | 4700 | 40.7 | 31.8 | (ended by accident) | | − 9.8° | 40 |
| | | (4400–5350) | | | | | | | |
| 8 | $10^h 45$–$11^h 15$ | 4400 | 4200 | 28.1 | 22.7 | | | ⋯ | ⋯ |
| 9 | $11^h 15$–$11^h 45$ | 1300 | 1200 | (9.7) | 11.5 | | | ⋯ | ⋯ |
| 10 | $11^h 45$–$12^h 10$ | 250 | 150 | 11.9 | 10.7 | | | + 16.0° | 68 |
| 11 | $12^h 25$–$13^h 12$ | 140 | 0 | 15.0 | 11.6 | (After landing at Pieskow, Brandenburg) | | | |

of Pieskow, 50 km east of Berlin. Figure 2 was taken when Hess and his collaborators touched down.

The results of Hess are shown in Table I. Instruments 1 and 2 are thick walled, while instrument 3, with thin walls, was sensitive to both beta and gamma rays. At 1500 to 2500 m, the radiation was about as strong as it was on the ground. There then began a clearly perceptible rise in the radiation with increasing height.

Combining these data with those of his other balloon flights, Hess arrived at these important conclusions: "The results of the present observations seem to be most readily explained by the assumption that a radiation of very high penetrating power enters our atmosphere from above, and still produces in the lowest layers a part of the ionization observed in closed vessels. The intensity of this radiation appears to be subject to transient variations, recognizable in hourly readings. Since I found a reduction in the radiation at the balloon neither by night nor at a solar eclipse, one can hardly consider the Sun as the origin of this hypothetical radiation, at least so long as one thinks only of a direct gamma radiation with rectilinear propagation."[52]

Hess's achievement was recognized in 1936, when Professor H. Pleijel of the Royal Swedish Academy of Sciences addressed these words to Hess, when the latter shared the Nobel Prize for physics with Carl David Anderson:

> By virtue of your purposeful researches into the effects of radioactive radiation carried out with exceptional experimental skill you discovered the surprising presence of radiation coming from the depths of space, i.e., cosmic radiation. As you have proved, this new radiation possesses a penetrating power and an intensity of previously unknown magnitude; it has become a powerful tool of research in physics, and has already given us important new results with respect to matter and its composition. The presence of this cosmic radiation has offered us new, important problems on the formation and destruction of matter, problems which open up new fields of research."[53]

### C. Confirmative flight

Werner Kolhörster, a German physicist, made five dangerously high balloon flights with more refined techniques, in 1913 and 1914. He checked the effect of low temperature

Table II. Kolhörster measurements in 1914.

Kolhörster

| Flight 1 Alt. | Flight 1 Ions | Flight 2 Alt. | Flight 2 Ions | Flight 3 Alt. | Flight 3 Ions | Flight 4 Alt. | Flight 4 Ions |
|---|---|---|---|---|---|---|---|
| 310 | − 1.2 | 500 | − 2.0 | 1090 | − 1.2 | 1000 | − 1.5 |
| 760 | − 1.3 | 600 | − 1.4 | 2130 | + 2.1 | 2000 | + 1.2 |
| 1650 | + 0.8 | 1000 | − 2.1 | 3550 | + 7.0 | 3000 | + 4.3 |
| 2110 | + 1.3 | 1400 | − 1.7 | 4700 | + 14.5 | 4000 | + 9.3 |
| 2400 | + 3.1 | 1500 | − 0.8 | 5600 | + 27.5 | 5000 | + 17.2 |
| 2600 | + 4.3 | 2400 | + 3.1 | 6200 | + 29.3 | 6000 | + 28.7 |
| 3000 | + 7.5 | 3300 | + 4.5 | | | 7000 | + 44.2 |
| 3400 | + 8.9 | 4000 | + 6.7 | | | 8000 | + 61.3 |
| 3500 | + 11.1 | | | | | 9000 | + 80.4 |

on the Wulf electroscopes before his balloon ascents, something to which Hess had not paid much attention. Kolhörster reached a maximum altitude of 9300 m, enabling him to greatly extend Hess's observations.

