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THE CONTRIBUTIONS OF BRUNO B. ROSSI TO PARTICLE PHYSICS AND ASTROPHYSICS

GEORGE W. CLARK
Massachusetts Institute of Technology, Cambridge, MA

Abstract. Bruno Rossi made fundamental contributions to experimental cosmic-ray and particle physics in the years before the rise of accelerators. Then he turned to new areas of exploratory research opened by the availability of space vehicles. He established a program for measurement of the interplanetary plasma, and he initiated the search for celestial sources of X-rays that opened the field of extra-solar X-ray astronomy. His books and review articles are a rich source of information about physics and physicists in the twentieth century.

1. INTRODUCTION

Bruno Rossi began his career in 1928 at the University of Florence as assistant in the Physics Institute located on the hill of Arcetri overlooking the city. Among its brilliant company was Giuseppe Occhialini, who became Rossi's first student and lifelong friend. In his autobiography, *Moments in the Life of a Scientist,* Rossi wrote how he searched for a project that would address a "fundamental problem of contemporary physics" that could be undertaken with the modest means available in the Institute. After a year of frustration, he happened to read a paper by Walther Bothe and Werner Kohlhörster.[1] It described an experiment with two parallel Geiger counters placed one above the other inside a box with thick walls of lead and iron. The counters were connected to fiber electrometers whose deflections, recorded photographically on moving film, sometimes coincided. The rate of coincident pulses decreased only slightly when a 4.1-*cm* thick gold brick was inserted between the counters. Coincident pulses were clearly caused by charged cosmic-ray particles that passed through the lead and iron and both counters. This was something entirely new in cosmic ray research. The experiment employed two revolutionary inventions of experimental physics – the tubular discharge counter invented by Hans Geiger and Wilhelm Müller in 1928, and the coincidence method invented by Bothe in 1924 for a study of Compton scattering. The experiment proved that cosmic rays contain charged particles with energies far greater than that of any previously known radiation.

[1] Bothe, Walter; Kohlhörster, Werner (1929). "Das Wesen der Höhenstrahlung", *Zeitschrift für Physik* 1929, *56*: 751.

To understand the impact of this paper on Rossi, one must recall the state of cosmic-ray and particle physics at the time. There had been only two devices available for cosmic-ray studies – the Wulf fiber electrometer for measuring ionization inside a sealed container, and the randomly expanded cloud chamber. There were only three apparently fundamental particles known to physics – electron, proton, and photon. The known energetic radiations were the well-understood emissions of radioactive elements, X-rays generated with high-voltage transformers, and the mysterious *Höhenstrahlung* discovered in 1912 by Victor Hess in a balloon flight in which he measured a four-fold increase in the ionization rate with Wulf electrometers as he ascended to an altitude of 5300 *m*.[2]

Since 1923 Robert Millikan had dominated cosmic-ray research with his fame, position, and large resources. He gave Hess's Höhenstrahlung the more marketable name *cosmic rays*. And he developed refined electrometers with which he measured the rates of ionization in the air, under water and around the world. Millikan interpreted his absorption curves as proof that cosmic rays were "high-frequency" gamma rays with discrete energies, which he believed matched the energies that would be released in the formation of atoms by fusion of hydrogen. He propounded an *atom building hypothesis* according to which cosmic rays were the *birth cries* of atoms formed by fusion of hydrogen in interstellar space.[3] In the face of evidence for cosmic rays with more energy than could be derived from fusion, he switched to an *atom annihilation hypothesis*.[4]

In 1927 Jacob Clay reported measurements of ionization rates obtained during a voyage from Holland to Java.[5] He found the rates decreased by several per cent to a minimum near the geomagnetic equator. This *latitude effect* proved that primary cosmic rays are deflected by the earth's magnetic field and must therefore be charged particles, not gamma rays. In the same year Dmitry Skobeltzyn published a photograph of a nearly straight track made by a high-energy particle in a randomly expanded cloud chamber that he had operated in a magnetic field for the purpose of measuring the tightly curled tracks of Compton recoil electrons. He noted the peculiar track but did not call it a cosmic ray. In 1929 he published a more complete report on "sehr schneller β-Strahlung", in which he attributed nearly straight tracks to cosmic ray particles.[6]

2. 1930-1938

Rossi had accepted the conventional wisdom that cosmic rays were gamma rays, but gave no credence to Millikan's theory of their origin. At the same time, he had seen no way to make a useful contribution to cosmic-ray research with the modest means available in his laboratory. And he was apparently not aware of the Clay and Skobeltzyn results. Rossi wrote about his reaction to the Bothe-Kohlhörster paper:

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[2] Hess, Viktor (1912). "Über Beobachtungen der durchdringenden Strahlung bei Sieben Freiballonfahrten", *Physikalische Zeitschrift* 1912, *13*: 1084.

[3] Millikan, Robert A.; Cameron, George H. (1928). "The Origin of the Cosmic Rays", *Review of Modern Physics* 1928, *32*: 533.

[4] Millikan, Robert A. (1949). "The Present State of the Evidence for the Atom-Annihilation Hypothesis", *Review of Modern Physics* 1949, *21*: 1.

[5] Clay, Jakob (1927). *Proceedings of the Amsterdam Academy of Sciences* 1927, *30*: 1115.

[6] Skobeltzyn, Dmitry (1929). "Über eine neue Art sehr schneller β-Strahlung", *Zeitschrift für Physik* 1929, *54*: 686.

> Here lay before me a field of inquiry rich in mystery and promises. Working in a field of this kind had been my dream. Now it seemed that this dream was coming true.

With some help from his colleagues, Rossi fabricated Geiger counters, and powered them with a bank of batteries. And he invented the *coincidence circuit*.[7] It employed triode vacuum tubes and was capable of registering coincident pulses from any number of counters with a ten-fold improvement in time resolution over the mechanical method of Bothe. The Rossi coincidence circuit was the first effective electronic device of particle physics. It was quickly adopted by experimenters around the world. Rossi used it in a series of experiments that are an essential part of the foundation of cosmic-ray and particle physics.

