Bruno Rossi

# BRUNO BENEDETTO ROSSI

*April 13, 1905–November 21, 1993*

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The initial motivation of the experiment which led to this discovery [of Sco X-1] was a subconscious feeling for the inexhaustible wealth of nature, a wealth that goes far beyond the imagination of man. That feeling was possibly generated by experiences in my previous work on cosmic rays; more likely it was inborn and was the reason why, as a young man, I went into the field of cosmic rays. In any case, whenever technical progress opened a new window into the surrounding world, I felt the urge to look through this window, hoping to see something unexpected.[1]

## BEGINNINGS

BRUNO ROSSI WAS BORN April 13, 1905, in Venice, the eldest of three sons of Rino Rossi and Lina Minerbi. His father was an electrical engineer whose successful career began with work on the electrification of Venice. He wrote in his autobiography[2] that his father loved science and would have chosen it for a career except for practical considerations. He attributes to his father the influence that turned what may have been an "inborn tendency toward science . . . into a lifelong commitment." He recalled:

perfectly clear winter mornings when the air was so unusually transparent that the Alps surrounding Venice became clearly visible and appeared incredibly close (Fata Morgana if you are a child or a poet, anomalous atmospheric refraction if you are a scientist). On those mornings I would try to find a sandalo (a small gondola) and, accompanied by a friend, I would row standing on the stern, Venetian style, from the Lido, where I lived, to the school in Venice, where I studied.

Throughout his life Rossi reveled in the natural beauty of the mountains, where he did many of his cosmic-ray experiments, the desert around Los Alamos, where he worked on the atomic bomb, and the seashore of Cape Cod, where he strolled in summer with a student or colleague, discussing the progress of research and his ideas for future experiments. He found pleasure and solace in art and poetry, especially the works of Dante Aligieri. His personality has been described by one of his young colleagues as "complex, that of a poet as much as a scientist."

Rossi was tutored at home until the age of fourteen, and then he attended the Ginnasio and the Liceo in Venice. After completing his university studies at the University of Padua and his doctorate in physics at the University of Bologna, he was appointed assistant to Antonio Garbasso, professor of experimental science at the University of Florence. His laboratory was in the Physics Institute of the university, located among the olive trees on the hill of Arcetri overlooking the ancient city. The austerity of the working conditions—an unheated laboratory and a meager salary—was offset by the stimulation of the intellectual life provided by a brilliant group that included Gilberto Bernardini, a recent doctoral graduate from the University of Pisa, the young Enrico Persico, professor of theoretical physics at the University of Florence, who gave lectures on the new quantum mechanics of Heisenberg and Schrödinger, and enthusiastic students, especially Guiseppe Occhialini, Rossi's first doctoral student and lifelong friend.

## ARCETRI AND PADUA (1928-38)

From the beginning of his work at Arcetri, Rossi sought a line of investigation that would lead to something novel and important. His first publications describe several investigations that fell short of his ambitions. Then he read the paper of Walter Bothe and Walter Kolhörster describing their discovery of charged particles that penetrated 4.1 cm of gold. Their results were astonishing at a time when the most penetrating charged particles previously known were beta-decay electrons, which could be stopped by less than a millimeter of gold. The penetrating particles were clearly related to the Höhenstrahlung discovered by Victor Hess in manned balloon flights during 1911-12. Hess had proved the existence of a "radiation from above" that arrives from outer space and generates ionization throughout the atmosphere. Höhenstrahlung was generally assumed to be composed of photons of very great energy, since it was believed (before the discovery of pair production) that the penetrating power of photons increased with energy without limit. During the 1920s Robert Millikan made extensive measurements of the ionization produced by the mysterious radiation, which he renamed cosmic rays, and he proposed the theory that they were photons created as the birth cries of the elements formed by the fusion of hydrogen atoms in interstellar space.

Although Rossi was skeptical of Millikan's theory, he had seen no way to make a significant contribution to cosmic-ray research by the established methods of investigation. It seemed to him that the Bothe and Kolhörster experiment, based on Bothe's recent invention of the coincidence method, had opened a new window on nature. They had set up two Geiger counters, one above the other in a vertical plane, each connected to a separate fiber electrometer. Discharge of a counter, caused by traversal of a charged particle, produced a fiber deflection, which was recorded photographically on a moving film. Coincident deflections within a small fraction of a second indicated a traversal of both counters by a single cosmic-ray-charged particle. Bothe and Kolhörster observed that insertion of a gold brick between the two counters caused only a small reduction in the rate of coincidences. This demonstrated that most of the cosmic rays at ground level are charged particles capable of penetrating at least 4.1 cm of gold. Their analysis led them to conclude that the primary radiation itself must also be charged particles. Independent evidence in support of this conclusion had been obtained in 1927 by the Dutch physicist Jacob Clay, who measured a small change in the rate of ionization produced by cosmic rays during a trip from Leiden to Java. Such a latitude effect was attributable to deflection of primary charged particles by the Earth's magnetic field. Millikan, on the other hand, had found no latitude variation in similar measurements, and stuck to his theory that the primaries were photons.

