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In search of the cosmic rays

The story of Domenico Pacini

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To my wife, my daughter
my family and my friends

Contents

Preface

This book is aimed at carrying on an historical and scientific report of the role of the italian physicist Domenico Pacini in the discovery of cosmic rays. To this aim I will analyze, based on the the original documentation, the experiments he performed and the conclusion he reached. The fundamental original italian articles of Pacini are reproduced in the dedicated chapter with the English translation aside. This way it is possible to follow the path which led Pacini to his discovery and the ideas he introduced little by little in the development of his studies.

Pacini started his work when the discovery of the existance of natural radioactivity on Earth had been yet made. Soon scientists wondered where this radioactivity's origin were. Between the various hypotheses the more credited was that it was due to radiation from the terrestrial crust. The solution of the mystery required ten years and the contribution of many scientists, and led to the Nobel Prize for the discovery of cosmic rays to Asutrian Physicist Victor Hess in 1936.

In this search for the origin of the radiation the Italian physicist Domenico Pacini [33] made a long series of experiments, between 1907 and 1911. In June 1911 at the Naval Academy of Livorno, Pacini performed his defi e experiment, which was then confirmed in Bracciano's lake some months later: he used an innovative experimental technique which allowed him to observe that the natural penetrating radiations decrease moving from the water surface to a few meters under water; this way he demonstrated that a significant part of these natural penetrating radiations could not have come from Earth[1]. Pacini published the results of this (and others) experiment in Italian in 1911, and the Austrian physicist Victor Hess published the results of his experiments made aboard a balloon in 1912. Hess measured that the rate of ionization increases with height, so reaching the same conclusions of Pacini about the origin of the radiation.

For sure the discovery of cosmic rays is due to several scientists, in Europe and the United States, and took place during a period where communication were very much more diffi than today, for technical, cultural and political reasons (for instance Pacini's articles are written in italian, not a powerful communication media at that time). In the way which led to the discovery, the figures of Pacini and Hess are certainly very relevant, probably the most of all, togheter with that of the Jesuit Theodor Wulf, who first introduced in 1910 the technique of measurement of penetrating radiation at high altitude (from the top of the Eiffel Tower). But, as I yet said, the name of Pacini is almost unknown in the history of science[2]. Despite the substantial disappearing of Pacini's name in the history of physics there is an important hint of his name found in the Amaldi Archives, at the Department of Physics of the University of Rome "La Sapienza". In fact in these Archives there is a copy of a letter dated July 14th XIX 1941, written by Edoardo Amaldi, in which Amaldi wrote that "the first discoverer of cosmic rays was the Italian Pacini who was followed by the germans Hess, Kolhörster and so on".

I started to work on Domenico Pacini together with Professor Alessandro De Angelis[3], who studied deeply the history and the discoveries

1. We now know that cosmic rays are particles (mostly hydrogen nuclei, that is protons) that impact the Earth's atmosphere at speeds close to that of light. Their energies are the highest observed in nature, must therefore come from powerful cosmic accelerators, probably remains of supernovae and in the vicinity of supermassive black holes. The mechanism of acceleration was explained by Enrico Fermi in 1949. Lower energy cosmic rays, however, come from the Sun.

2. It is worth noticing that in 1957 Walt Disney produced a one-hour documentary [149], directed by Frank Capra and with the scientific advice of the Nobel Prize Carl Anderson and of the italian Bruno Rossi, in which the story of cosmic rays was told as a mystery story involving puppets and cartoons. In this documentary there is an experiment of measurement underwater in a lake, just like Pacini did.

3. Alessandro de Angelis is a high-energy physicist and astrophysicist. Full Professor at the University of Udine Director of Research at INFN Padova, he is chairman of the

of Domenico Pacini [33]. This way I collected many objective elements that pushed be to write this book in order to explain clearly Pacini's role in cosmic rays discovery. Then in the following pages I will explain to the reader who was Domenico Pacini, in which sense he can be considered "the first discoverer of the cosmic rays", and how his discoveries should be related to the research at that time. I will point out also what are the influences of Pacini's intuitions and tecniques on nowadays research in physics. As I yet said, the reader should refer above all to the original articles by Pacini, which for the first time are translated and made available to the large public.

collaboration board of MAGIC gamma-ray telescope at La Palma, Canary Islands.