Fig. 1. Bruno Rossi in his laboratory at the Physics Institute of the University of Florence, ca. 1930. To his right are Geiger counters; in front are the batteries with which he powered them. (Rossi family collection.)

An early experiment checked whether the charge of the penetrating particles detected in the Bothe-Kohlhörster experiment carried negative charge as expected on the presumption that they were recoil electrons from Compton scattering of cosmic gamma rays. Rossi fabricated a *magnetic lens*, suggested by Antonio Puccianti, consisting of two adjacent vertical iron slabs magnetized in opposite horizontal directions. Two Geiger counters placed above and below the slabs and connected to a coincidence circuit favored detection of the passage of positive or negative penetrating particles through the iron slabs depending on the direction of current in the magnet coils. Much to his surprise, Rossi found that the counting rate for positive particles was slightly greater than for negative particles.[8] Seven years later in America, the penetrating particles were found to be a nearly equal mixture of positive and negative mesotrons, particles now called muons, with a mass between the electron and the proton.

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[7] Rossi, Bruno (1930). "Method of Registering Multiple Simultaneous Impulses of Several Geiger Counters", *Nature* 1930, *125*: 636.
[8] Rossi, Bruno (1931). "Magnetic Experiments on the Cosmic Rays", *Nature* 1931, *128*: 300.

During a visit to Bothe's Berlin laboratory in the summer of 1930, Rossi learned about Störmer's theory of the motion of a charged particle in a dipole magnetic field like that of the earth. He drew from the complex mathematics a previously unrecognized simple consequence, that if the primary cosmic rays are charged particles with one charge sign, then there will be a difference between the cosmic ray intensities from the east and the west.[9]

Back at Arcetri, Rossi measured the east and west intensities with a directional detector consisting of two parallel Geiger counters mounted on a swivel frame and connected to a coincidence circuit. He found no statistically certain difference. Knowing from his theory that the effect would be greater at low geomagnetic latitudes and high altitudes, Rossi began to plan an expedition to Asmara near the equator in the mountains of the Italian colony of Eritrea.

In the autumn of 1931 Enrico Fermi invited Rossi to give the introductory talk on cosmic rays at the Rome conference on nuclear physics. There Rossi met Millikan and Arthur Compton for the first time. Rossi began his talk with a prescient statement that he recounted in his autobiography:

> The most recent experiments have produced evidence of such strange events that we are led to ask ourselves whether the cosmic radiation is not something fundamentally different from all other known radiations, or, at least, whether in the transitions from the energies which come into play in radioactive phenomena to the energies which come into play in cosmic-ray phenomena the behavior of particles and photons does not change much more drastically than until now it was possible to believe.

He then discussed the recent experimental evidence for the corpuscular nature of cosmic rays and their extraordinarily high energies. The facts demolished Millikan's two pet ideas, that cosmic rays were gamma rays and the birth cries of atoms. Rossi wrote "from that moment on [Millikan] refused to recognize my existence." Years later, Compton gave Rossi his first appointment in America and told him that it was Rossi's talk in Rome that had inspired him to undertake his own cosmic ray research.

Among the experiments Rossi carried out at Arcetri in 1931 and 1932, three are of fundamental importance in the development of cosmic-ray and particle physics. Each required a triple coincidence among three Geiger counters.

Figure 2 shows a sketch from Rossi's notebook of the arrangement of Geiger counters and lead blocks with which he demonstrated that 60 percent of the charged cosmic-ray particles capable of traversing 25 *cm* of lead could also traverse 1 meter of lead.[10] The result proved the presence in cosmic rays of penetrating particles with energies more than 2 billion electron volts. Success in such a low counting-rate experiment depended critically on the triple coincidence requirement to reduce the rate of accidental coincidences.

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[9] Rossi, Bruno (1930). "On the Magnetic Deflection of Cosmic Rays", *Physical Review* 1930, *36*: 606.

[10] Rossi, Bruno (1932). "Absorptionmessungen der durchdringenden Korpuskularstrahlung in einem Meter Blei", *Naturwissenschaften* 1932, *20*: 65.

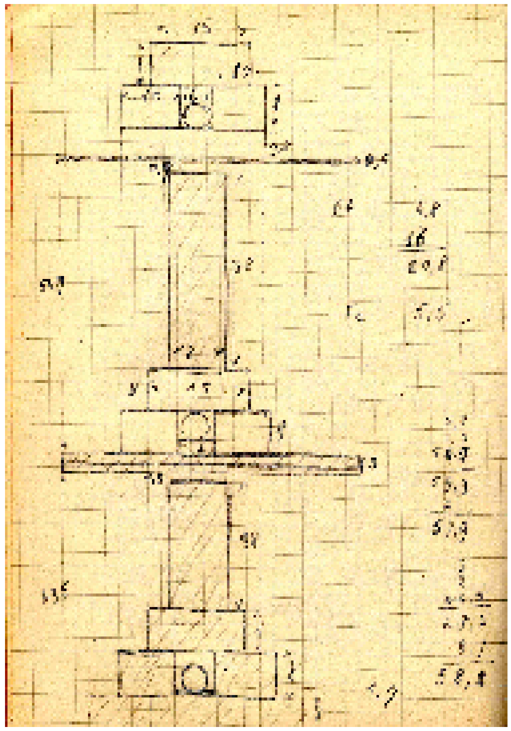

Fig. 2. Sketch from Rossi's laboratory notebook of the experimental arrangement for measuring penetrating particles that penetrated one meter of lead. (From MIT Archives and Special Collections.)

