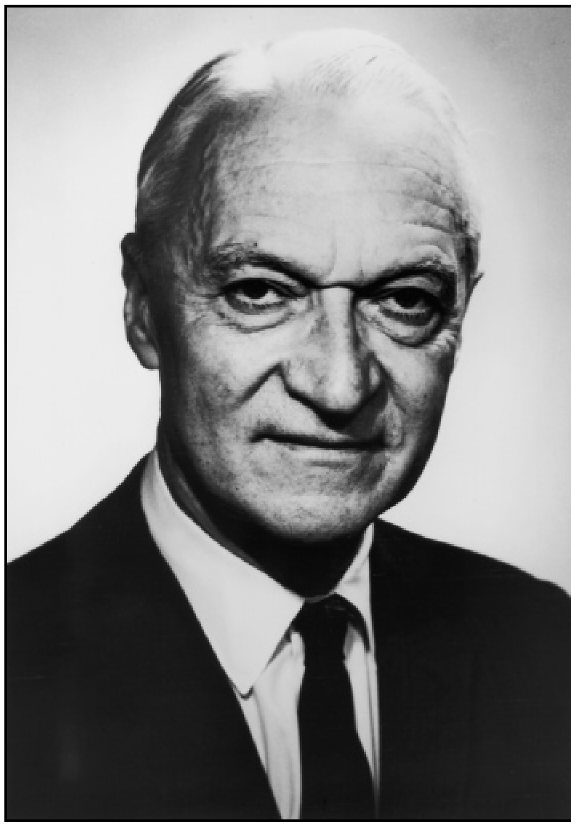
BRUNO BENEDETTO ROSSI



COURTESY OF THE MIT HISTORICAL COLLECTION

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ON THE OCCASION of his receipt of the Rumford Prize of the American Academy of Arts and Sciences for his pioneering role in the field of X-ray astronomy and the discovery of Sco X-1, the first extra-solar X-ray source, Bruno Rossi said:

> The initial motivation of the experiment which led to this discovery 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.

I. Beginnings

Bruno Rossi was born 13 April 1905, in Venice, the eldest of three sons of Rino Rossi and Lina Minerbi. His father, an electrical engineer whose successful career began with work on the electrification of Venice, loved science and would have preferred it as a career. Rossi attributed to his father the transformation of an "inborn tendency toward science . . . into a lifelong commitment." In his autobiography, *Moments in the Life of a Scientist*, Rossi 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, the desert, and the seashore. He found pleasure and solace in art and poetry, especially the works of Dante Alighieri. 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 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 at the University of Florence. His laboratory was among the olive trees on the hill of Arcetri. The austerity of the working conditions was offset by a brilliant group that included Gilberto Bernardini, Enrico Persico, and enthusiastic students, especially Giuseppe Occhialini, Rossi's first doctoral student and lifelong friend.

II. Arcetri and Padua (1928–1938)

From the beginning of his work at Arcetri, Rossi sought to discover something novel and important. Several early investigations fell short of his ambitions. Then he read the paper of Walter Bothe and Walter Kohlhörster, who reported the discovery of charged particles that penetrated 4.1 cm of gold, at a time when the most penetrating charged particles 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, who had proved in manned balloon experiments the existence of a "radiation from above" that generates ionization throughout the atmosphere. Höhenstrahlung was generally assumed to be composed of photons of very great energy, since it was believed that the penetrating power of photons increased with energy without limit. During the 1920s Robert Millikan had made extensive measurements of the ionization produced by the mysterious radiation, which he renamed "cosmic rays." He proposed 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 by existing experimental methods. The Bothe and Kohlhörster experiment opened a new window. 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. Coincident deflections indicated a traversal of both counters by a single cosmic-ray charged particle. 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 for this conclusion had been obtained in 1927 by Jacob Clay, who measured a small variation in the rate of ionization produced by cosmic rays with a change in geographic latitude. Such an effect was attributable to deflection of the 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 invented and published in *Nature* the design of an electronic coincidence circuit. The 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 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 future electronic computers. 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 and had carried out several coincidence experiments. He sent his results to Bothe, who invited him to visit his Berlin laboratory. There Rossi carried out an improved version of the Bothe and Kohlhörster experiment, detecting cosmic-ray particles that traversed 9.7 cm of lead. Rossi also perceived a simple consequence of Carl Störmer's work on the motion of charged particles in the Earth's magnetic field that led him to publish in the *Physical Review* his prediction of 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 "east-west effect" would not only demonstrate that the primary radiation is, indeed, charged particles, but would also determine the sign of their charge. Back at Arcetri his attempt to detect an asymmetry yielded a statistically inconclusive result, a consequence of the high geomagnetic latitude of Florence. According to his prediction, the asymmetry should be greater at low geomagnetic latitude. So he began preparations for an expedition to Eritrea, where he expected to find evidence that the primary particles were negative electrons.

