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Cosmic Ray Physics in Brazil

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Cosmic rays have long been a topic of intense research activities in Brazil. Due to the contagious enthusiasm and excellence of the men who introduced this field in the country around 1930, a tradition in cosmic ray physics was built and over the past eighty years there have always been one or more groups of scientists dedicating their efforts building detectors, performing experiments and obtaining top results in this research area. Although many physicists spent their lives working in cosmic ray physics in Brazil, one must acknowledge the enormous contribution of Gleb Wataghin and Cesar Lattes to making this one of Brazil's most traditional areas of research in Physics. Wataghin and Lattes are the main protagonists of the story of cosmic ray physics in Brazil.

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1. Introduction

The story of research in cosmic ray physics in Brazil over almost eighty years can be best followed by telling it over four successive periods. Even if the limits of these periods are sometimes blurred in time and part of the periods overlap, each one has its own characteristics and peculiarities. The seeds of cosmic ray research were sown almost simultaneously by Bernhard Gross, in Rio de Janeiro and by Gleb Wataghin, in São Paulo. Those seeds germinated around the two pioneers, grew and became particularly strong in São Paulo, where a group of young and dedicated scientists built detectors and performed measurements of cosmic ray showers at the ground, in a mine, in a tunnel, on a mountain or in a plane. One of the scientists in the group was Cesar Lattes. With him and his work began the second period of the story, with the first major results of the research and the discovery of the pion in nuclear emulsions exposed to cosmic radiation. Although the discovery was made while Lattes was abroad, it strongly influenced the future development of the research in physics, and particularly of cosmic ray physics, in Brazil. Returning to Brazil after participating in the first observation of artificially produced pions, Lattes participated in the creation of the Centro Brasileiro de Pesquisas Físicas in 1949 and of the Conselho Nacional de Pesquisas in 1951. He also contributed to the creation of the Laboratorio de Física Cósmica at the Mount Chacaltaya, in Bolivia, which was to be used by physicists of many countries in their research. The third period is characterized by the research done by the Brazil-Japan Collaboration. Over more than thirty years this collaboration exposed emulsion chambers at Mount Chacaltaya and studied high energy interactions induced by cosmic ray particles at energies between 10^{13} and 10^{17} eV. The fourth period is the contemporary one, in which Brazilian physicists are involved in the Pierre Auger Collaboration to study cosmic rays of the highest energies ever observed. The story of cosmic ray physics in Brazil will be told here with focus on the beginning and on the main developments which enabled the progress and success of the most recent years.

2. The beginning: the pioneers (1934-1949)

The story of cosmic ray physics in Brazil starts in 1933-34 and bears an interesting parallel with the story of the development of systematic research in Physics, and with the creation of universities and research institutions in Brazil. Although modern science in Brazil started much earlier, with the support of the Brazilian Academy of Science from 1916, it was the creation of universities in the third decade and of research institutions and support agencies in the fifth decade of the last century that provided conditions and gave impulse to the development of Science in Brazil. In all these steps the contribution of scientists involved in cosmic ray physics was of great importance.

Two European physicists arriving almost simultaneously in Brazil were responsible for introducing cosmic ray physics to scientists working, respectively, in Rio de Janeiro and in São Paulo. So it happened that research on this topic developed in parallel in these two cities, forming two schools with groups of young students gathering around the two inspiring figures.

The first cosmic ray physicist to arrive was Bernhard Gross, landing in Rio de Janeiro in 1933 just after finishing his PhD in Germany. Gross brought with him results of experiments he had performed there with the group of Erich Regener, measuring the intensity of cosmic rays in the stratosphere and under water. These measurements had been made at 250 m depth at Lake Constance and with probes on balloon flights up to almost 20000 m in the atmosphere. Gross held seminars and gave talks at the Escola Politécnica and at the Instituto de Tecnologia (later named Instituto Nacional de Tecnologia (INT)), presenting interesting aspects of those measurements. A short version of these presentations was published in 1934 and so Gross became the author of the first publication in Brazil about cosmic rays [1].

Gross is best known in the cosmic ray community for his work on the Gross Transformation [2], which relates the absorption of isotropic and unidirectional beams of radiation. Using this transform one can obtain the vertical intensity of a certain radiation per unit solid angle at a certain atmospheric depth in terms of the integral (omnidirectional) rate of that radiation at this depth. He applied this relation to cosmic radiation. This work was done prior to his arrival in Brazil, as was a study of the pressure dependence of the ionization caused by cosmic radiation [3].

In the following years, Gross worked at the INT and dedicated himself to research in cosmic rays and metrology. He published the results of his work in cosmic ray physics in international journals as well as in the Annals of the Brazilian Academy of Sciences [4-10].

His interest in the interaction of radiation with matter that had started in Europe with his early studies of the ionization caused by cosmic rays led him to gradually change the subject of his research and he later studied dielectric properties of various materials, like carnauba wax [11, 12]. After 1940, motivated by his multiple interests, he worked mostly on topics such as the theory of dielectrics, the thermodielectric effect, viscoelasticity and rheology. He was also responsible for the discovery of important charge storage effects in glasses and polymers. His contributions were most important for progress in electret research.

Gross was a complete scientist, analyzing phenomena both from the theoretical and experimental perspectives. He was one of the key players in the development of Physics in Brazil. His students and collaborators often acknowledged the important influence of Gross and his contribution to the development of Physics, as can be found in the words of some of his many students and colleagues, S. Mascarenhas [13] and G. M. Sessler [14]. It is also interesting to follow Gross' own testimony in an interview for a project on the History of Sciences in Brazil [15].