Table II shows the average difference between the ionization observed at various heights and that at sea level, in ions per cc per second.

These provided clear confirmation of Hess and should have made his conclusions incontrovertible. The ionization increased in Kolhörster's observations until it attained a value about 50 times that at sea level. The radiation from space thus had an attenuation coefficient of 1 × 10–5/cm, much more penetrating than any known gamma rays. Extrapolating Kolhörster's measurements back to ground level suggested an ionization of 2.5 ions per cc per second.[54]

Although radiation of cosmic origin seemed to be well established at this point, it still had no commonly accepted name. Egon Von Schweidler introduced the term "Hess rays" for it, but Hess himself used the term "ultragamma radiation" and Kolhörster called it "Höhenstrahlung."[55]

Probably because of the First World War and its aftermath, there were no reports of significance for this history from 1914 to 1922. Gockel, Hess, and Martin Kofler continued their researches by mountain ascents and balloon flights.[56] While in the army, Kolhörster continued cosmic ray observations at his meteorological observation station.[57] However, no big progress was made.

## VII. FURTHER EXPERIMENTS AND MILLIKAN'S DOUBTS

The conclusion of Hess and Kolhörster that there was an extraterrestrial source for the penetrating radiation was accepted gradually by most physicists, but Millikan claimed that it was not convincing to himself nor to some other specialists, including William Francis Gray Swann, Frederick A. Lindemann, and G. Hoffmann.[58] Millikan was the most skeptical of them. When he moved to the California Institute of Technology after the First World War, he set out energetically to determine whether the experimental data reported by Hess and other workers were correct, and whether there were compelling reasons to believe in the existence of a radiation from outer space. With collaborators, he carried out three series of experiments.

### A. First series; ascent into the stratosphere

In March and April of 1922, from Kelly Field, San Antonio, Texas, Millikan and Ira Sprague Bowen sent four unmanned balloons into the stratosphere, carrying self-registering light-weight electroscopes and thermometers. With all its recording and driving mechanisms, each apparatus weighed only about 200 g.

Three of the four balloons were recovered and two of these had made satisfactory records of their flights, during which they reached altitudes of 11.2 and 15.5 km, respectively. A comparison of the electroscope reading recorded at the 5-km level during ascent with the reading at the same level during descent showed that the average discharge rate of the electroscope while above the 5-km level was about three times its discharge rate at the surface of the Earth. Millikan found that that was only 25% of the value expected from the Hess–Kolhörster curve. Thus, Millikan and Bowen concluded, "The results then of the whole Kelly Field work constitute definite proof that there exists no radiation of cosmic origin having such characteristics as we had assumed." Their paper, published in 1926, continued, "They show that the ionization increased much less rapidly with altitude than would be the case if it were due to rays from outside the earth having an absorption coefficient of .57 per meter of water."[59]

### B. Millikan's mountain peak and airplane observations

In the summers of 1922–23, Millikan and Russel M. Otis carried out his second series of experiments. At Ross Field near Pasadena, Otis made measurements in captive balloons. These yielded results in agreement with those of other observers, in that up to an altitude of 2000 m the number of ions per cc per second was 1 to 3 less than that on the ground. Again, Otis sent his equipment on several airplane flights in 1922 at Marsh Field near Riverside and in 1923 at Rockwell Field near San Diego. These flights reached heights of more than 5000 m. The results obtained were in agreement with those we have quoted of Millikan and Bowen, in that they showed a markedly lower rate of leak at the highest altitudes than those reported by Hess and Kolhörster.