In another experiment, Rossi placed three counters in a triangular configuration surrounded by lead shielding as shown in Figure 3.[11] Since a single penetrating particle could not discharge all three counters, triple coincidences showed that interactions of cosmic rays in the shield above the counters produced showers of particles. The result was so astonishing that one journal refused to publish it, and another accepted it only after Werner Heisenberg vouched for Rossi's reliability. The discovery was soon confirmed by the photographs of particle showers obtained with the counter-controlled cloud chamber of Blackett and Ochialini.[12]

[11] Rossi, Bruno (1932). "Nachweis einer Sekundärstrahlung der durchdringenden Korpuskularstrahlung", *Physikalische Zeitschrift* 1932, *33*: 304.

[12] Blackett, Patrick M.S.; Occhialini, Giuseppe P.S. (1933). "Some Photographs of the Tracks of Penetrating Radiation", *Proceedings of the Royal Society (London)* 1933, *A139*: 699.

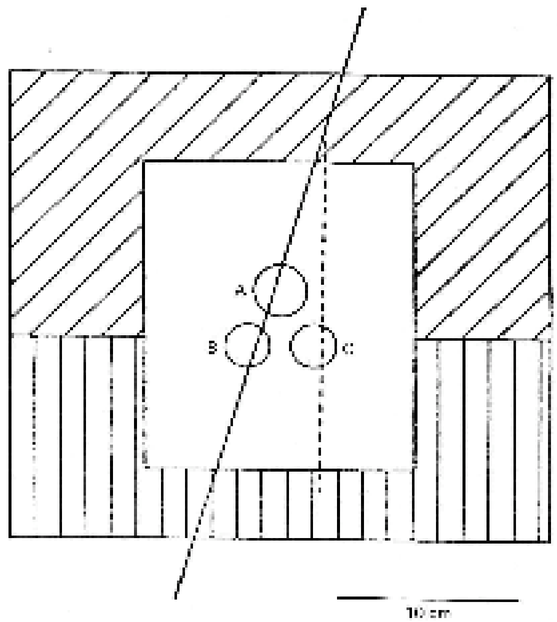

Fig. 3. Experimental arrangement for detection of particle showers produced by interactions of cosmic rays in the material above the counters.

In 1931 Rossi had arranged for Occhialini to visit the laboratory of Patrick Blackett at Cambridge University. Occhialini arrived with the idea of triggering cloud chamber expansions on signals from a coincidence circuit connected to Geiger counters placed above the chamber. With Blackett he developed the counter control system, which gained a huge advantage over random expansion and made possible systematic cloud-chamber studies of cosmic-ray phenomena.

In a third experiment, Rossi measured the occurrence rate of showers as a function of the thickness of a screen of lead or iron placed above the triangular arrangement of counters.[13] The result, displayed in Figure 4, was called the *Rossi curve*. It demonstrated the presence in cosmic rays of two distinct components: a *soft component*, soon identified as electrons and photons, which readily produces showers and is rapidly absorbed in lead, and a *hard component*, consisting of penetrating particles (muons) that produce showers much less readily, and is only gradually attenuated in lead. The Rossi curve and its dependence on the atomic number of the screen provided a critical test of the Bhabha-Heitler theory of electron-photon cascade showers.

[13] Rossi, Bruno (1933). "Über die Eigenschaften der durchdringenden Korpuskularstrahlung in Meeresniveau", *Zeitschrift für Physik* 1933, *82*: 151.

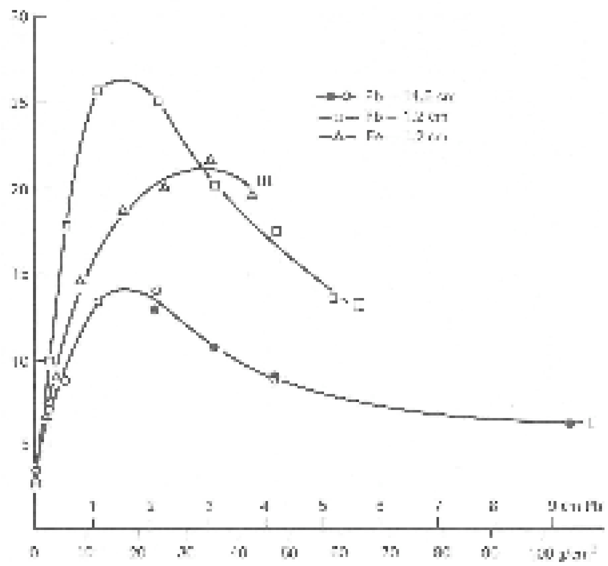

Fig. 4. The Rossi curves showing the growth in the rate of shower production in lead and iron, and the subsequent absorption of the shower–producing radiation. The soft component (photons and electrons) causes the rapid rise and initial decrease in the shower production. rate. The long tail of the lead curve is caused by the hard component (muons).

In 1932 Rossi was called to the University of Padua as professor of experimental physics. In addition to teaching and research, he had the responsibility for developing the new Institute of Physics, which stands today as a monument to his plan and management. Occupied by many duties, Rossi finally found time in 1934 to carry out the measurement of the East-West effect he had planned in 1930. As he was about to depart for Eritrea, he read reports of two experiments in Mexico City that had measured the effect[14,15] with results that his own measurements would soon confirm.[16] The intensity turned out to be greater from the West, which proved that most primary cosmic rays are positive particles, not negative electrons as had been expected. (In 1948 the primaries were identified as protons and the nuclei of heavier elements.) Both publications of the Mexico City results cited a theory of Lemaître and Vallarta published in 1933 instead of Rossi's 1930 paper. So Rossi missed both priority of discovery, and proper recognition of his prediction.

During a test of his equipment at Asmara, Rossi discovered extensive cosmic-ray air showers, a phenomenon that would prove to have great astrophysical significance

[14] Johnson, T.H. (1934). "The Azimuthal Asymmetry of the Cosmic Radiation", *Physical Review* 1934, *41:* 834.

[15] Alvarez, L.; Compton, Arthur (1934). "A Positive Charged Component of Cosmic Rays", *Physical Review* 1934, *41*: 835.