Within a few weeks of reading the Bothe and Kohlhörster paper, Rossi had invented and published in *Nature* the design of an electronic coincidence circuit, based on a novel use of triode vacuum tubes (1). The much finer time resolution of the Rossi coincidence circuit and its adaptability to the detection of coincidences among any number of pulses enabled the detection and identification of interesting rare events that produce coincident pulses in several counters in the midst of high rates of background pulses in each counter. It was the first electronic AND circuit, a basic logic element of the electronic computers of the future. Its applications by Rossi to experiments on cosmic rays marked the beginning of electronic experimentation in nuclear and particle physics.

By the spring of 1930 Rossi had fabricated Geiger-Müller counters according to the recently published description and had carried out several coincidence experiments. He communicated his early results to Bothe, who invited him to visit his Berlin laboratory that summer. There he carried out an improved version of the Bothe and Kolhörster experiment with his electronic coincidence circuit, detecting cosmic-ray particles that traversed 9.7 cm of lead. During his visit, Rossi's attention was drawn to the work of the Norwegian physicist Carl Störmer on the motion in the Earth's magnetic field of the low-energy-charged particles responsible for exciting the aurora. Where others had been daunted by the complexity of the Störmer theory, Rossi perceived a simple consequence that led him to predict an azimuthal asymmetry in the intensity of cosmic rays that would depend on the sign of the charge of the primary particles. Detection of such an effect would not only demonstrate that the primary radiation is, indeed, charged particles, but would also determine the sign of their charge. He published his prediction of what came to be known as the east-west effect in a letter to the *Physical Review* sent from Berlin in July 1930 (2). Back at Arcetri his attempt to detect an asymmetry yielded a statistically inconclusive result, a consequence of the high geomagnetic latitude of Florence, where the effect is small. On the basis of his theory, Rossi expected the asymmetry would be much greater at low geomagnetic latitudes and began preparations for an expedition to the Italian colony of Eritrea, where he expected to find a result consistent with the assumption that the primary particles were negative electrons.

At this time, an enduring friendship began between Enrico Fermi, already famous for his work in theoretical physics, and Rossi as they led their respective groups in pioneering experimental investigations—of nuclear physics in Rome and high-energy particle physics in Florence. At the invitation of Fermi, Rossi delivered the introductory talk on cosmic rays at the Rome international conference on nuclear physics sponsored by the Royal Italian Academy in the fall of

1931. To an audience that included Millikan and Arthur Compton, Rossi outlined the current experimental knowledge of cosmic rays and his reasons for doubting Millikan's theory of their nature and origin. He explained how coincidence experiments had demonstrated that most of the local cosmic rays are charged particles with more energy than could possibly be released in the synthesis of the heaviest atoms. Long afterwards, Rossi wrote[2] that "Millikan clearly resented having his beloved theory torn to pieces by a mere youth, so much so that from that moment on he refused to recognize my existence." Compton's reaction was quite different, and he later told Rossi that Rossi's talk had persuaded him to begin his own research on cosmic rays.

Two of Rossi's experiments, carried out in the period immediately following the Rome conference, are striking for their simplicity and far-reaching implications. In the first he demonstrated the existence of cosmic-ray particles capable of penetrating an astonishing 1 meter of lead by observing the threefold coincidences of pulses from three Geiger counters aligned with respect to one another and separated by blocks of lead (3). Four years later, in three independent investigations at Caltech, Harvard, and Tokyo, the penetrating particles were identified as charged particles of a new species called mesotrons (later renamed muons) with a mass of approximately 200 times that of the electron.

In the other experiment, inspired by Skobelzyn's description of high-energy particle tracks observed in a magnet cloud chamber, Rossi placed three Geiger counters in a triangular configuration so that they could not all three be discharged by a single particle traveling in a straight line. With the setup enclosed in a lead box, he found a rate of triple coincidences that demonstrated an abundant production of secondary particles (later called showers) by the interaction of cosmic rays in the lead (4). In an extension of this experiment, he measured the rate of triple coincidences as a function of the thickness of the lead above the counters. The results, which came to be known as the Rossi curve, showed a rapid rise of the triple coincidence rate as the thickness was increased to about 1.5 cm, followed by a slow decline (5). The Rossi curve showed that the local cosmic rays consist of two components, a soft component capable of prolific generation of particle showers but rapidly attenuated in lead and the penetrating component capable of traversing great thicknesses of lead and only occasionally giving rise to a shower. It also provided the first quantitative test of the theory of electron-photon cascade showers developed four years later by Bhabha and Heitler.

Meanwhile, Rossi had arranged for Occhialini to work with Patrick Blackett in Manchester. Bringing to Manchester the new technique of electronic coincidence, Occhialini collaborated with Blackett in developing the first counter-controlled cloud chamber, achieving thereby a great increase in the efficiency of operation over random expansions. Photographs were soon obtained of locally produced particle showers that confirmed Rossi's results.