Chapter I

The story of research about cosmic rays

As reported in [33], the first unexplained behaviours that very much later will be related to what we now call "cosmic rays" date 1785, when de Coulomb found [36] that electroscopes can spontaneously discharge, by the action of the air and not by defective insulation. Some years later, around 1835, Michael Faraday observed the same effect [37]; then Crookes, in this article dated 1879 [38], reported that there was a direct proportional relation between the pressure of air and the speed of the discharge effect. These and many other experiments about which I will write in the next parts of this book brought to the discovery of cosmic rays, the very high-energy, fast-moving particles coming from outside Earth, that still puzzle scientists about their origins. As professor Alessandro De Angelis tells in his article [33], there are several reviews on the history of the research on cosmic rays, for example [43–48, 63, 65?–70]. Here I consider the main experiments and discovery and in particular those of Domenico Pacini.

1.1 The mistery of atmospheric ionization

In 1896 Becquerel discovered natural radioactivity, using naturally fluorescent minerals to study the properties of the just-discovered x-rays by Roentgen [71]. The term radioactivity was actually coined by Marie Curie, who together with her husband Pierre, began investigating this phenomenon. Their experiments led to the discoveries of the radioactive elements polonium and radium in 1898 [72]. In particular Curie observed that electroscopes discharge in the presence of one of these natural radioactive materials. The explanation of this effect was that these radioactive elements emit charged particles that in turn caused the discharge of the electroscopes. There was then an important advance in research, because scientists began measuring the discharge rate as a tecnique for obtaining the level of radioactivity.

Radioactivity research then continued in parallel and linked with discharge physics. Fundamental discoveries related to these fields were those of the electron and of positive ions. So at the beginning of the 20th century there was a big increase in the research about the ionization phenomena which brought a lot of results, both in Europe and in the United States.

In 1900, Wilson [73] and Elster and Geitel [74] improved the technique for a careful insulation of electroscopes in a closed vessel, this way the sensitivity of the electroscope itself increased greatly [33]. Thanks to this improvement, it was from then on possible to get quantitative measurements of the rate of this spontaneous discharge. Wilson and Elster and Geitel could then use data to hypotesize the reason for this still unexplained behaviour: they concluded that the discharge was due to ionizing agents coming from outside the vessel. This conclusion in turn paved the way to other fundamental questions concerned the characteristics of this radiation and above all its origins.

As I said, the research about discharge phenomena and radioacitivity were somehow linked, so the hypothesis scientists proposed was that the origin of discharge was related to radioactive materials. This hypotesis gave an answer also to the question if this ionizing radiation was of terrestrial or extraterrestrial origin: it came from Earth. It is worth noticing that all these were hypotesis, as there was no experimental proof able to demonstrate the terrestrial origin of this radiation. Not all scientists agreed with the explanation of a terrestrial origin of this radiation, for instance Wilson [73] proposed that the origin of the ionization could be an extremely penetrating extra-terrestrial radiation: "[...]it is quite conceivable that we may be driven to seek an extraterrestrial source for the negative charge of the Earth's surface". So he conducted investigations in tunnels with solid rock overhead, but found no reduction in ionization [73]. Again there was no proof about the terrestrial or extra-terrestrial the origin of this ionizating radiation. As reported in [, deangelis Cimento] thoug now and the the extra-terrestrial origin was discussed again (e.g. by Richardson [75]), it was later dropped for the following years.

Some other important contributions, among the others, are those of 1903 Rutherford and Cook [76] and of McLennan and Burton [77]. They showed that the ionization was significantly reduced if the electroscope was protected by shields of metal purifi form any radioactive natural source. This way it was pointed out that a part of the ionizating radiation came from outside the apparatus. These and other experiments lead to establish that there was a "penetrating radiation", which depends partly from the walls of the vessel and partly from outside that is responsible of this ionization.

The works by Kurz [78] and by Cline [79] in 1909 explain the knowledge at that time regarding this penetrating radiation: scientists agree that even in insulated environments a background radiation did exist. Kurz in its 1909 review discussed three possible sources for this penetrating radiation: an extraterrestrial radiation from the Sun [75], radioactivity from the crust of the Earth, and radioactivity in the atmosphere. Among these three hypotesis, as reported in [33], Kurz concludes from the measurements of ionization made in the lower part of the atmosphere that it should not be of extra-terrestrial origin. So at that time the main explanation for this penetrating radiation was that it depended on the radioactive material in the crust of the Earth. Based on this assumption, scientists performed measurements and get calculations to establish how the radiation should decrease with height.