The second scientist to arrive was Gleb Wataghin, who came to São Paulo in 1934. The Governor of the state of São Paulo, Armando Salles de Oliveira, had created the Faculdade de Filosofia, Ciências e Letras (FFCL), that was one of the starting points of the Universidade de São Paulo (USP). He gave Teodoro Ramos, then professor of the Escola Politécnica in São Paulo, the mission of inviting eminent mathematicians and physicists in Europe to attract them to settle in São Paulo and contribute to develop the new Departments of Physics and Mathematics at the FFCL. The Italian mathematician Luigi Fantappié and the Russian-Italian physicist Gleb Wataghin accepted the invitation and by 1935 they were lecturing in São Paulo. The suggestion to invite Wataghin to come to São Paulo came from Enrico Fermi.

With the creation of the Universidade de São Paulo (USP), the Escola Politécnica, the Faculty of Medicine and the Faculty of Law were incorporated to the new university. Students of Engineering attended lectures together with those of the FFCL. At the very beginning Wataghin held lectures in Italian and some of his students began to learn the language just to follow these lectures. But his gift for languages soon allowed him to express himself in Portuguese. He introduced the students to modern physics, talking with his characteristic enthusiasm about the birth of quantum mechanics or the theory of relativity. He also talked about the great physicists responsible for these breakthroughs that he had met in Europe and who had become his friends.

Although he himself was a theoretician, Wataghin initiated research activities both in theoretical and in experimental physics. In 1938 he invited the Italian physicist Giuseppe Occhialini to São Paulo to join the department. Wataghin and Occhialini had worked together in Enrico Fermi's group in Rome. Occhialini had also worked in the period 1931-1934 with Patrick Blackett at the Cavendish Laboratory in Cambridge. They have applied the coincidence counter technique to a cloud chamber and confirmed the discovery of the positron in cosmic rays. His extraordinary experimental skills, acute intuition, insight and creativity made a strong contribution to increasing the expertise and capability of the experimental group in São Paulo.

Mario Schönberg was one of Wataghin's first students and soon started to work with him on theoretical problems. Although he is best remembered for his contributions to astrophysics, he also worked in cosmic ray physics, particularly in the theory of multiplicative showers and on the hard and ultra-soft components of cosmic radiation [16-20].

Among the students of engineering was Marcello Damy de Souza Santos who, inspired by the enthusiasm of Wataghin, became his assistant. He was later joined by Paulus Aulus Pompeia. Both were very keen on electronics, and were responsible for building the coincidence circuits used in the first experiments to explore cosmic radiation done by Wataghin's group. The instrumentation and electronics developed by this group were competitive with those used in Europe and USA at the time, as were the results of their research. The coincidence circuits that were built by the group were ten times faster than others existing in those days and enabled the measurement of penetrating showers, experiments which were at the vanguard of cosmic ray physics at the time.

Systematic measurements of the cosmic radiation started in São Paulo in 1937. As early as this, while preparing an experiment for measuring cosmic rays, Damy and Wataghin published their experimental progress in building new types of counters [21].

In the following decade many experiments detecting penetrating showers of particles in cosmic radiation were performed by Wataghin and his collaborators at ground level, in a tunnel, underground or at mountain altitudes.

In 1938, Wataghin and Marcello Damy published the preliminary results of a series of measurements of the cosmic shower intensity in the gold mine of Morro Velho, in the state of Minas Gerais, at water-equivalent depths of 200 and 400 m [22, 23].

In the following year, having been joined by Paulus Aulus Pompeia, they published in Physical Review the results of observations of groups of penetrating particles in cosmic ray showers which arrived simultaneously at the detectors [24]. Those measurements were done in

São Paulo at about 800 m above sea level. The counters registered groups of particles that had produced fourfold coincidences through a layer of 16 cm of lead.

Results of other measurements were reported to the Brazilian Academy of Sciences in 1940 [25] and published in the following year in the Physical Review [26]. In those measurements the multivibrator circuit that had been built by Damy was used [27].

By 1940 [25] the results of measurements made in the tunnel then under construction at the Avenida 9 de Julho, in São Paulo were presented. Measurements done below 30 m of clay (about 50 m water equivalent) in the tunnel confirmed the existence of showers with at least two associated particles penetrating 20 cm of lead (the thickness of the shielding around the counters) even underground. In the next publication of this series of measurements, the group reported the existence of showers with at least two particles having a range larger than 17 cm of lead and with a size of the penetrating core of the order of 0.2 m^2 [26]. In follow-up measurements, a fifth counter was added which allowed them to estimate a lateral spreading of the penetrating shower core over an area of 1 m^2 [28].

The year of 1941 was exceptional for cosmic ray physics in Brazil. A group of American physicists led by Arthur Compton visited the country on a mission with the purpose of measuring cosmic rays in the southern hemisphere. On this occasion, a symposium on cosmic rays was held in Rio de Janeiro, under the auspices of the Brazilian Academy of Sciences. The contributions of the Brazilian cosmic ray physicists at this symposium were outstanding. The list of authors includes Bernhard Gross, his former student Joaquim Costa Ribeiro, Yolande Monteux, Giuseppe Occhialini, Gleb Wataghin, Marcello Damy, Adalberto Menezes, Mario Schönberg, Francisco Xavier Roser, J. A. Ribeiro Saboya and Paulus Aulus Pompeia. Most of the presentations at this symposium were also published in international journals and only the reference to the annals of the symposium is given here [29]. It was also in this Symposium that Wataghin presented the hypothesis of multiple production of mesons [30]. A more complete treatment of the multiple production of mesons was to be presented by him some years later [31].