In 1932, having won a national competition for an academic position, Rossi was called to the University of Padua as professor of experimental physics. Planning a new physics institute and supervising its construction left him little time to continue his experimental investigations. His project for measurement of the azimuthal asymmetry in the cosmic-ray intensity at low latitudes was delayed until 1933, when he finally was able to travel to Eritrea. In a publication (6) on the results of the experiment Rossi asserted that "cosmic rays consist chiefly of a charged corpuscular radiation with a continuous energy spectrum extending to very great energies. Moreover, the new results on the azimuthal effect show that the charge is predominantly positive." Much to his disappointment, the delay of his expedition had cost him the priority of discovery. Just as he was leaving on the expedition, he read the *Physical Review* articles of Thomas Johnson and of Luis Alvarez and Arthur Compton, who had independently measured the east-west effect in experiments in Mexico City.

During the experiments in Eritrea, Rossi discovered a phenomenon that would have far-reaching consequences for cosmic-ray physics and astrophysics in the future—extensive cosmic-ray air showers (7). The discovery occurred during tests to determine the rate of accidental coincidences between the Geiger counters of his detector. To assure that no single particle could trigger all three counters he spread them out in a horizontal plane. He wrote (Rossi's translation from the original Italian):

> The frequency of the coincidences recorded with the counters at a distance from one another, shown in the tables as "chance coincidences" appears to be greater than would have been predicted on the basis of the resolving power of the coincidence circuit. Those observations made us question whether all of these coincidences were actually chance coincidences. This hypothesis appears to be supported by the following observation . . . Since the interference of possible disturbances was ruled out by suitable tests, it seems that once in a while the recording equipment is struck by very extensive showers [degli sciami molto estesi di corpuscoli] of particles, which cause coincidences between counters, even placed at large distances from one another. Unfortunately, I did not have time to study this phenomenon more closely.

Extensive air showers were rediscovered four years later by Auger and Maze, who carried out the first systematic study of their structure and size distribution. Air showers would be a principal theme of Rossi's postwar cosmic-ray research.

FROM ITALY TO AMERICA (1938-43)

While on vacation in Venice in 1937, Rossi was introduced to Nora Lombroso, daughter of Ugo Lombroso, professor of physiology at the University of Palermo, and Silvia Forti and granddaughter of the renowned physician and criminologist Cesare Lombroso. They were married in April of the following year.

Meanwhile, the political climate in Italy was darkening with the growing influence of Hitler on Mussolini and the enactment of the Jewish laws. In September of 1938 Rossi was deprived of his position at the university. Recognizing the danger that loomed, the Rossis left Italy. After a brief stay at the Bohr Institute for Nuclear Physics in Copenhagen, they were invited by Patrick Blackett to come to the University of Manchester. There Rossi renewed his cosmic-ray research in discussions with Blackett concerning the evidence for the instability of the mesotron, and in an experiment with Ludwig Jánossy on the production of cascade showers in lead by cosmic-ray photons, in which he introduced the novel technique of anti-coincidence.

In the spring of 1939 Rossi received an invitation from Arthur Compton to participate in a cosmic-ray symposium at the University of Chicago planned for the summer, and was offered the possibility of some kind of a job. With great reluctance to leave Europe and especially the warm hospitality of Patrick and Constance Blackett in Manchester, the Rossis sailed to New York in June. Before going on to Chicago they visited the Fermis, who had arrived six months earlier in New York City, where Enrico Fermi had accepted a professorship at Columbia University. Laura Fermi recalled their meeting: "Bruno, a few years younger than Enrico, was a quiet man, rather silent and shy. He let his lively wife do all the talking, and he was happy if he could withdraw into the background."[3] Many years later, Nora Rossi told me that she would replace the word "shy" with "reserved."

The mesotron was a major topic at the Chicago symposium. Afterwards, during a visit with the Comptons at their summer cottage in Michigan, Rossi roused enthusiastic support for a definitive test of the mesotron's instability. Within a few weeks he had constructed an apparatus to detect mesotrons by the coincidences of three Geiger counters aligned in a vertical plane and separated by blocks of lead. He packed it into an old bus and drove with Nora and a young collaborator, Barton Hoag, to Mt. Evans in Colorado. The measurements showed that the attenuation of the mesotron intensity is greater in the air between two altitudes on the mountain than in an equivalent thicknesses of a solid absorber. The result could be unequivocally attributed to radioactive decay of mesotrons in flight with a mean life at rest of approximately 2 microseconds. It was the first clear demonstration of the decay of a sub-nuclear particle (8).

Rossi was appointed associate professor of physics at Cornell University in the spring of 1940. There he acquired his first American Ph.D. student, Kenneth Greisen, who would become one of the leading contributors to cosmic-ray research after the war. Greisen has recalled that, as a graduate student in theoretical physics with no knowledge of experimental physics, he went to Rossi's office and "asked if I would be welcome as a student under him; and he needed one, no matter how ignorant. So he took me, and for a couple of years I was his only student." With a grant of $2,000, which Rossi had "demanded" for the startup of his research, they set up a facility for making Geiger counters and electronic circuits with the aim of carrying out an improved version of the experiment on the anomalous atmospheric attenuation of mesotrons and spent $1,000 on a station wagon to transport the equipment and themselves to the mountain. This last of Rossi's mountain experiments on mesotron decay yielded the quantitative verification of the relativistic dilation of time intervals and an improved estimate of the mean life of mesotrons at rest.

