NATIONAL ACADEMY OF SCIENCES

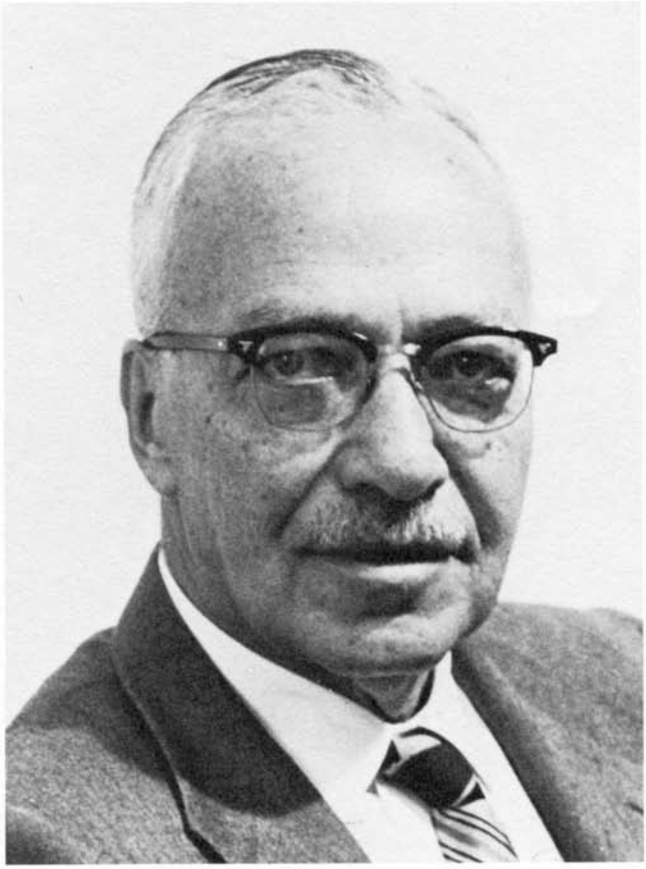
RUDOLPH MINKOWSKI

1895—1976

A Biographical Memoir by

DONALD E. OSTERBROCK

Biographical Memoir



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Rudolph L. Minkowski

RUDOLPH LEO BERNHARD MINKOWSKI

May 28, 1895–January 4, 1976

BY DONALD E. OSTERBROCK

RUDOLPH MINKOWSKI was born in Germany near the end of the last century and died in California during the final quarter of this century. He was trained as a laboratory physicist, but worked most of his life as an observational astronomer. Using the largest optical telescopes in the world, he made important contributions to nearly every branch of nebular and extragalactic astronomy, but his most important contribution of all was to the identification and interpretation of cosmic radio sources. His monument is the National Geographic Society–Palomar Observatory Sky Survey. He guided, encouraged, and counseled a generation of radio and optical astronomers.

Minkowski was born in Strassburg, then part of Germany, on May 28, 1895. His grandfather had hurriedly moved his family to Königsberg from their native Russia less than twenty-five years before to escape the policy of anti-Semitic persecution adopted by the Czar's government. Rudolph's father Oskar, educated in Königsberg, became a physician, and at the time of Rudolph's birth he was a well-known pathologist on the Strassburg University medical faculty. His research had played a very important part in understanding the causes of diabetes. Rudolph's older uncle, Max, took over the Minkowski family business in Königsberg, while his younger uncle, Hermann, became a world-famous professor of mathematics, first at Zürich, then in Göttingen. He made many very important discoveries and is perhaps best known for his idea of the space-time continuum, which provides the simplest and best mathematical basis for handling the special theory of relativity.