At this time, an enduring friendship began between Enrico Fermi and Rossi. At Fermi's invitation, Rossi delivered the introductory talk at the Rome international conference on nuclear physics in 1931. Before an audience that included Millikan and Arthur Compton, Rossi outlined his reasons for doubting Millikan's theory. 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 afterward, Rossi wrote 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. Rossi's talk persuaded him to begin his own research on cosmic rays.

In the first of two striking experiments carried out just after the conference, Rossi demonstrated the existence of cosmic-ray particles capable of penetrating an astonishing 1 meter of lead. In the other experiment, he discovered the abundant production of secondary particles (later called showers) by the interaction of cosmic rays in a thin sheet of lead. By this work he demonstrated that the local cosmic rays consist of two components, a soft component that readily produces particle showers but is rapidly attenuated in lead, and a penetrating component that can traverse great thicknesses of lead, but only occasionally produces a shower. The soft component was soon identified as electrons and photons and the hard component as mesotrons, now called muons.

In 1932, Rossi was called to the University of Padua. Planning a new physics institute and supervising its construction left him little time to experiment. His project for measurement of the azimuthal asymmetry in the cosmic-ray intensity at low latitudes was delayed until 1933, when he was finally able to take his experiment to Eritrea. The results led him to assert that "cosmic rays consist chiefly of a charged corpuscular radiation with a continuous energy spectrum extending to very great energies. . . . the charge is predominantly positive."

Later investigations demonstrated that the primary cosmic rays are mostly positively charged protons with a spectrum of energies extending to values far exceeding the highest attainable with accelerators. Unfortunately, the delay of the Eritrean expedition had cost Rossi the priority of discovery. Just as he was leaving, he read the *Physical Review* articles of Thomas Johnson and of Luis Alvarez and Arthur Compton, who had independently measured the east-west effect. Rossi was, however, the first to observe a phenomenon with far-reaching consequences for cosmic-ray physics and astrophysics—extensive cosmic-ray air showers. In his publication of the Eritrea experiments he gave the following account (Rossi's translation from the 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.

Air showers were observed several years later by Pierre Auger and his collaborators, to whom their discovery is generally attributed.

III. From Italy to America (1938–1943)

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.

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

In 1939 Rossi was invited by Arthur Compton to participate in a cosmic-ray symposium at the University of Chicago. With great reluctance to leave Europe, the Rossis sailed to New York. Before going on to Chicago they visited the Fermis. 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." Many years later, Nora Rossi said she would replace the word "shy" with "reserved."

The mesotron was a major topic at the symposium. Afterward, Rossi received support for a definitive test of its instability. In Compton's laboratory he 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, from Chicago to Mt. Evans in Colorado. There, measurements showed that the attenuation of the mesotron intensity is greater in the air between two altitudes on the mountain than in an equivalent thickness 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 two microseconds. It was the first clear demonstration of the decay of a sub-nuclear particle.

Rossi was appointed associate professor of physics at Cornell University in 1940. There he acquired his first American Ph.D. student, Kenneth Greisen, with whom he carried out an improved version of the experiment at Mt. Evans. This last of Rossi's mountain experiments on mesotron decay yielded the first quantitative verification of the relativistic dilation of time intervals, and an improved estimate of the mean life of mesotrons at rest.

Still intent on mesotron decay, Rossi and a graduate student, Norris Nereson, devised a new approach to the measurement of the mean life for which they invented the time-to-amplitude converter, an electronic circuit called a TAC in its modern commercial versions. With the TAC they measured 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.

In December 1940 the Rossis' first child, Florence, was born. Within a year America was in the war. Rossi began his contributions to the war effort in frequent trips to the MIT Radiation Laboratory to consult on radar instrumentation. When his official status as enemy alien was changed in 1943 to "cleared to top secret," he announced to Nora that they must go to a secret place in New Mexico. She remembered overhearing Fermi mention a monstrous bomb, and years later recalled how she "kept tight inside me this terrible secret which I happened on involuntarily."

IV. Los Alamos (1943–1945)

Robert Oppenheimer, director of the Los Alamos laboratory, asked Rossi to form a group to design and develop new electronic instruments for the urgent experiments in nuclear physics that were underway. He and Hans Staub formed the Detector Group, which soon had some twenty people, many just out of college. The group developed 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.