During the preparations for the new experiment Rossi began work on the article on the theory of cosmic-ray phenomena for the *Review of Modern Physics*, which became a standard reference for the interpretation of the electromagnetic aspects of cosmic-ray experiments (9). Greisen has recalled that:

> we worked on it, more or less as master and flunky. . . We had regular sessions in his office, leaving me each time with a heavy assignment of reading and numerical calculating. I mainly used logarithm tables, series expansions, slide rule, and straight arithmetic. I learned to use drafting pens, India ink, and french curves, and drew our figures myself. I also did a fair amount of editing, but it was his composition and his design.

Still intent on the problem of mesotron decay, Rossi devised a new approach to the measurement of the mean life. For this, he invented the time-to-amplitude converter, an electronic circuit called a TAC in its modern commercial versions (11). The TAC was used to measure the time between two pulses, the first signaling the arrival of a mesotron that had stopped in an absorber and the second the detection of its decay electron. The distribution of these times conformed perfectly to an exponential curve of radioactive decay with a mean life of 2.15 ± 0.06 microseconds, a result in agreement with the more precise value obtained much later in accelerator measurements (10).

The Rossi house in Ithaca was located some distance from the center of town. Accustomed to the close companionship of Italian city life, Nora found the small town strange but beautiful. However, in December of 1040, when their first child Florence was born, the ice and snow and the physical isolation were hard to bear. The following years, as American went to war, Nora was often alone during Bruno's frequent and tedious trips by train from Ithaca to Boston by way of Syracuse and Albany to consult at the MIT Radiation Laboratory on instrumentation for the development of radar. Nora's loneliness was relieved by teaching conversational Italian to future soldiers at Cornell, while Florence was tended at the university nursery school.

In late spring of 1943, after his official status as enemy alien was changed to "cleared to top secret," Bruno announced to Nora that they must go west to a secret place in New Mexico. She remembered having overheard Fermi mention a "monstrous bomb" in a conversation in Chicago and was dismayed by the realization that such a thing might be the reason for the move. Years later she recalled how she "kept tight inside me this terrible secret which I happened on involuntarily."[2]

### LOS ALAMOS (1943-45)

In July 1943 the Rossi family arrived by train at the station near Santa Fe. They were whisked by car to Los Alamos and housed in temporary quarters. The laboratory had been officially opened in April, and construction of laboratories and housing was proceeding at a furious pace, with bulldozers tearing up trees and leveling the ground. One day, barely settled in a new and more pleasant apartment, Nora saw a bulldozer approaching the last tree near their door. She rushed to place herself between the awful machine and the tree—and saved it.

The director, Robert Oppenheimer, asked Rossi to form a group to design and develop instruments for the experiments being planned. He joined forces with Swiss physicist Hans Staub to form the Detector Group, which soon had some twenty people, many just out of college, including

Matthew Sands, who would follow Rossi to MIT after the war. The Detector Group developed a variety of pulse electronics and radiation detectors, particularly fast ionization chambers that had large collecting areas and provided proportional and submicrosecond response to transient intensities of gamma rays.

In 1944 a group under the direction of Emilio Segrè discovered that the plutonium isotope $^{240}$Pu, a contaminant of the pile-produced bomb material $^{239}$Pu, has a high rate of spontaneous fission accompanied by emission of neutrons.[4] By midsummer it was clear that the gun method of assembling a supercritical mass of fissionable material, suitable for detonation of the uranium bomb, could not be made fast enough to prevent a fizzle of a plutonium bomb due to premature initiation of the chain reaction by a stray neutron. The only way to achieve efficient detonation was to compress a slightly sub-critical solid sphere of plutonium by implosion with chemical high explosives. Implosion technology had been explored in experiments on metal shells carried out under the direction of Seth Neddermeyer, but with disappointing results. In response to the crisis facing the plutonium project, a crash program to perfect the implosion method was undertaken requiring close interaction between theory, design, fabrication, and experiment.

In the RaLa experiment suggested by Robert Serber a strong radioactive source of gamma rays (radio-lanthanum) was placed in a tiny cavity in the center of a test sphere of metal, and the intensities of gamma rays at nearby detectors were measured as functions of time during the implosion. As the sphere was compressed, the thickness of metal between the source and a detector would increase, causing a decrease in the intensity of gamma rays reaching the detector. The signals generated by the detectors before they were destroyed in the test would reveal the degree of compression and isotropy achieved in the implosion. The only detectors with the requisite sensitivity and resolving time were the fast ion chambers of the Detector Group.