During the summers of 1922 and 1923, Millikan's team made a long series of observations on Mt. Whitney (4130 m) and Pike's Peak (4300 m). They found variations with altitude, but no dependence of penetrating radiation upon daylight or darkness, or upon the position of any of the heavenly bodies. In September 1923, on Pike's Peak, they made experiments outdoors and indoors, with all sides of the vessel shielded with lead, or with one or two sides unshielded and found that the penetrating radiation came equally from all sides.[60] Because of the screening effect, Millikan concluded that "there exists no such penetrating radiation as we have assumed (of cosmic origin)." Continuing, they "found as a result of a snowstorm on the mountain as large a percentage change (about 10%) in the ionization inside our 5-cm lead shield as outside it. We interpret this result also as meaning that the whole of the penetrating radiation is of local origin. How such quantities of radioactive material get into the upper air is as yet unknown."[61] The experiments of series (a) and (b) confirmed Millikan's doubts about the existence of radiation of cosmic origin.

### C. Measurements in snow-fed lakes: removing Millikan's doubts

In September 1925, Millikan and G. Harvey Cameron carried out a series of experiments in snow-fed lakes at high altitudes. They went first to Muir Lake at 3590 m above sea level, just under the brow of Mount Whitney, the highest peak in the United States (except for Alaska). The lake is very deep and some 700 m in diameter. They worked there for the last ten days of September, sinking two electroscopes to various depths down to about 20 m. The electroscope readings decreased steadily down to a depth of 15 m below the surface. The atmosphere above the lake was equivalent in absorbing power to 7 m of water, so that they were observing rays so penetrating that if they came from outside the atmosphere, they had the power of passing through 22 m of water before being completely absorbed.

In order to obtain definite evidence as to whether these very hard rays were of cosmic origin, coming wholly from above, the atmosphere acting merely as an absorbing air

Table III. Snow-fed lakes measurements by Millikan.

Readings in Lakes Muir and Arrowhead
Electroscope No. 3
Muir Lake

| Depth below surface (m) | 0 | 0.45 | 1.0 | 2.8 | 3.0 | 5.0 | 10.0 | 15.0 | 20.0 |
|---|---|---|---|---|---|---|---|---|---|
| Ionization | 13.3 | 9.7 | 7.7 | 6.0 | 5.45 | 4.9 | 4.0 | 3.6 | 3.6 |
| (ions/cc/s) | 13.2 | ⋯ | 7.8 | 5.8 | ⋯ | 4.6 | 4.0 | ⋯ | 3.7 |
| Means | 13.25 | 9.7 | 7.75 | 5.9 | 5.45 | 4.75 | 4.0 | 3.6 | 3.65 |
| | | | | ↙ | ↙ | ↙ | | | |
| | | | | Arrowhead | | | | | |
| Depth below surface (m) | 0 | 0.7 | 1.0 | 1.1 | 3.0 | 5.0 | ⋯ | 15.0 | ⋯ |
| Ionization | 7.0 | 5.8 | 5.5 | 5.15 | 4.85 | 4.4 | ⋯ | 3.7 | ⋯ |
| (ions/cc/s) | 7.2 | ⋯ | ⋯ | ⋯ | 4.9 | ⋯ | ⋯ | ⋯ | ⋯ |
| | 7.5 | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ |
| | 6.9 | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ |
| | 7.2 | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ |
| | | ↗ | ↗ | | ↗ | | | | |
| Means | 7.0 | 5.8 | 5.5 | 5.15 | 4.9 | 4.4 | ⋯ | 3.7 | ⋯ |

blanket, they next went to another deep snow-fed lake, Lake Arrowhead in the San Bernardino mountains, 480 km farther south and 2060 m lower in altitude. The atmosphere between the altitudes of the two lakes has an absorbing power equivalent to about 2 m of water. The data in Table III were from the more sensitive of the two electroscopes, No. 3. The arrows in the table show the equivalent mean depths in the two lakes, when the difference in altitude is taken into account. Using these data, Millikan plotted curves, with the ionization readings in the two lakes as ordinates, and as abscissas, the depths in meters beneath the top surface of the atmosphere, reduced to the equivalent depths in water.