When it was discovered that a plutonium bomb could not be efficiently detonated by the relatively easy gun assembly method, a crash program of theory and experiment was undertaken to perfect the far more difficult implosion method. In the "RaLa experiments" suggested by Robert Serber, a strong radioactive source of gamma rays (radiolanthanum) 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 detector signals 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 invented by the Detector Group. Rossi was assigned the hazardous task of carrying out the tests employing sources equivalent in activity to as much as a kilogram of radium. High-explosive "lenses" were packed around a metal sphere. Simultaneous detonation of the lenses was achieved with electrical triggers. After numerous trials the final tests demonstrated sufficient compression of metal test spheres to assure the success of the implosion method.

Rossi's climactic experience at Los Alamos was measuring the exponential growth of the chain reaction in the plutonium test bomb at Trinity on 16 July 1945. An ultrafast ionization chamber was placed near the bomb and connected to a distant oscilloscope. 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 stretched sinusoidal trace, called the Rossi sweep, was recorded photographically.

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

> 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 and marked a moment of division in the history of the world.

V. Return to Cosmic Ray Research: MIT (1946–1950)

With his work at Los Alamos finished, Rossi accepted a professorship at the Massachusetts Institute of Technology. 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 were soon joined by John Tinlot and Robert Hulsizer from the MIT Radiation Laboratory, and several others. With this group Rossi's manner of working changed fundamentally. He withdrew almost entirely from hands-on involvement to devote his efforts to broad strategy, to conception of experiments, to procurement of support, and, finally, to participation in the interpretation and presentation of results.

From 1945 to 1950, Rossi's Cosmic Ray Group carried out a wide variety of experiments on the properties of the primary cosmic rays and on the particles they produce in their interactions with the atoms of the atmosphere. Several of his then young colleagues have recalled the spirit of those times. Robert Hulsizer wanted to do his Ph.D. thesis research with Rossi, but was daunted by what appeared to be the full crew from Los Alamos. Nonetheless, he attended the afternoon teas. He recounts the following incident:

> One day 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 placed an upper limit of 1 percent on the proportion of electrons and gamma rays in the primary radiation, the first significant step toward the eventual detection of electrons and gamma rays in the primary radiation.

Robert Williams, who developed the density-sampling method for an air shower experiment that measured the energy spectrum of primary cosmic rays to 10^{17} eV, 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."

Matthew Sands has written,

> 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.

In 1949 the Rossi family, now including Frank, born at Los Alamos, moved to a large house in Cambridge, where their third child, Linda, would be born, and where they gave the parties described by Sands. The Rossis also began their summer trips to Wellfleet on Cape Cod. There they enjoyed walks on the beach and the company of artists, writers, and scholars. Bruno and Nora would swim alone to the middle of the nearby pond and talk quietly for the better part of an hour. At sunset there might be a small party, including a student to help opening oysters after being taught by Professor Rossi how to do it without excessive loss of blood.

VI. New Particles and Extensive Air Showers (1950–1960)

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 on Mt. Evans. Among their collaborators were Martin Annis and Stanislaw Olbert, both Rossi students, and Bernard Gregory visiting from France. Their work was a part of the worldwide effort to understand the new unstable particles. The MIT results included cloud chamber observations of heavy mesons and hyperons and evidence of the neutral pion and the antiproton, which preceded their detection in accelerator experiments.

Following Professor Rossi's suggestion, Pietro Bassi, visiting from Italy, and I developed an experiment that showed how the arrival direction of an air shower could be determined by timing the arrival of the shower particles over an array of large scintillation detectors. The only problem Pietro and I had in publication was to persuade Rossi to be a coauthor.

With the techniques of density sampling and fast timing now proven, Rossi gathered a group for an air shower experiment to advance knowledge of the energy spectrum and the origin of the primary cosmic rays. The group included William Kraushaar, Frank Scherb, James Earl, John Linsley, and myself. Minoru Oda from Japan and Bassi participated before returning to their countries. We set out an array of eleven scintillation detectors in the woods of the Agassiz Station. 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. Linsley took the next major step in air shower research, in collaboration with Rossi and Livio Scarsi. In its final configuration, their array of nineteen plastic scintillation detectors encompassed an area of 100 km^2 and determined the primary spectrum to 10^{20} eV. The results presented a challenging problem—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.