One of the most important fiigures who was involved in the search for the explanation of the origin of the penetrating radiation was Father Theodor Wulf, a German scientist and a Jesuit priest who served in the Netherlands and then in Rome. Wulf decided to measure the variation of radioactivity with height. His hypotesis was that penetrating radiation came from radiation in the crust, so ionization should decrease with increasing height. He then performed in 1909 [81] an experiment to measure the ionization rate on the top of Eiffel tower, using an improved electroscope (Fig. 1.1). In the Wulf electroscope, as reported in [33], the two leaves had been replaced by two metalized silicon glass wires, with a tension spring made also of glass in between. In detail, after the calculations made by the previous cited scientists, Wulf knew that the 300 meters of air which separated the electroscope from soil should have absorbed almost completely the radioactive emissions from Earth and that the tower was almost free from radioactivity. But during the four days of experiments the electroscope was still discharging, just a little less that at ground level. So the rate of ionization showed too small a decrease to confirm the hypothesis of the terrestrial origin of most of the radiation. He concluded that, in comparison with the values on the ground, the intensity of radiation "decreases at nearly 300 m [of altitude] not even to half of its ground value", while he expected "just a few percent of the ground radiation" [81] if the terrestrial hypotesis was correct. It is worth noticing that Wulf's observations were of great value, because he could take a great amount of data with a better precision and at different hours of the day and for many days at the same place.

Despite the results he found, Wulf concluded that the most likely explanation of his data was still emission from the soil and that perhaps the absorption power of air was lower than how it had been supposed. Still his improved electroscope had such a good detection power that many scientist all over the world started using it, verifiyng at the same time that it losed its charge wherever one would place it, also without evident radioactive sources. So there started a research carried on in many different places. For instance, also during Capitain's Scott expedition to Antartica in 1911 there was a meteorologist who made measurements using a Wulf's electroscope on the Ocean and on Antartica's soil [134]. Other measurements with similar results were also made (Bergwitz [82], McLennan and Macallum [83], Gockel [84]). In particular McLennan together with Burton observed an ionization reduction of about 40% with a water shield of 120 cm, which they know to be too a high reduction. McLennan and Burton's conclusion was in line with radioactivity in the air from known radioactive sources: «From these results it is evident that the ordinary air of a room is traversed by an exceedingly penetrating radiation such as that which Rutherford has shown to be emitted by thorium, radium and the excited radioactivity produced by thorium and radium» [77].

So this residual discharge was evident everywhere. However the general interpretation by scientists of the outcome was that radioactivity was mostly coming from the Earth's crust.

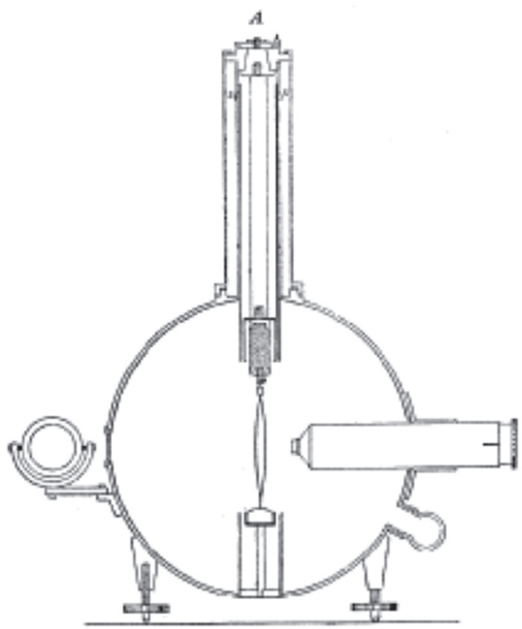

Fig. 1.1. The Wulf electroscope.

1.2. Pacini's measurements of penetrating radiation in water

Italian physicist Domenico Pacini debated the "terrestrial" explanation of the origin of penetrating radiation. In his experiments he compared the rate of ionization over a lake, on the mountains, and over the sea [1, 2]; in particular in 1911 he made important experiments in which he measured the level how ionization immersing an electroscope deep in the sea [3].

Pacini in the first period of his research on the penetrating radiation made measurements to relate the variations of the electroscope's discharge rate as a function of the environment [33]. To first the relation between environment and discharge rate he placed the electroscope before on the ground and then on the sea, a few kilometers off the coast in the Gulf of Genova. He performed the measures on the sea aboard the Italian Navy ship *cacciatorpediniere* (destroyer) "Fulmine" (Fig. 1.2), of the Naval Academy of Livorno. The results made on mainland and on the sea were comparable. In a summary of these results Pacini concludes that "in the hypothesis that the origin of penetrating radiations is in the soil, since one must admit that they are emitted at an almost constant rate (at least when the soil is not covered by remaining precipitations), it is not possible to explain the results obtained" [1]. The importance of Pacini's conclusion is that for the first time the results of many experiments about the rate of penetrating radiation showed that this rate was the same on the sea and on mainland, so this radiation could not be explained by the hypotesis of radioactive materials in the Earth's crust. Gockel's experiments confirmed Pacini's results [84].