[16] Rossi, Bruno (1934). "Misure sulla distribuzione angolare di intensita della radiazione penetrante all'Asmara", *Ricerca Scientifica* 1934, *5(1)*: 579.

because it reveals the properties of the highest energy cosmic rays. Rossi made the discovery during a check of the rate of accidental coincidences between pulses from the two Geiger counters used in his directional detector. To make the test, he placed the two counters some distance apart in a horizontal plane. Rossi found the coincidence rate was larger than the expected accidental rate derived from the counting rates of the individual Geiger counters and the resolving time of the coincidence circuit. In his 1934 publication about the Eritrean expedition he wrote[17] (Rossi's translation):

> It would seem therefore (since doubts about possible disturbances were ruled out by appropriate control experiments) that once in a while there arrive on the instruments very extended showers of particles which produce coincidences between counters even though rather far from each other. Unfortunately I lacked the time to study more closely this phenomenon in order to establish with certainty the existence of the supposed corpuscular showers and investigate their origin.

Four years later and apparently unaware of Rossi's report, Pierre Auger investigated air showers and claimed the discovery.

In April of 1938, Bruno Rossi and Nora Lombroso were married, and in September Rossi was expelled from the University in conformance with the racial laws of the fascist regime. They left Italy and found their first refuge at Niel Bohr's Institute in Copenhagen where Rossi wrote a paper on the instability of muons.[18] At a conference organized by Bohr, Rossi met Blackett who arranged a fellowship for Rossi at the University of Manchester. During his brief time at Manchester, Rossi collaborated with Ludwig Jánossy in a measurement of the absorption of high-energy photons in lead.[19] For that experiment Rossi invented the method of anti-coincidence, which has been widely used in particle experiments. The results confirmed the Bethe-Heitler theory of high-energy gamma-ray interactions in matter.

In 1939 Rossi accepted an invitation from Arthur Compton to attend a summer conference on Cosmic Rays at the University of Chicago. The Rossis sailed for America in June.

3. 1939-1943

After the conference, Rossi discussed with Compton his idea for a definitive test of mesotron instability. Compton, who had secured for Rossi a temporary appointment in his laboratory as research associate, urged him to carry it out immediately. So Rossi built the circuits, assembled the equipment, and transported it in a borrowed bus, with his wife and an assistant, a thousand miles across the prairies to Mt. Evans in Colorado in time to complete the measurements before the winter snows.

At each of four altitudes Rossi measured the penetrating particle intensity with and without a pile of graphite over the detector. The results, displayed in Figure 5, demonstrated that the attenuation of the mesotron intensity was greater in air than in an equivalent thickness of graphite due to the additional loss by decay in flight.[20] Enhanced

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[17] *ibid.:* 589.

[18] Rossi, Bruno (1938). "Further Evidence for the Radioactive Decay of Mesotrons", *Nature* 1938, *142*: 993.

[19] Jánossy, Ludwig; Rossi, Bruno (1940). "On the Photon Component of Cosmic Radiation and its Absorption Coefficient", *Proceedings of the Royal Society* 1940, *175*: 88.

[20] Rossi, Bruno; Hilberry, N.; Hoag, J.B. (1939). "The Disintegration of Mesotrons", *Physical Review* 1939, *56*: 837.

versions of the experiment during the next two summers proved that the mean life of mesotrons varies with momentum in agreement with the Einstein prediction that moving clocks tick slower.

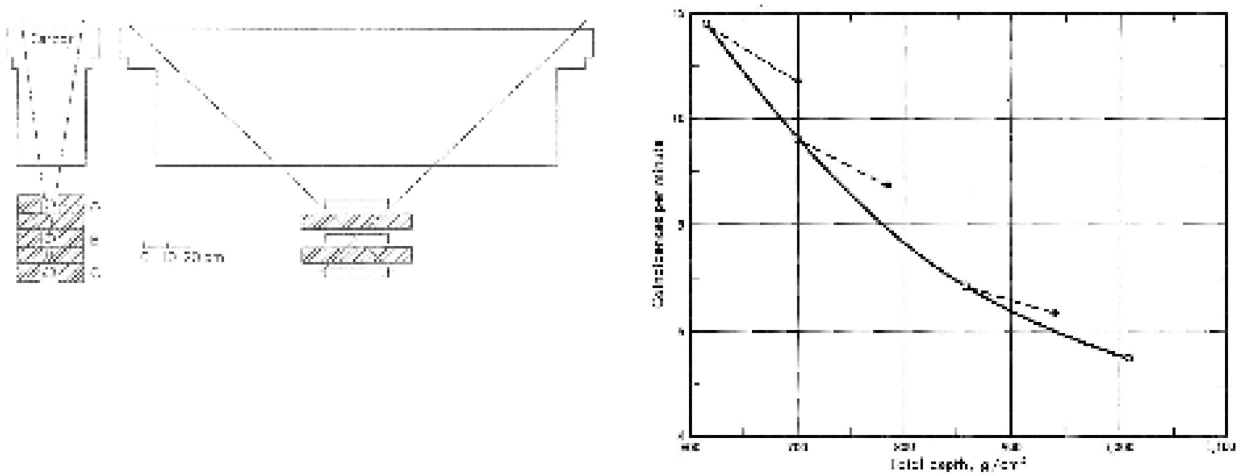

Fig. 5. (Left) Arrangement of counters and absorbers in the experiment that established the existence of anomalous absorption of mesotrons in the atmosphere, thereby proving the radioactive instability of mesotrons. (Right) Solid line–plot of the coincidence rate against depth in the atmosphere. Dashed line–connecting the coincidence rates before and after placing a graphite absorber above the detector.