VII. The Interplanetary Plasma and X-ray Astronomy (1960–1980)

By the end of the 1950s, particle accelerators had replaced cosmic rays for most particle physics research. Space vehicles and computers had opened a new window into the surrounding world. At a meeting of the Space Science Board, established by the National Academy of Sciences in the wake of Sputnik, Rossi was asked to form a subcommittee to identify areas of space science missing from the plans of the new National Aeronautics and Space Administration. One conclusion 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 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 and Alan Lazarus. The plasma cup, launched aboard the space probe *Explorer 10* on 25 March 1961 with a magnetometer prepared at the Goddard Space Flight Center, 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. Ever more sophisticated plasma cups developed by the MIT group have since been sent around the planets and to the boundary of the solar system.

Rossi was also eager to explore the sky in X rays. Pioneering work on solar X rays had been done by Herbert Friedman and his collaborators at the Naval Research Laboratory. Rossi sensed that an X-ray detector of much greater sensitivity than those used previously in solar studies might widen the window of observation sufficiently to reveal something unexpected among the distant stars.

The MIT group was fully occupied at the time with air shower experiments, a satellite gamma-ray astronomy program initiated by Kraushaar, and preparations for the interplanetary plasma experiment. Rossi therefore presented his idea to Martin Annis, then president of a research and development company in Cambridge called American Science and Engineering, Inc. Annis had founded the company in 1958 and invited me to participate as an investor and consultant. The following year Rossi accepted Annis's invitation to be chairman of the board and chief scientific consultant to the company. Annis has described Rossi as

> more excited and enthusiastic than 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. . . . 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 Riccardo Giacconi to implement the ideas. 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."

With the help of Olbert and me, Giacconi prepared an internal report on the prospects for X-ray astronomy, as a basis for proposals to NASA. The report contained estimates for the intensities of possible extra-solar X-ray sources. It also described an X-ray concentrator consisting of nested paraboloidal grazing-incidence mirrors invented by Giacconi and Rossi. NASA accepted a proposal for the development of X-ray optics, but refused the one for exploratory rocket experiments.

Giacconi then turned to the Air Force Cambridge Research Laboratory, which accepted his proposals for experiments using detectors of large sensitive area on rotating rockets to search a broad swath of the sky for possible X-ray sources including the Moon. The first two flights suffered mechanical failures. The third, in June 1962, detected an astonishingly bright X-ray star in the southern sky, which came to be called Sco X-1, the first of the thousands of extra-solar X-ray sources subsequently discovered. The paper, submitted to the *Physical Review Letters* by Giacconi, Herbert Gursky, Frank Paolini, and Rossi, was considered so strange by Samuel Goudsmit, the editor, that he accepted it only after receiving Rossi's assurance that "he assumed personal responsibility for its contents." The discovery of Sco X-1 inaugurated the major new field of extra-solar X-ray astronomy. The MIT Cosmic Ray Group soon developed a variety of activities in X-ray astronomy encompassing balloon, rocket, and satellite experiments, several carried out in collaboration with the Giacconi group.

For many years Rossi maintained an active role in the MIT plasma experiments. Though he did not participate directly in the MIT X-ray program, he supported it through his influence on promotions and allocation of MIT resources. Most of Rossi's work in X-ray astronomy was devoted to reviews and interpretations of progress in the field. Rossi's ideas, particularly in space plasma research, and his spirit of cooperation, continued to inspire the members of the Cosmic Ray Group as he encouraged the growing autonomy of his former students and colleagues and helped in every way to advance their careers.

VIII. Later Years: MIT (1980–1993)

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, and the autobiography previously mentioned, on which much of this memoir is based. These late works and his earlier technical books, which include *Ionization Chambers and Counters* (1949, with H. Staub), *High Energy Particles* (1952), *Cosmic Rays* (1964), and *Introduction to the Physics of Space* (1970, with S. Olbert), are remarkable for the grace and objectivity with which they describe his own work and that of others. His textbook *Optics* (1957) reflects the clarity and excitement of his lectures to undergraduates. These works 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.

Among Rossi's numerous honors and awards are the Order of Merit of the Republic of Italy (1963), the Gold Medal of the Italian Physical Society (1970), the International "Feltrinelli" Award of the Accademia Nazionale dei Lincei (1971), the Cresson Medal of the Franklin Institute (1974), the National Medal of Science (1985), the Wolf Prize (1987, shared with Friedman and Giacconi), an Institute Professorship at MIT, and honorary degrees from the universities of Palermo, Durham, and Chicago.

Bruno Rossi died at his home in Cambridge, on 21 November 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.

Elected 1959

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[This essay is an abridgment of Professor Clark's contribution to the *Biographical Memoirs* of the National Academy of Sciences 75 (1998). It is reprinted with the permission of the National Academy of Sciences, Washington, D.C.]