In 1941 Cesar Lattes started his studies at the University of São Paulo, also as a student of Wataghin. Wataghin recognized his potential and soon invited him to become his assistant. After graduating in 1943, Lattes started working with Mario Schönberg and Wataghin in Theoretical Physics. In 1944 he was designated third assistant in Theoretical and Mathematical Physics at the Faculdade de Filosofia, Ciências e Letras of the University of São Paulo. In his first work he studied the influence of extreme thermodynamic conditions on the abundance of nuclei in the universe. This work produced his first publication in international journals [32].

During 1945, Lattes was very interested in the activities of Occhialini and the experimental group. Occhialini was trying very hard to install a cloud chamber, but without success. Lattes liked very much to talk about his first experience in theoretical physics and what had been the reason for him to move to experimental physics. He confessed that what had made him change from theoretical to experimental physics was his difficulty in handling the calculations. Then he would add with a smile that the Langrangean he had to work with consisted of 99 terms. He talked about this choice in [33]. Nonetheless, the results of calculations he had done with Schönberg in collaboration with Walter Schützer involving the classical theory of charged point-particles with dipole moments were published in [34].

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Another student initiated his studies at about the same year as Lattes: Oscar Sala. During Compton's mission in 1941, measurements of cosmic ray intensities had been done with balloons launched from some cities in the state of São Paulo. This type of balloon was usually employed in meteorological measurements and reached up to 20 to 30 km in the stratosphere. In Bauru, a young student whose family lived in this city watched the scientists doing those experiments and got inspired and excited: this was Oscar Sala. He decided to study Physics in São Paulo and soon he began also working with Wataghin and measuring cosmic ray showers.

A thorough study of the frequency of penetrating showers was done by Oscar Sala and Wataghin [35]. In this work the authors presented results of comparative studies of showers of penetrating particles at various altitudes with different materials at altitudes of 1750 m and 750 m, in Campos de Jordão and in São Paulo, respectively. The experimental apparatus was similar to that used in previous experiments done by Wataghin and his group. Fourfold coincidence was observed between counters fully surrounded by lead of minimum thickness 10 mm and also separated by 10 cm of lead. Further measurements were done adding an absorber layer of water of 80 cm thickness. From their measurements the authors concluded that "this layer functions as an absorber and as a source of secondary radiation. Our observations seem to indicate that groups of particles penetrating more than 30 cm of Pb are produced in a layer of water of only 80 cm".

A second paper by Sala and Wataghin [36] also reported comparative measurements at different altitudes, at São Paulo (750 m) and Campos do Jordão (1750 m), and around 7000 m with measurements done in three airplane flights. The results showed that the intensity of particles generating the showers of penetrating rays decreased very rapidly with atmospheric depth, probably following an exponential law. For this experiment Wataghin was given assistance by the Brazilian Air Force (FAB).

In the following year, Wataghin published further results of measurements of the variation of the frequency of showers during flights in air plane at an altitude of 22000 feet and 26000 feet. With the inclusion of these two altitudes to the previous ones, he concluded that the observed variation with altitude was in agreement with the assumption of an exponential absorption law for the shower producing primary radiation, estimating the mean absorption length around 101 g/cm^2. Wataghin even reported an estimate of the cross sections per nucleus of oxygen or nitrogen around 2.5 x 10^{-25} cm^2 [37].

Further experiments were done in the group to study the cross section for the production of penetrating showers in various materials. The results of the first series of measurements with water and iron as shower-producing materials were reported in [38]. The data revealed that the cross section per nucleon was larger in water than in iron, indicating that either the absorption coefficient of primaries or the constitution and multiplicity of resulting showers depended on the nuclear structure. One of the authors of this work was Andrea, son of Gleb Wataghin. Meyer and Schwachheim also published an interpretation of the measurements performed by Cocconi [39], considering possible exchange phenomena of the nucleons that generate penetrating showers [40].

In later years two more papers appeared investigating the nature of the primary particles generating penetrating showers from the results of measurements at an altitude of 1750 m above sea level at Campos de Jordão. In the first paper [41] the authors explained their experimental

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results considering two different types of mesons, referring to the publication of Lattes, Occhialini and Powell in 1947, and identified the penetrating particles in the showers as "μ-mesons", as muons were called at that time. In the second paper [42] the mean range of the radiation that generates penetrating showers was determined in the atmosphere and in water, resulting in ~ 120 g/cm^2 and ~ 55 g/cm^2, respectively. No east-west asymmetry was observed of this radiation within the experimental errors. As a curiosity, in this paper the transformation proposed by Gross [2] was used in the study of the absorption of the radiation producing the penetrating showers.

Wataghin returned to Italy in 1949 and continued working in cosmic ray physics. He did not break his ties with the country and the many students, collaborators and friends he had made during the years in Brazil. He returned in the seventies to Campinas, to the recently founded University of Campinas, where Marcello Damy was the director of the Physics Institute and to where Cesar Lattes and his group of cosmic ray physics had transferred. In recognition to his extraordinary contribution to the development of Physics in Brazil, the Physics Institute of the new university was named after him. Wataghin also held lectures in Campinas and a new generation of students could learn from him and be influenced by his enthusiasm while telling about the birth of Quantum Mechanics, about General Relativity and about the production of fireballs in high energy interactions of cosmic rays, which was so dear to him. Then he would always repeat the comment of his friends at that time about this idea, opening his arms and imitating them: "Wataghin, you are dreaming….".

3. The discovery of the pion and its consequences (1946-1959)

When Occhialini arrived in Bristol at the end of the war, he came to work with Cecil Powell. At that time Powell and his group were using nuclear emulsions produced by Ilford Ltd. for studying nuclear reactions. The group had also exposed emulsions to cosmic radiation on the Jungfraujoch, in the Alps, at 3500 m and looked for nuclear disintegration products. Occhialini soon started to work with these emulsions and with some new ones with a higher concentration of silver bromide which had been produced experimentally by Ilford Ltd.