As his father moved up in the academic hierarchy, Rudolph was educated in Gymnasia at Cologne, Greifswald, and Breslau and then entered the University of Breslau, where he studied physics and earned his Ph.D. in 1921. He had served in the German army during World War I. At the university he specialized in optics and spectroscopy, and his thesis, done under the supervision of Rudolf Ladenburg, was on the Na I D lines and the information on the physical and chemical properties of sodium that could be drawn from them. After receiving his Ph.D., Minkowski continued to work briefly at Breslau, with Ladenburg, and then at Göttingen, with James Franck and Max Born. He then moved on to Hamburg, where he started as an assistant at the Physikalisches Staatsinstitut in 1922; he became a Privat-Dozent in 1926, and he was appointed to a professorship in 1931. Minkowski's research at Hamburg was at first centered on atomic physics and spectral lines. He worked in close association with a vigorous group of physicists, including, among others, Albrecht Unsöld and Wolfgang Pauli.

Minkowski, however, had been interested in astronomy from childhood; at Hamburg he soon met Walter Baade, then a young assistant to Max Wolf at the Hamburg Sternwarte. Although he continued his spectroscopic and experimental quantum mechanical research at Hamburg, Minkowski's field of specialization shifted increasingly to astrophysics, and he published his first astronomical paper with Baade, F. Goos, and P. P. Koch in 1933. It concerned the interferometric measurements of the profiles of emission lines in the spectrum of the Orion nebula, a subject to which Minkowski's training and experience enabled him to make important technical contributions.

By this time Adolf Hitler had come to power in Germany. Minkowski had married Luise David in Leipzig on August 23, 1926. Her father, Alfons David, was a judge who had been appointed to the Supreme Court of Germany in 1917. Hitler became Reichschancellor in 1933, and one of his government's first actions was to order the universities to get rid of almost every "full-blooded Jew" who held a teaching position. Justice David was forced off the high court by the Nazis because he was a Jew. Although Minkowski and his parents were baptized Christians, their family was historically Jewish. Baade, who earlier had spent a year in the United States as a Carnegie International fellow, had emigrated to take a position on the staff of the Mount Wilson Observatory in Pasadena in 1931. He urged his friend to join him there and in 1935, the year in which Hitler proclaimed his so-called "Law for the Protection of German Blood and Honor," Minkowski, with his wife and their children Eva and Herman, left his homeland. At first he had only a research assistantship at Mount Wilson; in addition he gave a series of lectures on atomic spectra to the staff members, for which they contributed a little cash to help him get established in America. Before the year was out he had been appointed to a regular position and was on his way.

Under Director Walter Adams, the Mount Wilson staff used the 60-inch and 100-inch reflectors, the latter the largest telescope then in existence, in a highly compartmentalized observational research program. One staff member, Paul Merrill, studied the spectra of M giants, supergiants, and long-period variables; another, Roscoe Sanford, studied the spectra of carbon stars; and a third, Alfred Joy, studied the spectra of variable stars that were not long-period variables or carbon stars. Edwin Hubble headed the attack on the cosmological problem of the expansion of the universe, concentrating his observational work on the determination of the distances of the galaxies, while Milton Humason took their spectra to measure the redshifts. Baade worked on the stellar content and general properties of star clusters and galaxies. Except for Merrill, they all tended to think in astronomical, rather than physical, terms.

Minkowski, with his wide knowledge of spectroscopy, atomic physics, and applied quantum mechanics, became involved in all these studies, but specialized in work on gaseous nebulae and related objects. He began by using the fast, low-dispersion spectrographs designed for Humason's measurements of galaxies to take spectra of faint supernovae, the highly luminous exploding stars that flare up to a brightness comparable to an entire galaxy, as they were discovered in surveys by Fritz Zwicky, Baade, and others. Minkowski classified the emission-line spectra of supernovae and studied their development in time. The combination of his spectral classification with Baade's light curves led to the recognition that there are two different types of these objects and that in many cases a supernova's absolute magnitude, and hence the distance to the galaxy in which it occurs, can be estimated from a single spectrogram.