Pacini in 1911 developed a new experimental technique for the measurement of radioactivity a few meters underwater[1]. The experiment was performed in the sea in front of the Naval Academy of Livorno, and later in the Lake of Bracciano. Pacini placed the electroscope three meters undewater and measured the discharge rate. He found a significant decrease in this rate by 20%. This decrease Pacini was consistent with the absorption by water of a radiation coming from outside [33].

Pacini reported these results in a note titled *La radiazione penetrante alla superficie ed in seno alle acque (Penetrating radiation at the surface of and in water)* [3]. In this note he concluded: "[It] appears from the results of the work described in this Note that a sizable cause of ionization exists in the atmosphere, originating from penetrating radiation, independent of the direct action of radioactive substances in the soil".

1.3. Balloon measurements

The next development on the path followeb by Wulf to measure the effect of altitude was to use balloon flights. The first balloon flight with this purpose took place in Switzerland in December 1909, with a balloon called Gotthard from the Swiss aeroclub. Aboard that balloon professor Alfred Gockel, from University of Fribourg, reached 4500 m above sea level (a.s.l.) during three successive flights. Gockel found [87, 88] that the ionization decrease with height was different from that expected in the hypothesis of a terrestrial origin of radiation. So Gockel, quoting Pacini, confirmed the same conclusion [1] and stated "that a non-negligible part of the penetrating radiation is independent of the direct action of the radioactive substances in the uppermost layers of the Earth" [88]. He also questioned Bergwitz's results, who had found [82] that the ionization at 1300 m altitude had decreased to about 24% of the value at ground, because Bergwitz's the electrometer was damaged during the flight [88].

Nonetheless physicists followed the hypothesis of a terrestrial origin for penetrating radiation. But then started a long series of balloon flights by the Austrian physicist Viktor Hess. These flights allowed to demonstrate the extra-terrestrial origin of at least part of the penetrating radiation[2].

Hess started his experiments from Wulf's results and using Eve's calculations [89] on the coefficients of absorption for radioactivity in the atmosphere. According to Eve, given a uniform distribution of RaC on the surface and in the uppermost layer of the Earth, "an elevation of 100 m should reduce the [radiation] effect to 36 percent of the ground value". Hess wrote: "This is such a serious discrepancy [with Wulf's results] that its resolution appears to be of the highest importance for the radioactive theory of atmospheric electricity" [91].

1. Mention of the Pacini experiments as the first example of "under-surface" measurements was made by C. Castagnoli [67]: "[the] depth was modest, but it established the beginning of a tradition of which we now represent the continuation".

2. Viktor Hess was born in 1883 in Steiermark, Austria, and he took his doctor's degree in 1910 in Graz. After graduation he was assistant under professor Meyer at the Institute of Radium Research of the Wiener Academy of Sciences, where he performed most of his work on cosmic rays, and in 1919 he became Professor of Experimental Physics at the Graz University. Hess was on leave of absence from 1921 to 1923 and worked in the United States, where he worked as Director of the Research Laboratory of the United States Radium Corporation, in Orange (New Jersey). In 1923 he returned to Graz and in 1931 he moved to Innsbruck as a professor. In 1936 Hess was awarded the Nobel Prize in physics for the discovery of cosmic rays. After moving to United States of America (US) in 1938 as professor at Fordham University, Hess became an American citizen in 1944, and lived in New York until his death in 1964.

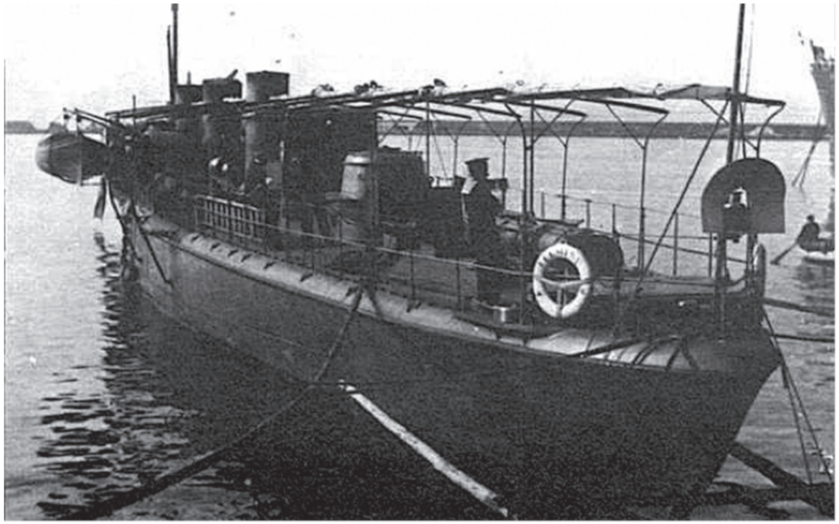

Fig. 1.2. The cacciatorpediniere (destroyer) "Fulmine", which Pacini used for his measurements.on the sea in the Gulf of Genova.