Millikan came to these conclusions: "Within the limits of observational error, every reading in Arrowhead Lake corresponded to a reading 6 feet farther down in Muir Lake, thus showing that the rays do come in definitely from above, and that their origin is entirely outside the layer of atmosphere between the levels of the two lakes." He stated further: "No single absorption coefficient is found to fit the absorption curve, the lower end of which requires a coefficient of 0.18 per meter of water; the upper end, a coefficient of 0.30 per meter of water. These coefficients correspond by Compton's equation to wave-length $\lambda_1 = 0.00038A$ and $\lambda_2 = 0.00063A$. These are fifty times the frequencies of ordinary gamma rays, $\lambda = 0.025A$, and the former corresponds to an energy of 32,000,000 volts."[62]

It was this high penetrating power of the radiation observed in these experiments that convinced Millikan and the other doubters (such as Swann and Hoffmann) about the correctness of Hess's claim. And it was Millikan who gave this radiation the name *cosmic rays.*

### D. "Millikan rays"?–a misunderstanding

The work of Millikan's team was important, not only because of the precise scientific results obtained, but also because of the novel and ingenious techniques employed. One great innovation was the application of sounding balloons in cosmic ray research. Hess and Kolhörster had to accompany their electroscopes in order to observe them. The use of unmanned balloons eliminated the danger and the high cost of manned balloon flights, but also the adventure. Millikan's electroscopes, masterpieces of ruggedness and sensitivity for their time, were borne aloft by two balloons; at a certain altitude one of the balloons would burst and the other would then bring the equipment gently back to Earth. During the flight, a simple device continuously recorded the electroscope readings on photographic film, to be developed and examined after recovery.

After Millikan won the Nobel Prize in 1923 for his work on the elementary charge of electricity and on the photoelectric effect, he was the most popular and respected physicist in America. He had a flair for publicity, and he obtained high praise for his experiments in snow-fed lakes. Exulting in Millikan's success, The New York Times published an editorial entitled "Millikan Rays," which said, "Dr. R. A. Millikan has gone out beyond our highest atmosphere in search for the cause of a radiation mysteriously disturbing the electroscopes of the physicists... His patient adventuring observations through twenty years have at last been rewarded... He found wild rays more powerful and penetrating than any that have been domesticated or terrestrialized, traveling toward the earth... The mere discovery of these rays is a triumph of the human mind that should be acclaimed among the capital events of these days. The proposal that they should bear the name of their discoverer is one upon which his brother-scientists should insist... 'Millikan rays' ought to find a place in our planetary scientific directory all the more because they would be associated with a man of such fine and modest personality."[63]

TIME reported, "Dr. R. A. Millikan...told the Academy about a new ray which he had discovered–a ray which begins in eternity... The Millikan Ray stabs earthward,...the Millikan Rays, wherever they are present in any quantity, have a sterilizing effect fatal to life,... The Millikan Ray will pierce six feet of lead..."[64] A picture of Millikan peering through a microscope was printed on the cover of TIME, while its caption breathlessly exclaimed. "DR. ROBERT ANDRES MILLIKAN...detected the cosmic pulse."[65]

The Scientific Monthly said, "Discovery of ultra-x-rays a hundred times more penetrating than ordinary x-rays were announced at the Madison meeting of the National Academy of Sciences on November 9 by Dr. R. A. Millikan,...some of his colleagues have suggested calling them 'Millikan rays' in his honor."[66] And SCIENCE, under the title "Millikan Rays," quoted the whole above-mentioned editorial from the New York Times.[67] All this did little to reduce Millikan's self-esteem.

In fact, however, because of Millikan's scientific dogmatism, he was twice on the losing side in controversies on cosmic rays. The first controversy concerned the existence of radiation of cosmic origin. The second time was in the 1930s and concerned the question of whether the primary cosmic rays were charged particles or, as Millikan believed, gamma rays. In the first case, after his own experiments, carried out over a long period of time, led to results that were contrary to his expectation, Millikan's skepticism evaporated.