Minkowski obtained many spectra of various regions in the Crab nebula, which had recently been identified by Jan Oort and Nicholas Mayall as the remnant of a supernova that occurred in our Galaxy in A.D. 1054. He confirmed Mayall's result, that the spectra of the filaments of the Crab nebula indicated a high velocity of expansion, and that the amorphous region had a purely continuous spectrum. Minkowski measured this continuum and correctly pointed out that it had no Balmer discontinuity, making it impossible to interpret as a thermal recombination spectrum. He did not realize at that time that the continuum was in fact nonthermal synchrotron emission; this was predicted much later by I. S. Shklovsky after the Crab nebula had been identified as a radio source, and it was observationally confirmed by optical polarization measured by V. A. Dombrovsky and M. A. Vashakidze and also by Oort and T. Wahlraven. Minkowski, from his spectra of the two stars identified by Baade as the possible supernova remnants because of their proximity to the center of expansion of the nebula, picked out the correct one—nearly thirty years later it became the first optically identified pulsar. Through the years Minkowski obtained spectra of the gaseous remnants of several other galactic supernovae. In particular, his measured radial velocities in the Cygnus loop and other roughly circular remnants have been widely used in theoretical discussions of the ages, distances, and energy outputs of these objects.

Planetary nebulae were another subject studied by Minkowski from his first days at Mount Wilson until years after his retirement. In his early work, he obtained spectrophotometric measurements of many low-surface-brightness planetaries that had been too faint for previous investigations, and he proved that their spectra were quite similar in overall pattern to the brighter objects. At Mount Wilson he organized a survey to find new planetary nebulae with an objective prism mounted on the 10-inch Cooke wide-angle camera. He used the 60-inch and 100-inch telescopes to take slit spectrograms of suspected planetaries turned up by this survey, objects with bright Hα and weak or nonexistent continua, and in this way more than doubled the number of known planetary nebulae. Minkowski then arranged for Karl G. Henize to take the same camera to South Africa and complete the planetary nebula survey in the southern Milky Way as part of his University of Michigan Ph.D. thesis.

Minkowski was engaged in a long program, originally in collaboration with Mayall at Lick Observatory, to measure the radial velocities of all the planetary nebulae, in order to study the kinematics of this old, disk system of objects that can be observed out to great distances from the sun. Eventually Minkowski obtained and measured nearly all the spectrograms himself, and, although he never published the individual velocities, he discussed the general results in a paper and in a review chapter published in 1965.

Minkowski was fascinated by the forms of planetary nebulae and invested large amounts of observing time with the 100-inch—and later with the 200-inch Hale telescope at Palomar—in taking direct photographs of individual objects. He used various combinations of glass filters and photographic emulsions to isolate narrow spectral regions around specific nebular emission lines, for instance, [O III] $\lambda\lambda$4959, 5007, and Hα + [N II] $\lambda\lambda$6548, 6563, 6583. These pictures, many of them taken in conditions of fine seeing, clearly illustrate the ionization structure of planetary nebulae, their frequently cylindrically symmetric overall structure, and their complicated fine structure, often consisting of filaments, condensations, knots, and the like down to the smallest resolvable scale. Although some of these planetary-nebula pictures were published by Minkowski himself, and more were used as illustrations in the two International Astronomical Union symposium volumes on planetary nebulae,[1] many of them have never been reproduced. Minkowski observed and analyzed the spectra of many individual planetaries, always trying to understand them physically: their masses, composition, temperature, and density structure, even their evolution.

As an expert in applied optics, Minkowski made many instrumental contributions to the Mount Wilson Observatory

[1] D. E. Osterbrock and C. R. O'Dell, eds., *Planetary Nebulae* (Dordrecht: D. Reidel, 1968), xv + 469 pp. and Yervant Terzian, ed., *Planetary Nebulae, Observations and Theory* (Dordrecht: D. Reidel, 1978), xxi + 373 pp.

spectrographs. Plane gratings were just coming into regular astronomical use in the 1940s, and Minkowski analyzed the curvature of the spectral lines they introduced, and how this effect may be corrected. His work on this subject received the sincerest form of appreciation when a paper was accepted and published in the *Astrophysical Journal* on the same subject over thirty-five years later, consisting entirely of results and conclusions that were included in Minkowski's original paper.