In the fall of 1940 Hans Bethe obtained for Rossi an appointment as associate professor at Cornell University. With his student, Norris Nereson, Rossi made a precise measurement of the decay curve of the mesotron at rest, the first such measurement of a fundamental particle. Their setup employed a combination of coincidence and anticoincidence circuits that signaled when a mesotron stopped in a block of graphite, and an *electronic chronometer* to measure the time interval between the stop signal and the pulse produced by the electron ejected in decay of the mesotron. Because of its potential military value, publication of the chronometer, now called a time-to-amplitude converter or TAC, was withheld until after the war.[21] Figure 6 shows the final result of the experiment in the form of semi-log plots of the integral distributions of decay times in lead and brass. The data fit straight lines characteristic of an exponential decay with a mean life of 2.15±0.07 μs, in agreement with the modern value for the muon.[22]

[21] Rossi, Bruno; Nereson, Norris (1946). "Experimental Arrangement for the Measurement of Small Time Intervals between the Discharges of Geiger-Müller Counters", *Review of Scientific Instruments* 1946, *17*: 65.
[22] Nererson, Norris; Rossi, Bruno (1943). "Further Measurements on the Disintegration Curve of Mesotrons", *Physical Review* 1943, *64*: 199.

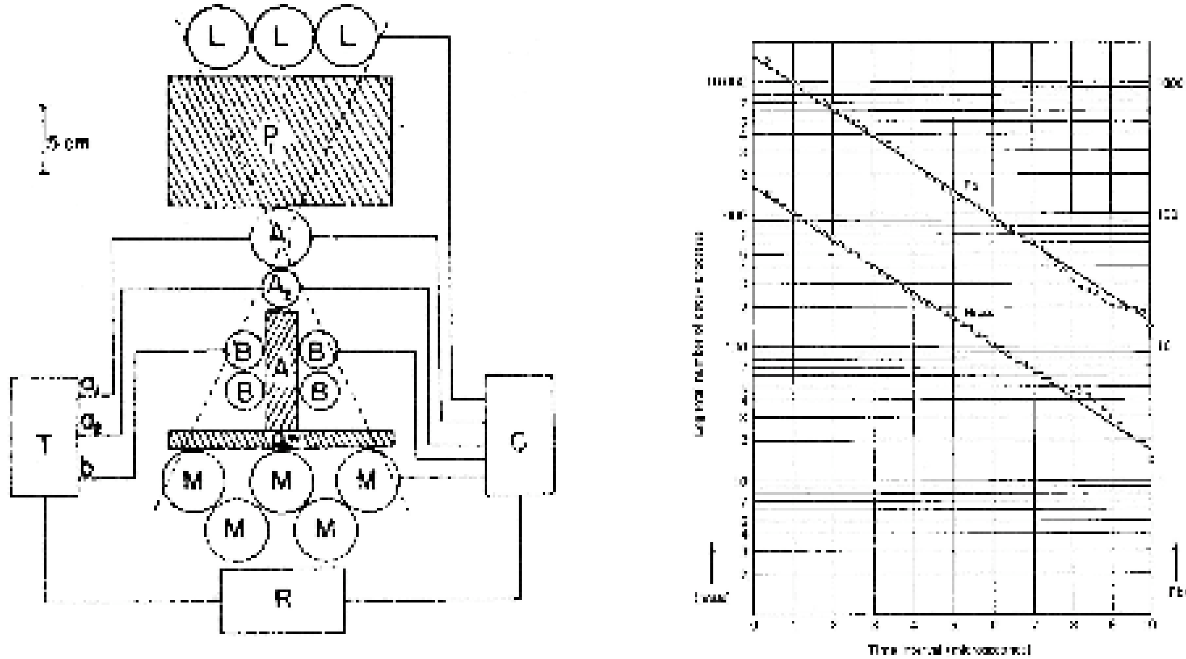

Fig. 6. (Left) Apparatus for measuring the decay curve of mesotrons. A 'start' pulse was generated by the anti–coincidence circuit (C) when coincident discharges occurred in counters L, A1, A2, but not M. A 'stop' pulse was generated if a discharge occurred in a B counter after the start pulse. A start pulse indicated that a mesotron had stopped in absorber A. A stop pulse was generated by the electron from the decay of the mesotron. The time–to–amplitude converter (T) measured the interval between the start and stop pulses. (Right) Integral decay curves of mesotrons in lead and brass.

4. 1943-1946

Rossi's cosmic-ray research was interrupted by work on the atomic bomb at Los Alamos. One product of that work was the *pulse ionization chamber*. It was capable of measuring the ionization produced by a burst of radiation from an atomic bomb, a nuclear interaction of a cosmic ray, or a cosmic-ray air shower.

5. 1946-1960

In 1946 Rossi was appointed professor of physics at MIT where he established the Cosmic Ray Group to carry out experiments aimed at three major topics:

1. Properties of the primary cosmic radiation;
2. Propagation of cosmic rays through the atmosphere;
3. Identification and characterization of new particles produced in high-energy nuclear interactions.

Rossi was joined initially by several experienced experimentalists who came from Los Alamos and the MIT radar laboratory to complete graduate studies that had been interrupted by war work. The group, including new students and skilled technicians, was well supported by MIT and the federal government. In his autobiography Rossi described how he changed his mode of operation:

Now I had the responsibility of an entire group, and what mattered was no longer my own work but the work of the group. In the first place my task was to identify the most promising research programs among those that were within our reach. I had then to help where help was needed in the planning of the instrumentation and evaluation of the experimental results, all of this without discouraging the individual initiative of the researchers.

The following are examples of the projects carried out by the group:

Robert Hulsizer set an upper limit of one percent on the proportion of photons and electrons in the primary cosmic radiation in an experiment with a detector carried aloft by a train of weather balloons. [23] (Primary electrons and gamma rays were discovered in the 1960s at intensities well below the one percent limit.)

Robert Williams carried out an experiment based on Rossi's idea of using *density sampling* to determine the core location, lateral structure, and size of an air shower. With an array of pulse ionization chambers set out at site son Mt. Evans, Williams determined the energy spectrum of primary cosmic rays up to 10^{17} eV, the highest energy that had been observed so far in cosmic rays.[24] Pietro Bassi and George Clark verified Rossi's idea of using scintillation detectors to determine the arrival directions of air showers by *fast timing*.[25] Air shower experiments, using plastic scintillators for both fast-timing and density-sampling, were carried out at a site near Boston[26] and in Bolivia and South India to measure the arrival directions and energy spectrum of the primaries to 10^{18}eV.