At the same time Lattes was working at USP on a cloud chamber and trying to put it to work in collaboration with Ugo Camerini and Andrea Wataghin. When they finally succeeded, Lattes sent some photographs obtained with this chamber to Occhialini in Bristol and received in return some positive prints of photomicrographs of tracks of protons and alphas in the new concentrated emulsions. Lattes immediately recognized the potential of this type of detector and demonstrated his interest in joining the group in Bristol and working with these new plates. Occhialini and Powell then invited him to come and he arrived in Bristol in 1946. Shortly after his arrival he invited Camerini to join the group and to work with the new emulsions.

One of the first tasks Lattes was given in Bristol was to study the α decay of samarium. Using the new concentrated emulsions and the range-energy relation obtained in the study of d-p and d-α reactions, Lattes and Peter Cuer were able to determine the samarium decay time [43].

Lattes was also given the task of obtaining the shrinkage factor of the new concentrated emulsions and to calibrate them. He decided to investigate the relation between the energy of protons, α particles and other light nuclei and their range in the new emulsions. The protons he used were produced in well-known nuclear reactions induced by homogeneous beams of primary deuterons of 900 keV (produced in the Cockcroft-Walton accelerator at Cambridge) falling on five targets of light elements. Knowing the masses involved it was possible to calculate the energies of the protons. The α particles used in the experiment were from natural decay of radioactive elements. Measuring the mean range of homogeneous groups of protons and alphas, Lattes, Peter Fowler and Peter Cuer were able to obtain a range-energy relation for protons up to 10 MeV which would be useful in future research on single charged particles [44, 45]. In this process he asked the fabricant Ilford Ltd to add borax to the emulsion. His intention was to use the reaction ^{11}B (d, n) ^{12}C to produce a beam of neutrons with an energy distribution peaked at 13.4 MeV and obtain the energy and momentum of the neutrons through the reaction ^{10}B (n, 2α) ^{3}H.

Lattes and Occhialini then decided to expose some emulsion plates at high altitude. Occhialini took the plates to the Pic-du-Midi (2800 m), in the French Pyrenees and exposed them for six weeks. Only some of the plates had been loaded with borax, but all were of the new concentrated type, for which the range-energy relation had been obtained. After recovering the emulsions, Occhialini developed them and a difference between the normal plates and those loaded with borax appeared: the borax-loaded emulsions had many more events than the normal ones. The addition of borax had made the emulsion more resistant to fading and the latent image was kept for a longer time. Consequently a greater number of particle tracks were registered compared to the normal plates. The number and the variety of the tracks in the borax-loaded emulsions were so impressive that the original intention of measuring neutron energy became secondary. After a few days of scanning, one of the microscopists found an unusual event. In Lattes own words, he describes this event as “one stopping meson and, emerging from its end, a new meson of about 600 μ range, all contained in the emulsion” [46]. The larger multiple scattering shown by that track and the variation of the grain density with the range made it possible to distinguish the observed particle from a proton. Within only a few days a second event was observed, but the secondary particle did not stop inside the emulsion. Measuring the grain density, it was possible to obtain the extrapolated range of the same order as in the first event, around 610 μ. The observation of these two events was published in Nature [47]. In the same volume Lattes and Occhialini published the determination of energy and direction of cosmic ray neutrons, obtained by means of such emulsions [48].

When it became clear that a larger number of events was necessary, Lattes went to the Department of Geography of the University and found that there was a meteorological station operating on Mount Chacaltaya, at 5200 m above sea level in the Bolivian Andes, only 20 km far from the capital La Paz. He proposed to Powell and Occhialini that he fly to South America and expose the borax-loaded emulsions. Lattes liked to tell everyone that he chose to fly with the Brazilian company instead of the British one and that this choice saved his life, because the flight he were supposed to be in crashed in Dakar killing all the passengers [46]. The rest of the story is well known. When he returned to Bristol, the emulsions were processed and scanned.

Thirty events were found showing the double meson decays. From the counting of the tracks it was also possible to obtain the mass ratio of the first and second meson. The results were published immediately [49, 50]. The authors identified the heavier meson with the particle predicted by Hideki Yukawa [51] and the secondary particle as the one detected in 1937 by Anderson and Neddermeyer [52] and independently by Street and Stevenson [53].

Lattes left Bristol at the end of 1947 with a scholarship from the Rockefeller Foundation with the intention of working with Eugene Gardner looking for pions produced artificially at the 184-inch cyclotron which had begun to operate at Berkeley. The general expectation was that the beam of α particles of 380 MeV had insufficient energy to produce pions. Lattes believed that the energy could be sufficient in those collisions in which the internal momentum of the nucleon was aligned with the momentum of the beam, providing enough energy in the centre-of-mass system. Only one week after arriving in Berkeley, he was able to find pion tracks in the emulsions. This rapid discovery points out the importance of knowing what to look for. Two papers were published describing the method which had been used and the results. The first one described the observation of negative pions [54] and the second, the observation of positive pions being produced [55]. Most of the results that were reported referred to pions produced in carbon targets. The photographic plates used were those from Ilford. Using the measured range of the pions in the emulsion and the radius of curvature in the applied magnetic field, the mass of the pions was estimated to be about 300 electron masses.