Rossi was assigned the hazardous task of carrying out the tests, which employed sources equivalent in activity to as much as a kilogram of radium, prepared from fission products rushed to Los Alamos from the Clinton reactor at Oak Ridge, Tennessee. High-explosive lenses, developed under the direction of George Kistiakowsky, were packed around a metal sphere. Simultaneous detonation of the lenses was achieved with electrical triggers developed under the direction of Luis Alvarez. The final tests, carried out by Rossi in a remote canyon during the spring of 1945, demonstrated sufficient compression of metal spheres to assure success of the implosion method.

The climactic experience of Rossi in the bomb project was his measurement of the exponential growth of the chain reaction in the plutonium test bomb at Trinity on July 16, 1945. Among his assistants was Herbert Bridge, who would also follow Rossi to MIT. An ultrafast ionization chamber of unique design was placed near the bomb and connected to an oscilloscope in a distant underground bunker with a tapered transmission line devised by Rossi to amplify the signal voltage without loss of fidelity. Shortly before the blast, a high-frequency oscillating voltage was applied to the vertical deflection plates of the oscilloscope. The rising intensity of gamma rays from the chain reaction produced a rising voltage signal, which was applied to the horizontal deflection plates of the oscilloscope. The resulting single stretched sinusoidal trace, called the Rossi sweep, was recorded photographically.

Rossi recalled his emotions as he drove back to Los Alamos after the test:[2]

Until then the pressure of work had been such as to leave no time for reflection. Now the terrifying significance of what we had done hit me like a blast. I must admit that at times I felt a certain pride at having played a role in an undertaking of such great difficulty, of such historical importance. But soon this feeling was overwhelmed by a feeling of guilt and by a terrible anxiety for the possible consequences of our work, a guilt feeling that would be reinforced a short time later when I learned of the destruction of Hiroshima and Nagasaki. Like many of my colleagues, I had hoped that the bomb would be used in a bloodless demonstration to induce Japan to surrender. I arrived in Los Alamos exhausted, and slept for an entire day and night.

The film was recovered several days later. Rossi and Fermi developed it and saw the faint one-microsecond trace that provided a precise measure of the bomb's efficiency, marking the moment dividing the history of the world before and after the beginning of the era of nuclear weapons.

### RETURN TO COSMIC RAY RESEARCH: MIT (1946-50)

With his work at Los Alamos finished, Rossi accepted an appointment as professor at the Massachusetts Institute of Technology, where a new approach was being taken to the support of university-based research. Large laboratories were being established on campus to facilitate and manage government-supported projects in broad fields of research, such as electronics and nuclear physics. Herbert Bridge, Matthew Sands, Robert Thompson, and Robert Williams followed Rossi to MIT from Los Alamos and formed the Cosmic Ray Group in the Laboratory for Nuclear Science and Engineering. They soon were joined by John Tinlot and Robert Hulsizer from the MIT Radiation Laboratory. All were mature and experienced experimental scientists whose graduate education had been interrupted by the war. The excitement and warmth of the Rossi group drew younger graduate students, some recently discharged from the armed services.

For this new phase of his life as a scientist, Rossi changed fundamentally his manner of working. Previously he had worked directly on all aspects of his experiments, fabricating instruments, operating the equipment, and analyzing the data. Now, with greatly expanded resources in people and support for carrying out his ideas, he withdrew almost entirely from hands-on involvement in the laboratory. He would devote his efforts to setting the broad strategy of his group, to the conception of experiments, to procurement of the necessary support, and finally, to participation in the interpretation and presentation of results. By discussion and suggestion he would engage his younger colleagues and students in carrying out his ideas for new experiments, keeping a close eye on progress, and offering occasional advice.

During the period 1945-50 Rossi's Cosmic Ray Group carried out a remarkable variety of experiments. The nuclear inactivity of the mesotron was demonstrated in Geiger counter experiments carried aloft in a converted B-29 airplane (12). An upper limit of 1% on the proportion of electrons and gamma rays in the primary radiation was established in a high-altitude balloon experiment (13). The energy spectrum of the primary cosmic-ray particles was extended to $10^{17}$ eV by a new technique of determining the properties of extensive air showers from samples of the particle density measured by an array of fast ionization chambers, and the nuclear absorption of negative mesotrons was demonstrated. Examples of the new unstable particles were found in photographs of nuclear interactions in a multiplate cloud chamber.

Robert Hulsizer has described how he wanted to do his Ph.D. thesis work with Rossi, but was daunted by what appeared to be the full crew from Los Alamos. Nonetheless, he attended the afternoon teas, and:

> one day in the fall, Professor Rossi came in full of excitement. He had realized that the pulse ion chamber made it possible to detect electrons coming into the atmosphere as part of the cosmic radiation . . . Everyone else was already working on some project, so when Prof. Rossi said it needed someone who knew about amplifiers and electrons, and radio, I offered that I had spent four years at the MIT Radiation Laboratory doing just that . . . The next three years working on that experiment were sheer joy. Prof. Rossi arranged for all the resources I needed, asking how things were going from time to time, but never pushing.

The experiment was the first significant step toward the eventual detection of electrons and gamma rays in the primary radiation.

Matthew Sands has written about the spirit of the Rossi Cosmic Ray Group.