John Linsley and Livio Scarsi set up the largest of the MIT air shower experiments on the Volcano Ranch in New Mexico. They measured the energy spectrum of primary cosmic rays to more than 10^{19} eV with 19 detectors in a hexagonal array inscribed in a circle enclosing 2.5 km^2. The primary particle of the largest shower observed had an energy of $6\text{x}10^{19}$eV.[27] After the area was expanded to 10 km^2 a shower from a primary with 10^{20} eV was recorded.[28] None of the MIT air shower experiments revealed a significant departure from isotropy in the distributions of celestial arrival directions.

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[23] Hulsizer, Robert I.; Rossi, Bruno (1948). "Search for Electrons in the Primary Radiation", *Physical Review* 1948, *73*: 1402.
[24] Williams, Robert W. (1948). "The Structure of the Large Cosmic-Ray Air Showers", *Physical Review* 1948, *74*: 1689.
[25] Bassi, Pietro; Clark, George; Rossi, Bruno (1953). "Distribution of Arrival Times of Air Shower Particles", *Physical Review* 1953, *92*: 441.
[26] Clark, George; Earl, J.; Kraushaar, W.; Linsley, John; Rossi, Bruno; Scherb, F. (1957). "An Experiment on Air Showers Produced by High-Energy Cosmic Rays", *Nature* 1957, *180*: 353.
[27] Linsley, John; Scarsi, Livio; Rossi, Bruno (1961), "Extremely Energetic Cosmic-Ray Event", *Physical Review Letters* 1961, *6*: 485.
[28] Linsley, John (1963). "Evidence for a Cosmic-Ray Particle with Energy 10^{20} eV", *Physical Review Letters* 1963, *10*: 146.

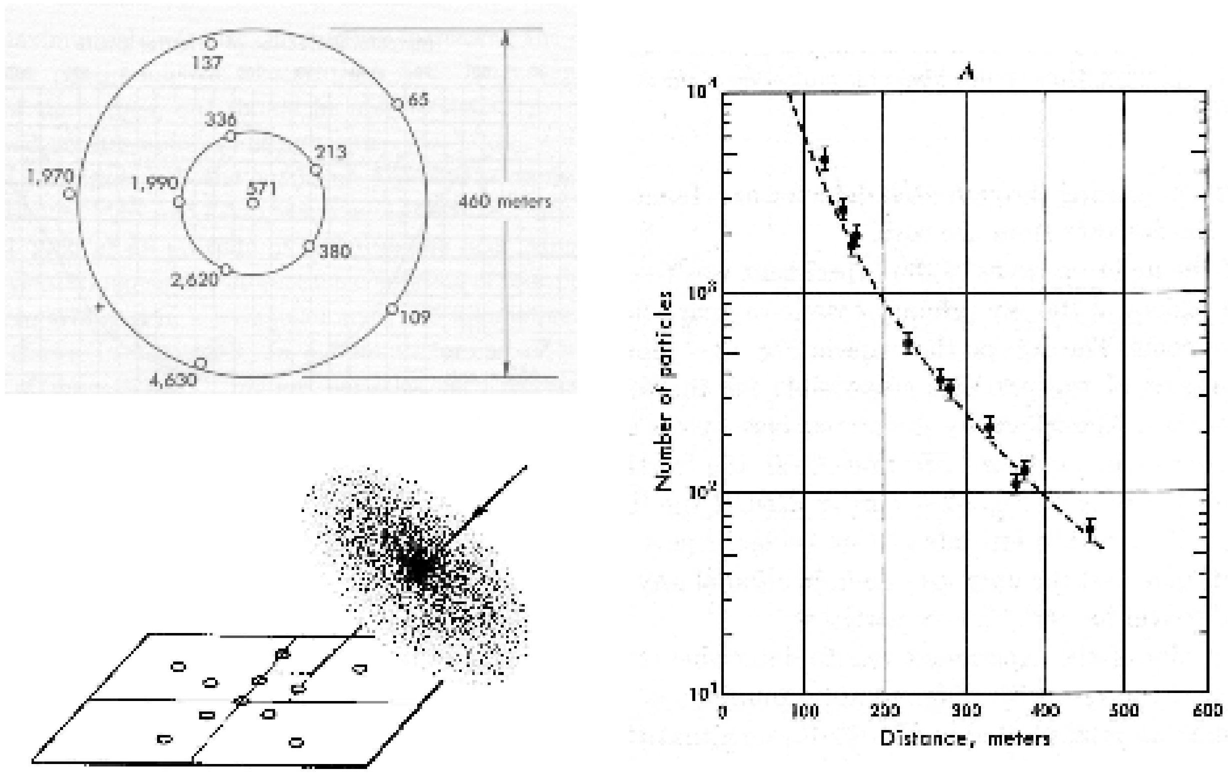

Fig. 7. (Bottom left) Shower disk approaching an array of air–shower detectors. The arrival direction is derived from the differences between the arrival times at the various detectors. (Top left) Diagram of the Agassiz air shower array with the numbers of particles recorded at each detector in the largest air shower. (Right) Plot of the numbers of particles against the distance from the shower axis in the largest shower.

John Tinlot used a pulse ionization chamber in an experiment that showed the rate of nuclear interactions of cosmic rays increases with altitude more rapidly than the intensity of muons.[29] The result proved that high-energy muons rarely produce nuclear interactions, confirming the conclusion that muons were not the nuclear-active particles predicted by Yukawa's theory of the nuclear force.

Herbert Bridge developed a counter-controlled multi-plate cloud chamber that was operated on Mt. Evans in numerous studies of high-energy nuclear interactions and their products. Figure 8 shows one of the most interesting events it recorded. A heavy particle enters the chamber from above and stops in the sixth plate. Two showers develop in opposite directions from the place where the incident particle stopped. The total energy in the two showers was greater than 1470 MeV, more than the value of mc^2 of a single proton. The event was the first evidence for the annihilation of a heavy particle, most likely an anti-proton[30].