Lattes reported another curious fact in [46]. Just before he was leaving Berkeley in February 1949, Edwin McMillan asked him to look at some plates that had been exposed to gamma rays produced at the 300 MeV- electron synchrotron, then in operation. Lattes tells that in one night he was able to detect about a dozen pions, and that in the next morning he delivered the plates to McMillan with maps informing where to find them. These observations were never reported, but according to Lattes, these would be the first photoproduced pions to be detected.

Lattes returned to Brazil in 1949 and with other Brazilian scientists created the Centro Brasileiro de Pesquisas Físicas (CBPF) in Rio de Janeiro. He left USP and transferred to Rio de Janeiro to become the first director of the new research centre and lecture at the Faculdade Nacional de Filosofia, Universidade do Brasil. In the following years research activities in Physics at CBPF developed and attracted students from all over South America. Cosmic ray physics has been one of the main research fields since the early years. The first scientific work done by physicists in CBPF reflects the legacy of Lattes. Elisa Frota Pessoa and Neusa Margem employed nuclear emulsions irradiated at the accelerator of Berkeley, which were offered by Lattes, for studying the decay of positive pions and concluded that the decay mode resulting in electrons was at least hundred times less frequent than that in muons [56]. Another simple gesture of Lattes impacted on cosmic ray Physics in South America. He presented the Argentinian Estrella Mazzolli de Mathov with some emulsion plates which had arrived from Bristol. Estrella formed a group of students and started to work on these emulsions. This gesture gave an impulse for the future development of cosmic ray physics in Argentina [57].

In 1951 Lattes also participated in the effort to create the Conselho Nacional de Pesquisas (CNPq), now Conselho Nacional de Desenvolvimento Científico e Tecnológico. CNPq is a federal agency, connected to the Ministry of Science and Technology, for fostering research in

Brazil and has been of utmost importance for the scientific and technological development of the country in the last sixty years.

In the same period, work began on the construction of a permanent laboratory of cosmic ray physics at Mount Chacaltaya. Ismael Escobar had been the person responsible for installing a network of meteorological stations in Bolivia, including the one on Mount Chacaltaya that had drawn Lattes' attention when looking for a place for exposing his emulsions. The importance of the discovery of the pion and the observation of its decay by Lattes, Occhialini and Powell had worldwide repercussion and inspired Escobar to present the proposal of constructing a permanent cosmic ray laboratory at Chacaltaya in 1949. His proposal was approved by the Universidad Mayor de San Andrés and by the Bolivian Government in 1951 and the Laboratorio de Física Cósmica was created in this same year. Even before approval, scientists from various countries came to Bolivia in missions to expose detectors to cosmic radiation at this special site. In 1952 an agreement between the Universidad Mayor de San Andrés and CBPF was signed and Brazilian physicists also came to work at Chacaltaya. In the following years scientific expeditions from various countries arrived and meetings were organized and held in Bolivia giving an enormous impulse to the development of Science there. A very detailed report about the history of the Laboratorio de Fisica Cosmica at Chacaltaya over the decades and its relevance for the development of Science in Bolivia and in various other countries can be found in [58]. Various Brazilian physicists were involved in cosmic ray research at the Laboratorio in collaboration with Bolivian physicists and technicians. Apart from Lattes, also Occhialini and Camerini, both returned from Bristol to CBPF, Roberto Salmeron, Hervasio de Carvalho, Alfredo Marques, Rudolph Thom, Ricardo Palmeira, Fernando de Souza Barros worked there with Ismael Escobar and Alfredo Hendel from Bolivia, just to name a few. Georges Schwachheim and Andrea Wataghin developed a project for studying the dependence of penetrating shower creation on altitude, but their results were not published in international journals.

In the early fifties the main instrumentation for research in cosmic ray physics was available at CBPF and subsequently taken to Chacaltaya. Whenever possible, the transportation from Rio de Janeiro to La Paz was done in regular flights of the Correio Aéreo Nacional of the Brazilian Air Force, which assisted in transporting equipment and personnel to and from Bolivia. For larger or heavier detectors, when the use of planes was impossible, transportation was done by train and small trucks. Rivers were crossed in ox carts. Such expeditions are described and documented in [59]. One expedition was organized for transporting to Chacaltaya a cloud chamber donated to CBPF by Marcel Schein, from the University of Chicago. The intention of Lattes and collaborators was to use the chamber for measuring the mean life time of the pion and investigating the density and energy spectrum of showers at Chacaltaya. They also intended to study other mesons and unstable particles in the detected showers.

Between 1955 and 1956 Lattes spent a sabbatical in the United States, as Research Associate at the Enrico Fermi Institute for Nuclear Studies of the University of Chicago and later at the University of Minnesota. He participated in studies of the decays of pions produced in high-energy cosmic ray interactions. Nuclear emulsions were used as detectors and exposed on balloons at 30 km altitude. From this period came publications [60, 61].

Returning to Brazil in 1957 Lattes resumed his research and teaching activities at CBPF and at the Universidade do Brasil in Rio de Janeiro. In 1960, Schoenberg invited him to return to the University of São Paulo. He accepted the invitation and initiated a research group at USP for investigating cosmic ray interactions at high energies with nuclear emulsions exposed at Chacaltaya.

Between 1960 and 1962 Lattes also participated in the project "International Cooperative Emulsion Flight", with emulsion chambers that had been exposed to cosmic radiation in balloon flights by Marcel Schein and his co-workers from the University of Chicago. The balloons reached an altitude of around 30 km. After chemical processing, the emulsions were distributed among various laboratories in 15 different countries. The group of Lattes in USP was one of those.

A new period of intense experimental activities started in the early sixties, when Lattes and collaborators prepared the construction of the first emulsion chambers to be exposed at Mount Chacaltaya, by the Brazil-Japan Collaboration.