The term "Millikan Rays" was used quite often, and Millikan enjoyed being the "discoverer" of cosmic rays. But after Hess and others expressed their chagrin about this, Millikan wrote Hess a letter, in which he said, "I made no claims of any sort about the discovery of penetrating radiations... If anybody has suffered from misrepresentation so far, it seems to me that I am the sufferer... The really important thing is that between all of us we have been able to make pretty certain the existence of a radiation which comes to the earth from outside... The evidence seems to me now to be unambiguous,... That such cosmic rays, if they exist, must be of nuclear origin is altogether obvious. It has been suggested literally scores of times."[68]

In 1936, when Hess won the Nobel Prize for his discovery of cosmic rays, Millikan expressed his warm congratulations and wrote:

> Every informed physicist will acclaim the award of the Nobel Prize in Physics to Victor F. Hess; for after a decision had been made that the first significant work in the field of cosmic rays was to be honored by a Nobel Prize there was certainly no living person who could for a moment be considered for that award except Dr. Hess. The Swiss, Gockel, the Austrian, Hess, and the German, Kolhörster, were undoubtedly the three persons who opened up this field. Their early work was done from 1910 to 1914, and no other particularly important work of this sort appeared until about a decade later, when the modern era of cosmic ray research was entered in. Gockel died about a decade ago, and Kolhörster's important work definitely followed that of Hess... . Hess...was the earliest living experimenter in the initiation of a new field of physical knowledge.[69]

## VIII. THE END OF ONE ERA AND A NEW BEGINNING

In 1927, individual charged particles of cosmic rays were observed by Dmitrii Vladimirovich Skobelzyn with a Wilson cloud chamber. In 1928, Walter Bothe and Kolhörster applied the coincidence-counting method to the study of viewing fast charged particles in the cosmic rays. With these two new kinds of observation, the study of cosmic rays entered a new era: the positron and pair production were discovered; the mesotron (muon) and pion were discovered; the cosmic rays gave rise to many important discoveries. Until the early 1950s, when high energy particle accelerators took over this role, the cosmic rays were the only source of very high energy particles used for the study of elementary particle physics. Even now, the cosmic rays still provide much higher energy particles than can be produced on Earth. Studies of cosmic rays with rockets and Earth satellites have contributed greatly to the field of modern astrophysics.

NOTE: The reader who wishes to learn more about cosmic rays before 1927 will find few sources other than the original scientific papers we have quoted, especially in the English language. However, several modern books with some historical material are D. J. X. Montgomery, *Cosmic Ray Physics* (Princeton U. P., NJ, 1949); Bruno Rossi, *Cosmic Rays* (McGraw-Hill, New York, 1964); Martin A. Pomerantz, *Cosmic Rays* (Van Nostrand Reinhold, New York, 1971); Satio Hayakawa, *Cosmic Ray Physics* (Wiley, New York, 1969); A. M. Hillas, *Cosmic Rays* (Pergamon, Oxford, 1972). The forthcoming Vol. 5 of Jagdish Mehra and Helmut Rechenberg's, *The Historical Development of Quantum Theory* (Springer, New York) will contain an account especially of Austrian contributions before World War One, including Hess, and a discussion of Erwin Schrödinger's cosmic ray analysis of 1912. (We thank Dr. Rechenberg for showing us this material, and for useful advice.) For late (nearly) contemporary accounts, see Victor F. Hess, *The Electrical Conductivity of the Atmosphere and its Causes* (translation, Van Nostrand, New York, 1928); Karl K. Darrow, "Data and Nature of Cosmic Rays," Bell Syst. Tech. J. **11**, 148 (1932); R. A. Millikan, *Electrons (+ and −), Protons, Photons, Neutrons, and Cosmic Rays* (University of Chicago Press, Chicago, IL, 1935). Of some interest also is W. F. G. Swann, "The History of Cosmic Rays," Am. J. Phys. **29**, 811 (1961) and Stephen Rosen, Ed., *Selected Papers on Cosmic Ray Origin Theories* (Dover, New York, 1969).

---

[a] Permanent address: Physics Department, Xiamen University, Xiamen, Fujian Province, China.

[1] J. J. Thomson, Proc. R. Soc. London **49**, 93 (1891).

[2] J. J. Thomson, Proc. R. Soc. London **58**, 244 (1895).

[3] Nobel Lectures, *Physics* (Elsevier, Amsterdam, 1967), 1901–1921, p. 142.