> One of the exciting aspects of the life of the group was the flow of distinguished visitors. Oppenheimer, Fermi, LePrince-Ringuet, Bethe, Vallarta, Amaldi, Rabi, Yukawa, Bohr, etc. Perhaps most important of all was the warm family atmosphere in the group engendered by the manner with which Bruno led the group—with warmth, thoughtfulness, gentleness, human concern. There was a regular weekly meeting to discuss scientific developments, and then individual discussions about progress of the work. I don't remember that Bruno ever "ordered" anyone to do something; activities always grew out of discussions of the possibilities. Often the group was invited to a social evening at the Rossi home, sometimes with an important visitor. Nora Rossi was an important contributor—with her warmth and concern for each student.

Robert Williams, who pioneered the density sampling method in his air shower experiment, has written that Rossi:

> had a natural reserve, but when he wanted something and felt in the right he would fight very hard and effectively for it. Perhaps the reserve tended to hide the quality I wish to stress: a deep and very sincere humanity. This led him to acts of compassion, which were effective and surely required some courage.

More than one of his students and associates came to know this quality in a time of personal trouble.

In 1949 the Rossi family, now including their son Frank born at Los Alamos, moved to a large house on Scott Street in Cambridge, where their third child Linda would be born. There they gave the parties described by Sands, with students straining to hear the barely audible words of Niels Bohr or some other visiting luminary of physics. The Rossis also began their summer trips to Wellfleet on Cape Cod, where they eventually acquired a cottage overlooking Long Pond. There they enjoyed walks on the beach and the company of artists, writers, and scholars. A favorite moment of the day for Bruno and Nora came when they would swim alone to the middle of the pond and talk quietly for the better part of an hour. At sunset there might be a small party, including a student (perhaps the writer of this memoir), who would share the job of opening oysters after being taught by Professor Rossi how to do it without excessive loss of blood.

## NEW PARTICLES AND EXTENSIVE AIR SHOWERS (1950-60)

When I joined the Cosmic Ray Group in 1950, Rossi and Bridge were studying the products of high-energy nuclear interactions with a counter-controlled multiplate cloud chamber operating on Mt. Evans in Colorado. Among their collaborators were Martin Annis and Stanislaw Olbert, both Ph.D. students of Rossi, and Bernard Gregory, a visitor from France, who later became director of CERN. Their work was a part of the worldwide effort to unravel the increasing complexity of the new unstable particles, which began with the discovery of the pi meson by Cesare Lattes, Guiseppe Occhialini, and Cecil Powell, and the so-called V particles by George Rochester and Clifford Butler. The MIT results included cloud chamber observations of heavy mesons and hyperons (15,16) and evidence of the neutral pion (14) and the antiproton (19), which preceded their detection in accelerator experiments.

Although Professor Rossi was abroad during much of 1952 when I was working on my thesis project, he returned to summer residence in Wellfleet when the time came to review my write-up. Aside from his critique of my experiment, I received a gentle and never forgotten lesson in scientific writing. His spoken English was clear, concise, almost poetic, although once, when he heard a recording of himself speaking, he expressed surprise at his accent. His writing style was a model of precision and grace, evident already in his earliest articles in English sent from Berlin and Arcetri. That style illuminates everything he wrote—journal articles, a college text on optics, treatises on cosmic rays and space physics, and books and articles for a lay audience.

That same summer Professor Rossi suggested that Pietro Bassi, a visitor from the University of Padua, and I should explore the possibility of determining the arrival directions of extensive air showers by measuring the relative arrival times of shower particles over an array of detectors. Our experiment, with three scintillation detectors on the roof of an MIT building, validated the fast-timing method for determining the arrival directions of air showers (17). The only problem that Pietro and I had in the publication of the experiment was to persuade Rossi to be a co-author.

With the techniques of density sampling and fast timing now proven, Rossi gathered a group to plan and carry out an air shower experiment aimed at achieving a major advance in the exploration of the energy spectrum and origin of the primary cosmic rays. The group included William Kraushaar, who had done his graduate studies with Greisen at Cornell and had recently joined the MIT physics faculty, Frank Scherb, James Earl, and myself. Minoru Oda, who was visiting from Osaka City University in Japan, and Bassi participated in the preparations before returning to their home countries. John Linsley, a postdoctoral fellow from the University of Minnesota, soon joined the group. We set out an array of eleven scintillation detectors in the woods of the Agassiz Station of the Harvard College Observatory. The experiment determined the energy spectrum of the primary particles to $10^{18}$ eV and showed no evidence of anisotropy in the distribution of their celestial arrival directions (20).

Linsley took the next major step in air shower research in an experiment he developed on the Volcano Ranch in New Mexico in collaboration with Rossi and Livio Scarsi, a visitor from Italy. In its final configuration, the array of nineteen plastic scintillation detectors encompassed an area of 10 $km^2$ and determined the primary spectrum to $10^{20}$ eV (22). The results presented astrophysics with one of its most challenging problems—to find the origin and acceleration mechanism of individual atomic nuclei with kinetic energies sufficient to lift a billiard ball to a height of 10 meters.