At Hamburg, Baade and Minkowski were close friends with the eccentric, one-armed optician, Bernhard Schmidt, who invented the Schmidt camera in 1930. This camera, a combination of a spherical mirror with a thin aspheric corrector at its center of curvature, forms a very fast, wide-field optical system. Used as photographic telescopes, Schmidt cameras can produce excellent deep exposures of nebulae and star fields, as shown by Schmidt himself, and later by Fritz Zwicky, with the 18-inch at Palomar Mountain. Minkowski was one of the leaders in pushing the use of Schmidt cameras in spectrographs, where they are far superior to the lens cameras previously employed. In particular, the *f*/1.5 conventional Schmidt and the *f*/0.67 solid-block Schmidt cameras designed by Minkowski for the 100-inch Newtonian spectrograph were faster and produced much better images than the older, thick-lens, microscope-objective systems used by Humason for obtaining spectra of faint galaxies.

By the time Minkowski came to America in 1935, the design and construction of the 200-inch telescope for Palomar Observatory was well under way on the campus of the California Institute of Technology in Pasadena. It was built with funds provided by the Rockefeller Foundation, with the understanding that Palomar was to be operated jointly with Mount Wilson Observatory by Caltech and the Mount Wilson staff. Undoubtedly, Baade and Minkowski were among the strongest voices in urging Adams, Hubble, and the rest of the Observatory Council to recommend enlarging the project by building the largest Schmidt telescope in the world to supplement the largest reflector in the world. The result was the 48-inch Schmidt telescope at Palomar, a magnificent *f*/2.5 instrument that takes plates covering over six degrees square with excellent definition.

The first large task for the 48-inch Schmidt, after it went into regular operation in 1950, was the National Geographic Society–Palomar Observatory Sky Survey. The entire sky from the north pole down to declination −33° was surveyed in 935 preselected, overlapping fields. Two plates—a blue exposure, covering the wavelength region λλ3600–4800, and a red exposure, covering λλ6200–6700—were taken in immediate succession. If these exposures passed rigid quality and uniformity requirements, they were reproduced by a carefully standardized contact-print procedure and distributed to the research institutions that had ordered them.

Minkowski was in overall charge of this entire operation. He tested and adjusted the Schmidt telescope; set up the observing procedures; personally supervised Albert G. Wilson, Robert G. Harrington, and George O. Abell, the observers who took nearly all the plates; and examined all the plates that passed their preliminary screening, made the final judgment as to whether or not they were acceptable, and constantly inspected the duplicate negatives and final prints and plates produced from them. His very high standards, coupled with his technical expertise and experience, made the resulting Sky Survey prints and plates an extremely high-quality body of research material. Every serious observatory and research astronomy department has a set, and they have been used for innumerable research investigations.

The survey was later extended to −45° declination, in one spectral region only, λλ 5400–7000, by John Whiteoak, using the Palomar 48-inch Schmidt. The far southern hemisphere is now being surveyed, in a very similar way, by the new European Southern Observatory Schmidt telescope at La Silla, Chile and the United Kingdom Schmidt telescope at Siding Springs, Australia.

When the 200-inch telescope was completed after World War II and went into operation with the 48-inch Schmidt at Palomar Observatory, Minkowski and his colleagues became staff members of Mount Wilson and Palomar Observatories, as the joint operation was named, and faculty members at Caltech. Ira S. Bowen, longtime Caltech laboratory spectroscopist and solver of the puzzle of the identification of the forbidden lines in gaseous nebulae, became director of the institution. Convinced of the advantages of Schmidt cameras for astronomical spectroscopy, he took personal charge of the high-dispersion coudé spectrograph of the 200-inch Hale telescope, but left Minkowski responsible for the fast, low-dispersion prime-focus spectrograph and the 48-inch Schmidt. Bowen had made the final choice of the basic optical parameters of the 48-inch, and as director he insisted that the Sky Survey be completed before the telescope was turned over to the research programs of individual staff members. Bowen and Minkowski had great respect for one another's optical and instrumental abilities, and they discussed new developments frequently.