[4] C. T. R. Wilson, Proc. R. Soc. London **64**, 127 (1898).

[5] C. T. R. Wilson, Proc. R. Soc. London **65**, 289–290 (1899).

[6] A. Pais, Rev. Mod. Phys. **49**, 930 (1977).

[7] J. Elster and H. Geitel, Ann. Phys. **2**, 425–446 (1900); J. J. Thomson, *Conduction of Electricity through Gases* (Cambridge U. P., Cambridge, 1906), 2nd ed., p. 3.

[8] F. Linss, Meteorol. Z. **4**, 345 (1887).

[9] C. T. R. Wilson, Proc. Cambridge Philos. Soc. **11**, 32 (1900); C. T. R. Wilson, Proc. R. Soc. London **68**, 159 (1901).

[10] J. C. McLennan and E. F. Burton, Phys. Rev. **16**, 184 (1903).

[11] C. T. R. Wilson, Proc. Cambridge Philos. Soc. **11**, 428 (1902).

[12] C. T. R. Wilson, Proc. R. Soc. London **69**, 277 (1901).

[13] J. C. McLennan and E. F. Burton, Phys. Rev. **16**, 185 (1903).

[14] R. J. Strutt, Nature **67**, 369 (1903).

[15] J. Patterson, Proc. Cambridge Philos. Soc. **12**, 44 (1903).

[16] C. T. R. Wilson, Proc. R. Soc. London **69**, 281 (1901).

[17] G. Jaffe, Philos. Mag. **8**, 564–565 (1904).

[18] G. Simpson, Trans. R. Soc. **A205**, 61–97 (1906).

[19] A. Wood, Nature **73**, 583 (1906).

[20] T. F. McKeon, Phys. Rev. **25**, 399–421 (1907).

[21] E. Rutherford and H. L. Cooke, Phys. Rev. **16**, 183 (1903).

[22] J. C. McLennan and E. F. Burton, Phys. Rev. **16**, 191–192 (1903).

[23] J. Elster and H. Geitel, Phys. Z. **2**, 560 (1901); J. J. Thomson, *Conduction of Electricity Through Gases* (Cambridge U. P., Cambridge, 1906), 2nd ed., p. 7.

[24] A. S. Eve, Philos. Mag. **13**, 248, 258 (1907).

[25] C. S. Wright, Philos. Mag. **17**, 311, 317–318 (1909).

[26] E. Rutherford, *Radioactive Transformation* (Yale U. P., New Haven, 1905), p. 197.

[27] A. S. Eve, Philos. Mag. **10**, 108 (1905).

[28] R. A. Millikan, *Electrons ( + and − ), Protons, Photons, Neutrons, and Cosmic Rays* (Chicago U. P., Chicago, 1935), p. 303.

[29] C. T. R. Wilson, Proc. R. Soc. London **68**, 159, 161 (1901).

[30] C. T. R. Wilson, Proc. Cambridge Philos. Soc. **11**, 428–430 (1902).

[31] C. T. R. Wilson, Proc. Cambridge Philos. Soc. **12**, 85 (1903).

[32] C. T. R. Wilson, Nature, **68**, 103 (1903).

[33] C. T. R. Wilson, Nature, **68**, 104 (1903).

[34] G. Simpson, Nature **69**, 270 (1904).

[35] C. T. R. Wilson, Proc. Cambridge Philos. Soc. **13**, 378, 382 (1906).

[36] O. W. Richardson, Nature **73**, 607 (1906).

[37] Karl Kurz, Phys. Z. **10**, 834 (1909).

[38] J. Elster and H. Geitel, Ann. Phys. **2**, 441 (1900).

[39] Th. Wulf, Phys. Z. **10**, 153 (1909).

[40] Refer to Refs. 45 and 48 below.

[41] Th. Wulf, Phys. Z. **11**, 811 (1910).

[42] A. S. Eve, Philos. Mag. **21**, 27–40 (1911).

[43] J. C. McLennan and E. N. Macallum, Philos. Mag. **22**, 640–642 (1911).

[44] H. Ebert, Ann. Phys. **5**, 718–724 (1901).