## THE INTERPLANETARY PLASMA AND X-RAY ASTRONOMY (1960-70)

By the end of the 1950s particle accelerators had replaced cosmic rays for most particle physics research. For Rossi this was the time for another change of direction in his scientific odyssey. Space vehicles and computers had opened a new window into the surrounding world for the kind of exploratory investigations that had always attracted him. At a meeting in July of 1958 of the Space Science Board established by the National Academy of Sciences in the wake of the furor over the launch of the Soviet *Sputnik*, Rossi was asked to form a subcommittee to consider what areas of space science might be missing in the plans already formulated by the new National Aeronautics and Space Administration. One of the conclusions was that the interplanetary medium had been neglected. Rossi sensed a unique opportunity "to see something unexpected" through the new window of space technology.

Rossi discussed with Herbert Bridge and Frank Scherb his ideas for an experiment aimed at measuring the composition and motion of ionized gas in interplanetary space. These ideas were embodied in the MIT plasma cup, developed and flown in a collaboration that included Alberto Bonetti, visiting from Italy, and Alan Lazarus. The plasma cup was launched aboard the space probe *Explorer 10* on March 25, 1961, together with a magnetometer prepared at the Goddard Space Flight Center. The probe yielded data that revealed the boundary of the geomagnetic cavity and determined the supersonic speed and direction of the solar plasma flowing just outside the cavity (24). There followed a series of experiments in which ever more sophisticated plasma cups were sent on journeys around the planets and to the farthest reaches of the solar system, some on trips that returned data for more than two decades.

Another idea that excited Rossi as he thought about the scientific opportunities offered by space vehicles was the possibility of exploring the sky in X rays. The pioneering work on solar X rays by Herbert Friedman and his collaborators at the Naval Research Laboratory was carried out with detectors with small sensitive areas and narrow fields of view. Their observational strategy, well suited to solar studies, had limited the chances of detecting an extra-solar source. It was obvious that if the nearest stars were only as luminous in X rays as the Sun, they would be far too faint to be detected by the most sensitive instruments then available. Even the most optimistic estimates of the intensities of possible celestial X-ray sources that had been made by various astronomers were discouragingly low. Rossi, however, sensed that the X-ray window on the universe had not yet been fully opened. It seemed to him that an exploratory observation with an X-ray detector having a much greater sensitivity than those used previously in solar studies might widen the window sufficiently to reveal something unexpected.

The MIT group was fully occupied at the time with air shower experiments in Bolivia and New Mexico, a satellite gamma-ray astronomy program initiated by Kraushaar, and preparations for the interplanetary plasma experiment. Rossi therefore presented his idea for an exploratory effort in X-ray astronomy to Martin Annis, then president of a research and development company in Cambridge called American Science and Engineering, Inc. (AS&E). Annis had founded the company in 1958 with my participation and that of two other investors. The following year Rossi accepted Annis's invitation to be chairman of the board and chief scientific consultant to the company, and to devote whatever time he could spare from his MIT responsibilities and scientific advisory activities. In addition to his desire to find a means to carry out such an exploration, Rossi was eager to find new activities for the company outside of the defense-related research on which it was dependent at the time.

Annis has described how Rossi was:

> more excited and enthusiastic that I ever saw him, before or since. He told me that on the way home on the plane [from a meeting] he had one of the best ideas that he had ever thought of. He described, in detail, his view that there was a "window" in the universe through which we had never looked. This window was the soft X-ray region of the spectrum. He was totally convinced that there were exciting discoveries to be made in this unknown world . . . Perhaps I would be willing to spend AS&E money to begin the effort. I shared his enthusiasm, although I had no idea how the company might benefit. During that first conversation, he requested that I ask my people to think about new designs of large-area X-ray detectors and means to focus these soft X rays.

Annis suggested that the person to implement the ideas might be Riccardo Giacconi, who had recently joined the company. Giacconi had done his thesis research at the University of Milan, where he had worked with Occhialini on cosmic-ray experiments, and he had held postdoctoral positions at the University of Indiana with Robert Thompson and at Princeton. Giacconi later wrote:

> In September 1959 [I] attended a party at Rossi's house and met Rossi for the first time. Rossi suggested that a venture into X-ray astronomy might prove very fruitful, not because of any theoretical predictions, but because nothing was known and there was the possibility for major new discoveries.[5]

Giacconi initiated a study of the theoretical and experimental possibilities for X-ray astronomy. With the help of Stanislaw Olbert and myself, acting as consultants to the company, he prepared an internal report[6] that surveyed the prospects for X-ray astronomy and provided a basis for proposals to NASA. The report contained estimates for the intensities of various possible extra-solar X-ray sources, including certain types of stars, the Crab Nebula, and the Moon as a source of scattered solar X rays. It also described several instrumentation concepts, including an X-ray concentrator consisting of nested paraboloidal grazing-incidence mirrors invented by Giacconi and Rossi (21). NASA accepted a proposal for the development of X-ray optics, but refused the one for exploratory rocket experiments; NASA had already funded proposals from Cornell University and Lockheed Corporation for X-ray astronomy experiments, which ultimately failed to produce significant results.