4. The Brazil-Japan Collaboration (1959 -)

At the end of the second period the pressure on the field of cosmic ray research was growing, with more accelerators being built and attaining even higher energies. Research in cosmic rays gradually changed the focus to studying nuclear interactions at energies unobtainable in accelerators at the time.

In the third period the majority of physicists dedicated to cosmic ray physics in Brazil were participating in the emulsion chamber experiment with the Brazil-Japan Collaboration. This collaboration lasted over thirty years and produced significant results about nuclear interactions induced by cosmic ray particles at energies between 10^{13} and 10^{17} eV.

It is interesting to remember the circumstances that resulted in this fruitful collaboration and the ties that connected physicists from those two countries. The discovery of the pion and its decay into the lighter muon by Lattes, Occhialini and Powell in 1947 gave decisive evidence of the existence of mesons predicted in 1935 by Hideki Yukawa [51] and was consistent with the hypothesis of the two-meson theory of Sakata and Inoue [62] and also of Tanikawa [63]. It is worth mentioning that although these authors presented their theories in Japan in 1942, the corresponding papers were published in international journals only years later. Japanese physicists had also participated in discussions about the spin of the particle predicted by Yukawa. While Marshak and Bethe [64] presented arguments in favour of it being a fermion, Taketani and his collaborators defended the idea that the particle responsible for nuclear forces should be a boson [65]. Yukawa received the Nobel Prize in Physics in 1949 after the confirmation of existence of mesons. This was a very important event for Japan at that time still recovering from the war. In recognition of this importance, the community of Japanese immigrants in Brazil and their descendants started a movement to invite Yukawa to São Paulo and collected funds for his visit. Yukawa's health prevented him from accepting the invitation at this occasion, so that the funds were sent to Japan to be used in the support of research activities

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there. In particular, part of the money was given to a group of young experimentalists for a study of cosmic rays using nuclear emulsions. Y. Fujimoto reports in [66] about the importance of this support and the influence it had on the future development of collaborative research activities between scientists of Brazil and Japan. In his testimony, he describes the progress achieved in producing nuclear emulsion plates of good quality in Japan. Fujimoto also reports about a project to develop a new type of detector consisting of a multi-layered sandwich of lead plates and photosensitive material. The photosensitive layers were composed of nuclear emulsion plates and highly sensitive X-ray films also made in Japan. These X-ray films recorded electromagnetic showers as a black spot which is distinguishable to the naked eye for showers of 1 TeV or above. The X-ray films were added to enable a faster scanning by naked eye over large areas. Such a detector was tested in a balloon flight in 1956 and was successful in the observation of mesons produced in high energy cosmic interactions. In order to attain higher energies, it was planned to increase the area of this emulsion chamber, as the detector was named, exposing it to cosmic rays at Mount Norikura, at 2800 m above sea level, in 1958. Since this altitude was found to be too low for a reasonable flux of events to be observed, the Japanese group considered the possibility of exposing such a chamber at Mount Chacaltaya, where Lattes had exposed the emulsions in which the pion had been discovered. It was also known in Japan that Lattes was still working at the Laboratorio de Física Cósmica, so the idea of collaboration was natural.

So it came about that in 1959 Yukawa wrote a letter to Lattes informing him about the Cooperative Emulsion Group of Japan that experimental physicists had organized in 1954 and presenting the intention of this group to carry out an experiment at Mount Chacaltaya. Yukawa also suggested that this experiment should be done in a collaboration between Japanese and Brazilian groups. Lattes responded positively and in 1961, when he visited Japan to attend the International Cosmic Ray Conference at Kyoto, he met the group of Japanese scientists and together they planned the steps to turn the project into reality. This was the birth of a long-lasting and fruitful collaboration among institutions in both countries. In more than thirty years twenty five emulsion chambers have been assembled at the Laboratory at Mount Chacaltaya, the first one in 1962 and the last one in 1993.

The basic structure of the emulsion chambers exposed at Mount Chacaltaya was of a multi-layered sandwich of lead plates and photosensitive layers of nuclear emulsion plates and X-ray films of high sensitivity. A typical assembly of the chambers consisted of an upper chamber, a target layer of pitch, an air gap of 150 cm and a lower chamber. In this way the upper chamber was intended to detect showers initiated in the atmosphere or in its lead plates, at the same time working as shield for the lower chamber against atmospheric gamma rays and electrons. The pitch layer was almost transparent to gamma rays produced in local interactions due to its thickness and the low atomic number of the constituent carbon. The lower chamber recorded showers produced in nuclear interactions at the target layer. The air gap provided the traveling distance necessary for sufficient separation among the gamma rays in the lower chamber. Typical dimensions of the upper and lower chamber are 44 m^2 and 33 m^2, respectively. The average time of exposure of a chamber was around 500 days.

An excellent review of the main results obtained by the Brazil-Japan Collaboration over the years up to 1980 is given in [67]. Results were also presented regularly at the International

Cosmic Ray Conferences which occur every two years and congregate the community of cosmic ray physicists worldwide.

Systematic studies of nuclear interactions in the carbon layer and in the atmosphere revealed three phenomenological types of pion multiple production, called mirim, açu and guaçu (meaning small, large and very large in the native Brazilian Indian language, respectively). Mirim jets were those consistent with simple scaling extrapolation from the accelerator region around 1 TeV. Açu jets were considered responsible for the scaling breaking, and their frequency showed an increase with energy, being ~50% by 100 TeV. Guaçu jets were found in the atmospheric interactions at even higher energies, around 1000 TeV. The gamma rays produced in those three intermediate states are characterized by increasing average transversal momentum, and increasing rapidity density. Further, the multiplicity increases more quickly with energy than predicted by a logarithmic dependence and a positive correlation between the rapidity density and the average transversal momentum was observed. Three fireballs were supposed to correspond the three types of jets, characterized by rest energies around 2~3 GeV, 15~30 GeV and 100~300 GeV, respectively.