Caltech started its own astronomy department, to which—in addition to Zwicky—Jesse Greenstein, Guido Münch, and I were the first three members appointed. Fred Hoyle was a frequent visitor. We had a regular, weekly Astronomy–Physics lunch at the Atheneum, the Caltech faculty club, at which Baade, Minkowski, and Armin Deutsch from the Mount Wilson offices were always faithful participants, usually along with a few others. Minkowski was always eager to hear of the latest developments in physics and astrophysics and happy to tell William Fowler, Richard Feynman, Matthew Sands, Leverett Davis, and the other physicists what he had been doing at the telescopes.

With the increased light-collecting power of the 200-inch, Minkowski was able to get better data on fainter supernovae, planetary nebulae, and other nebulous objects. But he soon found himself heavily involved in the problem of the optical identification of radio sources. Radio astronomy was born in the early observations of Karl Jansky and Grote Reber, but it came to vigorous life after World War II. Radio engineers and physicists such as E. G. Bowen, J. L. Pawsey, Bernard Lovell, Martin Ryle, John Bolton, R. Hanbury Brown, and Bernard Mills returned to academic and government positions in England and Australia from the wartime laboratories in which they had developed radar and other advanced detection, location, and identification systems. They had seen solar and celestial radio-frequency radiation by its interference effects, and resolved to study it to learn more about the universe. Although their first interferometers and reflectors gave only very rough angular coordinates of the individual radio sources (originally often called radio stars), the very bright source, Taurus A, was soon identified with the Crab nebula by Bolton and Gordon Stanley.

In late 1948 Bolton—who with Stanley and O. B. Slee had by then also identified Centaurus A and Virgo A with the optical galaxies NGC 5128 and M 87, respectively—wrote to several prominent optical astronomers to seek their help in making further identifications. He chose between Baade and Minkowski by flipping a coin. The luck of the toss decreed he should write to Minkowski; he did, and received a reply from Baade. Therefore Bolton addressed his next letter to Baade, and received a reply from Minkowski. They were both highly interested in the radio-source identification problem, and collaborated very closely in their investigations; Minkowski did all of the spectroscopic work and shared with Baade the taking of the direct exposures. As senior members of the Mount Wilson and Palomar Observatories staff, they were able to command large amounts of prime dark observing time with the two most powerful telescopes in existence, and they were willing to commit a sizeable fraction of their time to searching for the optical counterparts of radio sources.

Some of their first identifications were additional supernova remnants within our galaxy, such as Cassiopeia A and Puppis A; others were galaxies with strong broad emission lines, such as Cygnus A and Perseus A. These galaxies opened the fascinating hope of a whole new attack on the cosmological problem. Cygnus A, for instance, is a faint and insignificant optical object, but one of the strongest radio sources in the sky. Surely among the numerous weak radio sources there must be other galaxies physically similar to Cygnus A, faint only because of their great distances, greater than the distances of any galaxies then known. To recognize such objects was the task Baade and Minkowski set for themselves. The problem was always the insufficient accuracy of the radio positions. In their papers, in their correspondence, in their personal conversations with all the radio astronomers whom they met at conferences and who visited Pasadena, Baade and Minkowski constantly urged the necessity of improving the positional accuracy to the standard of optical astronomy—which the radio astronomers have by now essentially achieved, with probable errors of order one-tenth of a second of arc, rather than the several degrees of the early days.

By their pioneering identification work, Baade and Minkowski established that some strong radio sources are supernova remnants within our Galaxy and that many others are galaxies with strong emission lines in their spectra, sometimes distorted in form, sometimes heavily obscured by dust. They were less successful in their physical interpretation of the radio galaxies as galaxies in collision, an idea derived from Baade's earlier work with Lyman Spitzer on S0 galaxies. The spectra and forms of Cygnus A, Perseus A, and Centaurus A suggested that these objects were actual examples of colliding galaxies, but this interpretation has now generally gone by the board. Most astronomers and astrophysicists are now seeking the basic cause of the generation of magnetic fields and relativistic electrons that produce the observed nonthermal radio radiation in the galactic nuclei.