Giacconi then turned to the Air Force Cambridge Research Laboratory with which AS&E had contracts for research on the effects of X rays from high-altitude nuclear explosions. One of the offices of AFCRL, interested in the possibility of determining the lunar surface composition by analysis of scattered solar X rays, accepted proposals for experiments using detectors of large sensitive area on rotating rockets, which would scan a broad swath of the sky that included the Moon. The first two flights suffered mechanical failures. The third, in June 1962, detected no X rays from the Moon, but instead, an astonishingly bright X-ray source in the southern sky, which came to be called Sco X-1 (23). The paper, submitted to the *Physics Review* by Giacconi, Herbert Gursky, Frank Paolini, and Rossi, was considered so strange by Samuel Goudsmit, the editor, that he accepted the paper for publication only after receiving Rossi's personal assurance that "he assumed personal responsibility for its contents."[2] Optical studies of the optical counterpart of Sco X-1 by others eventually showed that it is a close binary system consisting of an ordinary dwarf star and a neutron star in a 19-hour orbit, one of several hundred similar systems in the galaxy in which matter drawn from a normal star falls to the surface of the neutron star. In the process, the potential gravitational energy of the falling matter is converted into heat and radiated as X rays with an energy yield per unit mass of accreted matter on the order of one-third times the square of the speed of light.

The discovery of Sco X-1 inaugurated the new field of extra-solar X-ray astronomy, which became a major activity of the world's space research programs. AS&E maintained its leading position in X-ray astronomy for a decade until Giacconi left to become professor at Harvard University. Meanwhile, the MIT Cosmic Ray Group developed a variety of activities in X-ray astronomy encompassing balloon, rocket, and satellite experiments, several of which were carried out in collaboration with the AS&E group.

For many years Rossi maintained an active role in the design and interpretation of the MIT plasma experiments.

He did not participate directly in the MIT X-ray program, but he encouraged and supported it through his influence on promotions and the allocation of institute resources. Most of Rossi's work in X-ray astronomy was devoted to writings and talks devoted to reviews and interpretations of progress in the field.

### LATER YEARS: MIT (1970-93)

During the 1960s the manner of Rossi's participation in space research changed once again, due to changes in the sociology of university research and the mechanisms of federal support. Just after the war, support came mostly in the form of large grants from the Office of Naval Research and the Atomic Energy Commission to institutions like the MIT Laboratory for Nuclear Science and Engineering. Resources were allocated according to the judgments of its director and senior professors, each responsible for some broad area of research. As more professorial positions became available, responsibility gradually shifted to individual faculty members for procuring funding to support graduate students, portions of their own salaries, and the purchase of materials for carrying out instrument-building projects or observational programs using existing national facilities. This trend was especially characteristic of the space research sponsored by NASA. Although NASA distributed large grants in its formative years, success of individual investigators in peer-judged competition for support of proposals gradually became the principal criterion for funding and a factor in academic promotion. In the Cosmic Ray Group, now located in the MIT Center for Space Research, Rossi's ideas continued to be influential, particularly in space plasma research, and the spirit of cooperation he engendered continued to pervade its activities. Although it was not an easy time for him as he became more remote from day-to-day scientific planning and analysis, he encouraged the growing autonomy of his former students and colleagues and helped in every way to advance their careers.

In the last decade of his life, Rossi wrote several monographs on the history of the sciences in which he had been engaged for half a century (25, 26) and an autobiography. His writings are remarkable for the accuracy and objectivity with which he describes his own work and its relations to the work of others. They form a permanent monument to a scientist whose genius laid many of the foundations of high-energy physics and astrophysics, and whose leadership and humanity profoundly enhanced the lives of students and colleagues around the world. His own writings, together with the reminiscences generously provided in letters to me by his former students, have eased the task of a memoirist who owes the satisfactions of his own life in science to the leader of the group he joined as a graduate student.

Bruno Rossi died at his home in Cambridge, Massachusetts, on November 21, 1993. His ashes rest in the graveyard of the church of San Miniato al Monte, which looks over the city of Florence and across to the hill of Arcetri, where he began his scientific odyssey.

## HONORS AND AWARDS

1949 Research Corporation Scientific Award
1963 Order of Merit of the Republic of Italy
1964 Honorary doctorate, University of Palermo
1965 Honorary professor, Universidad Mayor de San Andres, La Paz, Bolivia
1970 Gold Medal of the Italian Physical Society
1971 International "Fellrinelli" Award, l'Academia dei Lincei
1971 Honorary fellow, Tata Institute of Fundamental Research, India
1974 Honorary doctorate, University of Durham
1974 Cresson Medal, Franklin Institute, Philadelphia

1975 Honorary fellow, Physical Research Institute, Ahmadabad, India
1976 Rumford Prize Award, American Academy of Arts and Sciences
1977 Honorary doctorate, University of Chicago
1985 National Medal of Science
1987 Wolf Prize in Physics

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