Among the interesting results of the Brazil-Japan Collaboration was the observation of events named Centauro. The main characteristic of this type of event was the almost total absence of gamma rays that originated from neutral pion decays, and the presence of a large number of decays attributed to hadrons. The observation was reported by the Collaboration at the International Cosmic Ray Conference of 1973 [68]. This type of interaction has never been observed in accelerator experiments. Presently the CASTOR detector, which is part of the CMS experiment at the Large Hadron Collider at CERN, will allow detailed studies of particles produced in collisions at energies 14 TeV in the centre-of-mass system, which correspond to the cores of cosmic ray showers. The search for exotic interactions such as those observed in cosmic rays is one of the motivations for this detector in the very forward region. Brazilian physicists under the leadership of A. Santoro are participating in the experiment.

It is worth mentioning that in one of the first lines of a publication of the Collaboration concerning fireballs in pion multiple production [69] one can read "about the pioneer work of Wataghin in 1941, in which he introduced the idea of a fire-ball from his cosmic-ray experiment on penetrating showers…". That had been the contribution of Wataghin at the Symposium on Cosmic Rays held in Rio de Janeiro in 1941 [30].

In the thirty years of collaboration many Japanese physicists visited Brazil. Yoichi Fujimoto, Shunichi Hasegawa, Akinori Ohsawa, Toru Shibata, Kei Yokoi, Kotaro Sawayanagi, Naoyuki Arata and many others stayed for long and short periods in Rio de Janeiro and Campinas, working together with the Brazilian colleagues.

In Brazil, physicists participating in the research activities were from institutions in the states of São Paulo (first at USP and from 1967 on at the University of Campinas, to where Lattes and his group had transferred) and Rio de Janeiro (CBPF from 1964 on, and latter also Universidade Federal Fluminense). In Campinas, many physicists worked with Lattes over the years, as Edison Shibuya, Armando Turtelli, Claudio Santos, Marta Mantovani, José Augusto Chinellato, Margarita Ballester, Carola Dobrigkeit, Miguel Luksys, José Bellandi, Valdir Rodrigues, Marcio Menon and many others. In Rio, the first physicist from CBPF to get involved in the collaboration was Anna Maria Freire, soon joined by Neusa Margem Amato and

Francisco de Oliveira Castro, and later by Carlos Navia and Regina Maldonado from UFF. When Lattes retired from the University of Campinas, Edison Shibuya took over the work leading the Brazilian team.

Many students were also involved in the experiment, working in the assembling and disassembling of the chambers, in the development of the X-ray films and emulsions, and in the analyses of the results. Most of them obtained their PhD and continued later on working in cosmic ray physics. These students form the third generation of cosmic ray physicists in Brazil.

5. The Pierre Auger Observatory (1992 -)

In the beginning of the nineties, a new and challenging idea to focus on cosmic ray research in the highest energy region motivated the inception of the Pierre Auger Observatory.

The Pierre Auger Observatory is the largest cosmic ray detector ever built and is the result of an ongoing effort of a major international collaboration involving more than 350 scientists from 17 countries. Its main goal is the study of cosmic rays of the highest energies observed so far - above 10^{18} eV - to get clues about their composition, energy spectrum, origin, and acceleration mechanisms.

The Auger Observatory is located in the Argentinian pampas, near the town of Malargüe, at 1400 m above sea level. It explores two complementary techniques to detect air showers induced by cosmic rays of extreme energies: water-Cherenkov detectors and fluorescence telescopes. A water-Cherenkov detector consists of a polyethylene tank filled with pure water, three photomultipliers, solar panels and batteries for driving the electronics, an antenna for data transmission and a GPS receiver to fix the time of arrival of the shower particles at the detector. The water Cherenkov detectors are used to measure the energy flow of electrons, photons and muons in the air shower. Cherenkov light produced in the water of a tank by shower particles is collected by the photomultiplier tubes. The surface array of the Observatory is comprised of 1660 water-Cherenkov detectors deployed over the area of 3000 km^2 on a hexagonal grid with 1.5 km side. The volume over the surface array is covered by 24 fluorescence telescopes, installed in four buildings on the perimeter of the surface array. The telescopes measure the faint fluorescent light emitted isotropically by nitrogen molecules excited by showers particles traversing the atmosphere. Each telescope consists of a camera that collects light falling on an 11 m^2 spherical mirror. The camera consists of 440 photomultipliers. Schmidt optics is adopted to eliminate coma aberration. Above 3 x 10^{18} eV a shower arriving at an angle below 60° is detected by the surface array with 100% efficiency. A detailed description of the detectors of the Pierre Auger Observatory and their operation and performance is given in [70, 71].

Although the construction of the Auger Observatory was completed in 2008, data taking has been continuous since January 2004, even during the construction. The most significant results published by the Pierre Auger Observatory refer to the energy spectrum [72], the arrival direction distribution [73-75] and composition of the cosmic rays [76]. Results involving limits on the neutrino fluxes [77, 78] and on the photon fraction [79, 80] have also been published. Updates of the most important results obtained recently by the Pierre Auger Observatory were the focus of a contribution to these Proceedings [81].

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Cosmic ray physicists in Brazil have participated in the Pierre Auger Observatory in Argentina since the beginning of the project, under the leadership of Carlos Escobar and Ronald Shellard. Both acted as chairman and co-chairman of the Auger Collaboration, respectively, for two successive mandates.