A still greater contribution to radio astronomy by Baade and Minkowski was the welcome and encouragement they extended to the early radio physicists. They passed on their optical knowledge, skills, and resources to the newcomers, helping them to become respected members of the astronomical community. Caltech's Owens Valley Radio Observatory was built as a result of Baade, Greenstein, and Minkowski urging that the Institute get into this important new field of research.

Baade's participation in the radio work ended when he retired from the Mount Wilson and Palomar Observatories' staff in 1958, at the age of sixty-five. After brief periods as a visiting professor at Harvard and at the Australian National Observatory in Canberra, he moved to Göttingen, where he died less than two years after his retirement, leaving unfinished many projects he had hoped to complete.

Minkowski continued to identify and obtain spectra of radio sources alone after Baade's retirement, but he in turn had to retire two years later, on June 30, 1960. A few months before his retirement, he used the 200-inch to take a spectrogram of the faint radio galaxy 3C 295, which had been identified by Bolton on a 48-inch Schmidt plate from an accurate radio position. On his spectrogram Minkowski identified the single emission line as [O II] λ3727, the only reasonable identification possible, and measured its redshift as $z = 0.46$, nearly half the velocity of light. This broke the observational barrier at about $z = 0.2$ for normal galaxies, which Humason had been struggling to surpass for nearly ten years. Minkowski's record redshift remained the largest known for a galaxy for over fifteen years, until it was topped by Hyron Spinrad, James Westphal, Jerome Kristian, and Allan Sandage with $z = 0.75$ for 3C 343.1 The first quasistellar radio sources, or quasars, were identified after Minkowski's retirement, again from very accurate radio positions. The riddle of their spectra was broken by Maarten Schmidt, who thus proved that they have very large redshifts. At the present writing, the quasar with the largest known redshift is OQ 172, with $z = 3.53$ or 91 percent of the velocity of light.

Minkowski also worked on another important problem, the mass-luminosity ratio in elliptical galaxies. Although in spiral galaxies it is possible to measure the rotational velocity as a function of distance from the center, and thus derive the mass distribution, in elliptical galaxies there are no H II regions or bright OB-star associations that can be observed spectroscopically, as there are in spirals. Minkowski realized that the only way to proceed was to obtain good, high-dispersion spectra of the nuclei of elliptical galaxies, measure the width of the absorption lines to get the velocity dispersion of the stars near the nuclei, and thus determine the central mass densities. The values of mass-to-luminosity ratios he derived in this way were the best available for many years, until they were recently supplanted by Sandra M. Faber, W. L. W. Sargent, and others using detectors much more sensitive than the photographic plates available to Minkowski.

After his retirement from Mount Wilson and Palomar Observatories, Minkowski spent the year 1960–1961 as a visiting professor at the University of Wisconsin. He lectured on gaseous nebulae, supernovae, and radio sources and started C. R. O'Dell on a thesis on the evolution of planetary nebulae and their central stars, a thesis O'Dell completed under my supervision. Earlier, at Caltech, Minkowski had been an unofficial adviser for Abell's thesis on clusters of galaxies, for which I was also the official sponsor; I believe that these were the only two Ph.D. theses with which Minkowski was closely involved. After his year at Madison, Minkowski spent some months as a guest investigator in Australia, working with Bolton on radio-source identifications.