Fig. 1.3. Historical photograph of Hess' balloon flight.

At that time the penetrating radiation was identifi with gamma rays so Hess decided to improve the experimental accuracy of the measurement of radiation length by "direct measurements of the absorption of gamma rays in air" [90]. As reported in [33], Hess used probes of about 1 g $RaCl_2$ at distances up to 90 m, and obtained an absorption coefficient consistent with Eve's one. And then also Hess results were in contradiction with those of Wulf. Hess wrote that "a clarification can only be expected from further measurements of the penetrating radiation in balloon ascents" [90] (Fig. 1.3).

Hess made his first ascent on August 28, 1911. "[T]he balloon 'Radetzky' of the Austrian aeroclub with Oberleutnant S. Heller as a pilot and me as sole passenger was lifted" [90]. The ascent lasted four hours, reaching an height of 1070 m above ground. Then Hess made a new ascent during the night of October 12*th* 1911 aboard the balloon ("Austria"). On both balloon ascents Hess found that the intensity of the penetrating radiation was constant with altitude, within errors.

During the next year, from April 1912 to August 1912, Hess flied seven times with three different t instruments. On August 7*th*, 1912, Hess reached 5200 m. As we can see from the reported results (Fig. 1.4), ionization, after passing through a minimum, increases considerably with height. "(i) Immediately above ground the total radiation decreases a little. (ii) At altitudes from 1000 to 2000 m there occurs again a noticeable growth of penetrating radiation. (iii) The increase reaches, at altitudes from 3000 to 4000 m, already 50% of the total radiation observed on the ground. (iv) From 4000 to 5200 m the radiation is stronger [more than 100%] than on the ground" [91].

The conclusion was that the increase of the ionization with height must depend on a radiation coming from above of extra-terrestrial origin. Hess excluded the Sun as the direct source of this radiation because he didn't found any day-night variation. Hess published a summary of his results in Physikalische Zeitschrift in 1913 [92], an this paper reached the wide public.

Kolhörster [94] made balloon experiments after Hess, reaching 9200 m above sea level and confirmed Hess' results. Kolhörster found an increase on the ionization up to ten times. He estimated the absorption coefficient of the radiation as 10^{-5} per cm of air at NTP. It is worth noticing that this value was eight times smaller than the absorption coefficient of air for gamma rays as known at the time.

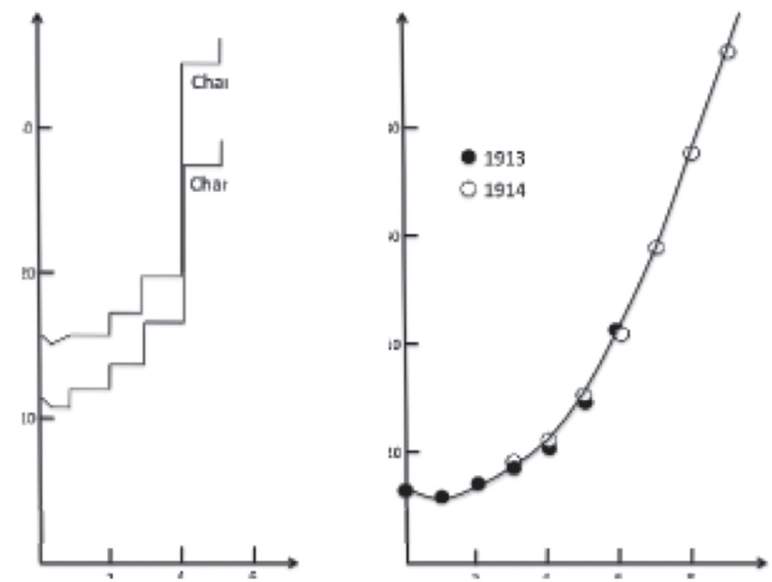

Fig. 1.4. Variation of ionization with altitude. Left panel: August 7th's ascent by Hess (1912), where he carried two ion chambers (chamber 2 was shielded with thicker walls). Right panel: Ascents by Kolhörster (1913, 1914).