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[29] Tinlot, John (1948). "Variation of Penetrating Showers with Altitude", *Physical Review* 1948, *73*: 1476.
[30] Bridge, Herbert S.; Courant, H.; DeStaebler Jr, H.C.; Rossi, Bruno (1954). "Possible Example of the Annihilation of a Heavy Particle", *Physical Review* 1954, *95*: 1101.

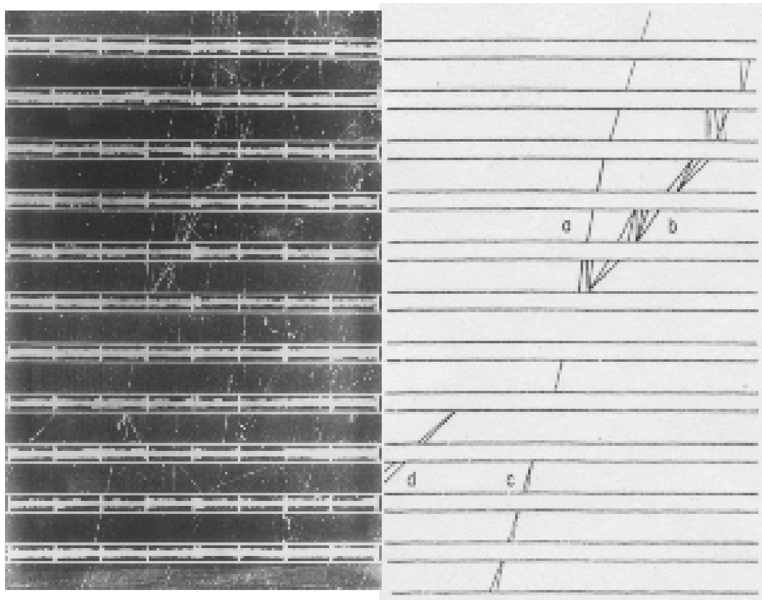


Fig. 8. Photograph and schematic diagram of the annihilation of an anti–proton in the multi–plate cloud chamber. The particle (a) enters from above and stops in the sixth plate. Showers (b) and (cd) emerge from the point of annihilation in opposite direction with a total energy exceeding the rest energy of a single proton.

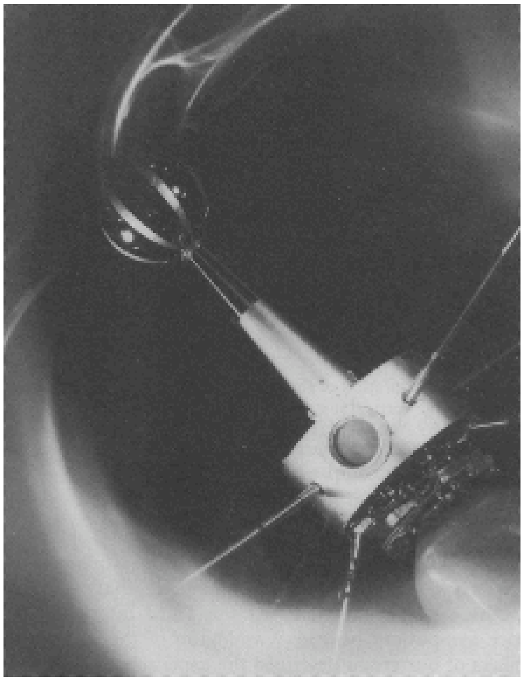
6. 1960-1975

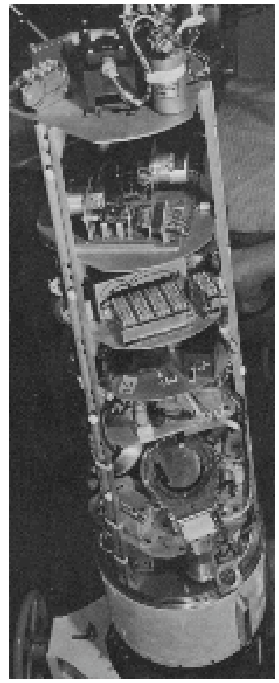
Toward the end of the 1950s, as accelerator experiments came to dominate particle physics, Rossi turned to space research as a promising frontier for exploratory investigations. At MIT he initiated a program of detector development and rocket experiments aimed at direct measurements of the interplanetary plasma. A group, headed by Herbert Bridge, devised a *plasma probe* to measure the energy and direction of particles in a plasma stream arriving from anywhere within a wide angle. Explorer 10, launched on March 25, 1961 carried the plasma probe just beyond the boundary of the geomagnetic cavity where it made the first direct measurements of the speed and direction of the solar wind.[31] MIT plasma probes have been carried on numerous deep space missions to measure the interplanetary plasma throughout the solar system.

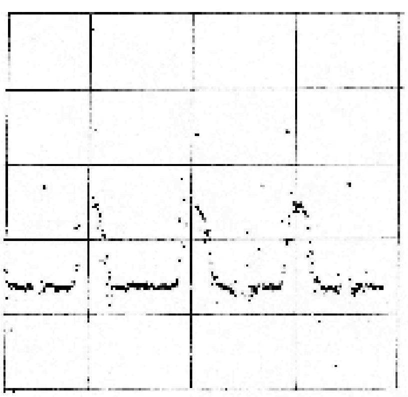
To implement his ideas about the possibilities for X-ray astronomy, Rossi turned to his former student, Martin Annis, president of American Science and Engineering, Inc., founded in 1958 by Annis and several colleagues. Annis had engaged Rossi as Chairman of the Board and scientific consultant. The main business at the time was research for the Defense Department on the effects of X-rays from nuclear explosions above the atmosphere. Annis was enthusiastic, and suggested Rossi discuss his ideas with Riccardo Giacconi, whom Annis had recently hired to initiate a space research program. Giacconi, a former student of Occhialini, began a study that produced proposals to NASA for development of grazing-incidence reflection X-ray optics, and for an exploratory rocket program. NASA accepted the former and rejected the latter. Rossi participated in the invention of a nested parabolic grazing-incidence reflection X-ray concentrator.[32] Giacconi obtained support for rocket experiments from the Air Force Cambridge Research Laboratory. After two failures, the third experiment, launched on June 18, 1962, discovered an astonishingly bright X-ray source in the southern sky, later