In 1961 Minkowski was appointed a research astronomer at the Berkeley Radio Astronomy Laboratory of the University of California. He and his wife moved their home to Berkeley, where they were close to both their children. There he continued writing up his own research results as well as several review articles and served as a constant source of encouragement and advice to faculty members, postdoctoral fellows, and graduate students. He collaborated on several projects, particularly on the properties of normal galaxies, with various Berkeley faculty members. In 1964 he took part in the Solvay Conference in Brussels on the structure and evolution of galaxies. In 1965 he formally retired a second time at the mandatory age of seventy, but continued to come to the campus regularly and discuss research. The last paper he wrote, fittingly enough, was a report on the accomplishments of the Palomar 48-inch Schmidt telescope, which he presented at a conference in Hamburg devoted to planning the European and United Kingdom southern-hemisphere Schmidt surveys.

Minkowski was elected to the National Academy of Sciences in 1957 and was awarded the Catherine Bruce Gold Medal of the Astronomical Society of the Pacific in 1961 for his distinguished services to astronomy. In 1968, at the centennial of the University of California, Minkowski received an honorary doctorate at the Berkeley commencement exercises for his outstanding astronomical achievements.

Personally, Minkowski was a large, friendly, bearlike person. He was much stronger than most astronomers, and he could always get an extra turn out of any screw, clamp, or guiding eyepiece adjustment. The designers and instrument makers at the Mount Wilson shops used to joke that their products had to be not only "astronomer-proof" but "Minkowski-proof."

His office, at the Mount Wilson headquarters on Santa Barbara Street in Pasadena, was famous for being the most cluttered of any in the building, no mean distinction. Over the years he had accumulated tremendous quantities of folders of measurements, calculations, drafts of papers, reprints, preliminary results, and the like. His standard procedure was to keep this material piled on top of his desk where he could get at it. Photographic plates of the objects he was studying, in paper envelopes, were immersed in these piles, which were heaped up to the angle of repose. If a visitor came into his office to discuss some planetary nebula with him, Minkowski would begin to talk about it; then dive unerringly into the right place in the right pile to come up with a plate of its spectrum; open the envelope; pull out the tiny glass plate that should have been, but often was not, mounted on a microscope slide; blow the cigarette ashes off of it; sometimes stick it together with scotch tape if it had fallen off the desk and broken in some previous conference; look at it through an eyepiece and describe it while a lighted cigarette dangled from his mouth a few inches from the plate; hand the visitor the plate and an eyepiece while he continued expounding; recapture the plate; wipe it off with the side of his hand; put it back in the envelope; and put the envelope back in the exact same place in the exact same pile. There was clearly a higher system to the mess, which he alone understood.

Minkowski was a very good observer. He was experienced, skilled, understood the telescope and the spectroscopes, what they could do and could not do, and what he himself could do and could not do. He was a curious mixture of patience and impatience. Setting on a faint planetary nebula or supernova remnant, he was impatient and eager to begin. For some years the night assistants at Palomar had a tape, surreptitiously recorded, of Minkowski talking to himself in the prime-focus cage of the 200-inch as he made a setting: "Where is that thing? . . . I think that's it over there. [Sound of slow motion motor] Damn! Wrong button [Slow motion again]. . . . There it is. . . . Now where's that little double to the left? . . . No that's not it. . . . [To the night assistant] Try a little west. . . . Stop! [To himself] Here it comes [Slow motion]. . . . Yes I think that's it. . . . Pull it down a little [Slow motion]. . . . Ah! Too Much! [Slow motion]. . . . Now I've got it [Sound of dark slide opening—then, to the night assistant] Start the exposure! I'll take three hours on this one. You can rest a while." This is followed by a long sigh, then he began to hum the "Ode to Joy" from Beethoven's Ninth Symphony, and the tape mercifully ends.

He was very patient in the guiding, doing a careful job all during the tiresome long exposures he took, but impatient to see the results. He would hurry into the darkroom with a recently exposed plate, develop it, give it quick rinse in water, plunge it into the hypo fixing solution, count thirty seconds, light a cigarette, and have the plate out of the hypo and be looking at it with his eyepiece before it had cleared.