[45] K. Bergwitz, Habilitationsschrift, Braunschweig, 1910, s37; M. A. Pomerantz, *Cosmic Rays* (Van Nostrand Reinhold, New York, 1971), p. 4.

[46] Armin Hermann, *The New Physics* (Heinz Moos, Munich, 1979), pp. 11–13.

[47] Karl Kurz, Phys. Z. **10**, 834–845 (1909).

[48] A. Gockel, Phys. Z. **11**, 280–283 (1910).

[49] A. Gockel, Phys. Z. **12**, 595–597 (1911).

[50] V. F. Hess, Phys. Z. **12**, 998–1001 (1911).

[51] V. F. Hess, Phys. Z. **13**, 1085–1086 (1912).

[52] V. F. Hess, Phys. Z. **13**, 1088–1091 (1912).

[53] Nobel Lectures, *Physics* (Elsevier, Amsterdam, 1965), 1922–1941, p. 356.

[54] W. Kolhörster, Phys. Z. **14**, 1153 (1913); Dtsch. Phys. Ges. **16**, 719 (1914).

[55] V. F. Hess, *Electrical Conductivity of the Atmosphere and its Causes* (Van Nostrand, New York, 1928), p. 117.

[56] A. Gockel, Dtsch. Schweiz. Natur. Ges. **54**, 1 (1917); Hess and Kofler, Phys. Z. **18**, 585 (1917).

[57] W. Kolhörster, Z. Phys. **11**, 379 (1922).

[58] Millikan to Hess, July 24, 1926, Millikan Collection Caltech.

[59] Millikan and Bowen, Phys. Rev. **27**, 360–361 (1926).

[60] Millikan and Otis, Phys. Rev. **27**, 650–657 (1926).

[61] Otis and Millikan, Phys. Rev. **23**, 778–779 (1924).

[62] Millikan and Cameron, Phys. Rev. **28**, 851, 856 (1926).

[63] The New York Times, November 12, 1925, p. 24.

[64] TIME **6**, 26, November 23, 1925.

[65] TIME **9**, Cover, and p. 16, April 25, 1927.

[66] The Scientific Monthly **21**, 661 (1925).

[67] SCIENCE **62**, 461–462 (1925).

[68] Millikan to Hess, July 24, 1926, Millikan Collection Caltech.

[69] Millikan, Award of Nobel Prize in Physics to V. F. Hess and Carl D. Anderson, November 23, 1936, Millikan Collection Caltech.

---

# The vibrating string controversy

Gerald F. Wheeler
*Department of Physics, Montana State University, Bozeman, Montana 59717*
William P. Crummett
*Department of Physics and Geophysical Engineering, Montana College of Mineral Science and Technology, Butte, Montana 59701*

(Received 6 December 1985; accepted for publication 10 February 1986)

In the mid-1700s a debate raged between Jean d'Alembert, Leonhard Euler, and Daniel Bernoulli concerning the proper solution to the classical wave equation. This controversy was partially solved by Lagrange and, more conclusively, by Fourier (50 years later) and it provides an interesting case study for the role of mathematics in the modeling of physical phenomena. Of particular note in this debate, was the meaning of boundary conditions. The controversy is summarized from the point of view of this mathematical physics perspective.

## INTRODUCTION

Mathematical descriptions of wave phenomena are fundamental to many areas of physics. A clear understanding of the relations which describe the vibrating string is required to comprehend more complex wave motions. Few physicists, however, are aware of the intense controversy that existed over the original descriptions of the vibrating string proposed during the eighteenth century. At the height of the controversy one of the most fundamental and powerful theorems of mathematical physics emerged, was overlooked, and had to wait 50 years for its rediscovery.

While the debate has long held interest for mathematical historians, there has been little discussion of the way this debate signaled the emergence of a new kind of physicist. There are excellent reviews of the controversy,[1,2] each presented as a topic from the history of mathematics. In presenting our view of the debate, we have drawn extensively from these sources, as well as the original papers.

Physicists will find the controversy enlightening. Many