[31] Bonetti, Alberto; Bridge, Herbert S.; Lazarus, A.J.; Rossi, Bruno; Scherb, F. (1963). "Explorer X Plasma Measurements", *Journal of Geophysical Research* 1963, *68*: 4017.
[32] Giacconi, Riccardo; Rossi, Bruno (1960). "A 'Telescope' for Soft X-Ray Astronomy", *Geophysical Research* 1960, *65*: 773.

called Sco X-1 (Figure 10).[33] The result was so strange and unexpected that the editor of *Physical Review Letters* agreed to publish the report only after he received the personal assurance of Rossi that the result was certainly correct.







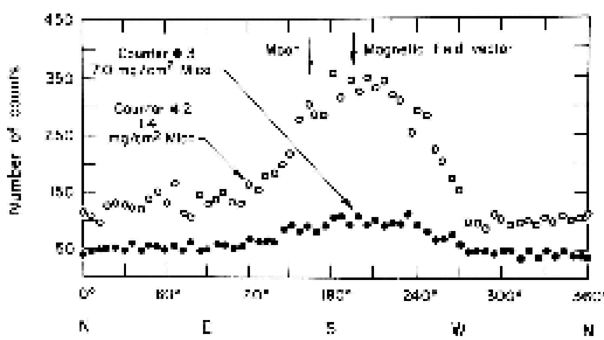


Fig. 9. (Top) The plasma probe mounted on the side of Explorer 10.
(Bottom) Modulation of the recorded plasma flux due to rotation of the spacecraft. Vertical lines show the azimuth of the sun.

Fig. 10. (Top) Rocket payload for the June 18, 1962 flight that discovered Sco X–1 in the southern sky.
(Bottom) Numbers of counts recorded by the counters plotted against the azimuth of the line of sight of the counters.

[33] Giacconi, Riccardo; Gursky, H.; Paolini, F.; Rossi, Bruno (1962). "Evidence for X Rays from Sources Outside the Solar System", *Physical Review Letters* 1962, *9*: 439.

After the discovery of Sco X-1, X-ray astronomy flourished at AS&E, MIT, and elsewhere. Though Rossi did not participate directly in it, he wrote and lectured extensively about the new and growing field of X-ray astronomy. He remained close to the developments in space plasma research at MIT, and wrote a treatise on the physics of space with Stanislaw Olbert.[34] Professor Rossi remained an active promoter of space research well beyond his official retirement in 1970.

Fig. 11. Bruno Rossi and Giuseppi Occhialini at the MIT Center for Space Research ca. 1975. (G. Clark private collection.)

BIBLIOGRAPHY

Details of Bruno Rossi's contributions to particle physics and astrophysics and the relations of his work to that of others are in the following books and articles:

Rossi, Bruno (1992). *Moments in the Life of a Scientist* (Cambridge: Cambridge University Press, 1992).
Rossi, Bruno (1964). *Cosmic Rays* (New York: McGraw-Hill, 1964).
Rossi, Bruno (1952). *High-energy Particles* (Englewood Cliffs: Prentice-Hall, 1952).
Sekido, Yataro; Elliot, H. (eds.) (1982). *Early History of Cosmic Ray Studies* (Dordrecht: Reidel, 1982)
Rossi, Bruno (1934). "Some Results Arising from the Study of Cosmic Rays", *Papers and Discussions of the International Conference on Physics, London I*, 233.
Rossi, Bruno (1948). "Interpretation of Cosmic-Ray Phenomena", *Review of Modern Physics* 1948, *20*: 537.
Rossi, Bruno (1949). "Electrons and Photons in Cosmic Rays", *Review of Modern Physics* 1949, *21*: 104.

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[34] Rossi, Bruno; Olbert, Stanislaw (1970). *Introduction to the Physics of Space* (New York: McGraw-Hill 1970).

References for figures:

Fig.1 Rossi in his Arcetri Laboratory. From Rossi, Bruno (1990). *Moments in the Life of a Scientist* (Cambridge: Cambridge University Press 1990) (hereafter MLS).

Fig. 2 Sketch from Rossi's notebook. From the original notebook in MIT Archives and Special Collections.

Fig. 3 Experimental arrangement for detection of showers. From Rossi, Bruno (1932). *Physikalische Zeitschrift* 1932, *33*: 304.

Fig. 4 The Rossi curves. From Rossi, Bruno (1933). *Zeitschrift für Physik* 1933, *82*: 151.

Fig. 5 Arrangement of counters and absorbers. From Rossi, Bruno; Hoag, J.B. (1940). *Physical Review* 1940, *57*: 461.

Fig. 6 Apparatus for measuring the decay curve. From Nereson, Norris; Rossi, Bruno (1943). *Physical Review* 1943, *64*: 199.

Fig, 7 Shower disk approaching an array. From Rossi, Bruno (1964). *Cosmic Rays* (New York: McGraw-Hill, 1964).

Fig. 8 Photograph and schematic diagram of the annihilation of an anti-proton in the multi-plate cloud chamber. From Bridge, Herbert S.; Courant, H.; DeStaebler Jr, H.; Rossi, Bruno (1954). *Physical Review Letters* 1954, *95*: 1101.

Fig. 9 The plasma probe. From MLS.

Fig. 10 Rocket payload. From Tucker, W.; Giacconi, Riccardo (1980). *The X-Ray Universe* (Harvard: Harvard University Press 1980).

Fig. 11 Rossi and Occhialini. From G. Clark, private collection.