Brazilian physicists participated in the stages of construction, data taking and in the analyses of the data. Their contribution to the construction of the Auger Observatory was significant both for the surface array and the telescopes. Industries in Brazil were also involved in the development of the detectors for the Pierre Auger Observatory.

One of the major contributions of Brazilian collaborators to the construction of the Observatory was in the production process of the corrector lenses for the fluorescence telescopes. The inclusion of a corrector ring in the outer radial part of the diaphragm was motivated by the idea of increasing the effective light collection area of the telescope and also increasing the signal to noise ratio, without causing a significant loss in resolution. The Brazilian group studied the optical system doing simulations of its performance with different designs of the corrector ring, and concluded about the most suitable shape of the ring. The next step consisted in finding the industry in Brazil which had the expertise and capability to produce the ring and develop the machinery necessary for the production. The enterprise Schwantz Ltd, in the city of Indaiatuba, accepted the challenge of producing the corrector ring for the Observatory and designed and built the proper machinery for the production. Diamond grinding tools were used to shape the ring of lenses with inner radius of 85 cm and outer radius of 110 cm, divided in 24 segments of aspherical shape. After the production of the first complete set of segments, the prototype was tested and the performance approved. All the 24 telescopes of the Observatory and also the three telescopes of the High Elevation Auger Telescopes (HEAT) extension are equipped with such corrector rings. The full report about the manufacturing of the Schmidt corrector lenses is presented in [82].

There was also Brazilian participation in the first design of the aperture box, shutters and safety curtains for the fluorescence telescopes.

The contribution for the surface detector was also significant. Practically half of the 1660 tanks of polyethylene were produced by Brazilian industries Rotoplastyc and Alpina. Also a large fraction of batteries which power the electronics for the data acquisition is Brazilian, from Moura.

Presently there are physicists from Brazil acting as coordinators and conveners of Physics Tasks and Detector Performance Tasks and also many participants in the various analysis tasks.

The participation of Brazilian institutions and physicists has received the continuous support of the agencies fostering the development of Science in Brazil (FAPESP, FAPERJ, CNPq, FINEP and MCT). The scientific director of FAPESP was chairman of the Finance Board of the Auger Collaboration in two mandates.

It is worth mentioning that with the Pierre Auger Observatory the community of cosmic ray physicists in the country expanded and exceeded the limits of the axis São Paulo - Rio de Janeiro. Presently physicists from eleven institutions in Brazil are involved in the operation of the Observatory and in the analysis of the data. In the state of Rio de Janeiro, the institutions are Centro Brasileiro de Pesquisas Físicas, Pontifícia Universidade Católica, Universidade Federal do Rio de Janeiro and Universidade Federal Fluminense. In the state of São Paulo there are

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physicists from Universidade Estadual de Campinas, Universidade Federal do ABC and Universidade de São Paulo (both the Physics Institutes in São Paulo and in São Carlos) participating. In the state of Bahia three universities are also involved: Universidade Estadual de Feira de Santana, Universidade Estadual do Sudoeste da Bahia and Universidade Federal da Bahia.

In all those institutions young scientists of the fourth generation in cosmic ray physics are initiating new groups working in cosmic ray physics. The students that are presently working under their supervision form the fifth generation of cosmic ray physicists in Brazil.

6. Conclusion

What is common in all four periods is that the work done in cosmic ray physics in Brazil has always been at top level and competitive at the international level.

Particularly important in the first period was the pioneer work of Gleb Wataghin and his group in São Paulo, both from the point of view of the theoretical prediction of Wataghin about multiple meson production and from the experimental results obtained by him and his students. It is worth mentioning that all the work was done far from the main centres of Physics at the time. Wataghin always took care that the results were presented in international journals and at a time when the access to international journals was much more difficult than nowadays he proved to be well aware of the latest achievements and developments in mainstream Physics. Wataghin knew how to overcome the isolation of Brazil from the main centres in Physics. He published many of the results in Letters to the Editor of Physical Review, so the results could become public faster. He cultivated good relationships with important physicists worldwide and made it a tradition to send his students abroad. He sent his students to work with the most famous scientists. [1] This tradition also facilitated the exchange of ideas with scientists of the highest level and contributed to the development of Physics in Brazil.

Wataghin and Lattes left a legacy for the new generations working in cosmic ray physics in Brazil. They both set international standards in their work and worked at the frontier of knowledge in their fields. They always worked in intense collaboration with physicists from other countries.

The new generation of cosmic ray physicists in Brazil follows the tradition and keeps the strong international cooperation alive. It is up to them to sustain this atmosphere of internationalism and vanguard, continuing the tradition left by their predecessors.

[1] Just to name a few: Marcello Damy went to Cambridge to work with William Bragg, Paulus Aulus Pompeia was sent to Chicago and worked with Arthur Compton, Mario Schoenberg went to Rome and worked with Enrico Fermi, Sonia Aschauer was sent to Cambridge to work with Paul Dirac, Walter Schützer was sent to work with Eugene Wigner in Princeton, Jayme Tiomno worked with John Wheeler and Eugene Wigner in Princeton, Oscar Sala was sent to Wisconsin to work with Raymond George Herb and finally Cesar Lattes and Ugo Camerini went to Bristol to work with Cecil Powell.

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This report is a personal recollection, rather than a historical document. Therefore it is strongly biased by the reminiscences of the author, who had the opportunity to know many of the protagonists and to work on cosmic rays over many years. The author would also like to thank all the colleagues in the Brazil-Japan Collaboration and in the Pierre Auger Collaboration, with whom she had the pleasure of sharing the adventure of exploring cosmic ray physics over the last decades.

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