I well remember when he showed me how to use the nebular spectrograph at the Newtonian focus of the 100-inch telescope one hot summer night in 1954. Minkowski, in his shirt sleeves, was wearing a fur-lined cap of the type popularized by the Chinese infantrymen in Korea a few winters before. Sweat was dripping down his face as he demonstrated how to raise the heavy spectroscope to see the star field, and then lower the instrument again to center the object and start the exposure. "Why do you wear that hat?", I asked him. "Makes a good crash helmet," he muttered, and I laughed. I understood what he meant the next month when, observing by myself, I hurried down the ladder from the platform with a just-exposed plate to develop, dashed across the observing floor toward the stairs to the darkroom, and slammed my bare head into the black, steel, absolutely immovable bottom end of the 100-inch. My head stopped right there, but my feet kept on going, and I was knocked out for a second. As I came to, lying flat on my back, feeling for the telescope above me, I resolved to pay a little more attention to what Rudolph was trying to teach me. With me, as with everyone else who approached him, he was extremely friendly, very helpful, and always happy to talk astronomy.

Minkowski worked very hard and single-mindedly on research. I once told Luise, his wife, that when I was a student, some years before, I had seen a magazine article about the staff members who were to work at Palomar and what their hobbies were. In a picture in that article Rudolph had been shown at his hobby, playing the piano, and I asked her if he still played. (Humason had been shown in the same article, washing his car.) She replied in her emphatic way "Oh, I remember that article. That reporter didn't understand anything! He wanted hobbies, but I told him none of those men had any hobby but astronomy! He wouldn't believe it. Rudolph used to play the piano, ages ago when he was young, but he hasn't touched it for years." How right she was. Yet he always enjoyed the outdoors and managed to find time for camping and fishing expeditions with his family in the High Sierras, just as in earlier years he had made time for climbing expeditions in the Alps with his fellow students.

Minkowski and Baade remained close friends all the years they were together at Pasadena. Baade, two years older, was far more intense, mercurial, and flamboyant. His conversation and lectures were peppered with stories, always apt, always interesting, sometimes true. He once correctly described his own voice as "sounding like a barking dog." Minkowski was quiter, more phlegmatiic, but never at a loss for words. Often the two of them were at Mount Wilson together, on the 60-inch and 100-inch telescopes, or later at Palomar, on the 200-inch and the 48-inch Schmidt. Then they would walk together slowly up to the domes in the evening and back to the monastery in the morning, discussing astronomy loudly, in voices that carried all over the mountaintops. As they argued vehemently in a queer mixture of German and English, it sounded to the uninitiated as if a battle were about to begin, but they always listened to one another and remained fast friends.

Minkowski and his wife were completely Americanized, in a way Baade and his wife never were. Rudolph and Luise and their children became naturalized United States citizens as soon as they could, in 1940. During World War II, Minkowski worked as a civilian scientist on one of the Office of Scientific Research and Development projects at Caltech, while Luise went to night school to learn to be a draftsman, which enabled her to get a job at the Lockheed plant in Burbank. They never thought of retiring anywhere but in America. Throughout their lives they were both very hospitable people; there were few astronomical visitors to Pasadena whom they did not entertain.

Even after his retirement from his second job at the age of seventy, Minkowski remained in good health until, in the 1970s, he began to suffer from kidney disease. His condition gradually worsened, although he was up and about until the end. In his later years he had become a television football addict, and the last game he saw, and enjoyed mightily, was the 1976 Rose Bowl in which UCLA roundly defeated Ohio State. He died in Berkeley of a sudden stroke on January 4, 1976. The Astronomical Society of the Pacific, under the leadership of Harold F. Weaver, organized a memorial symposium in Minkowski's honor, held at their annual meeting in June 1977 at Berkeley, in which reviews were presented of the various subfields of astronomy in which he had specialized. His wife and daughter attended part of the symposium, and Luise particularly enjoyed a luncheon in connection with it, at which she renewed her acquaintance with many old friends. Although she was in good health then, she was soon attacked by a very rapidly developing case of cancer and died on March 11, 1978. Their children, Eva Minkowski Thomas and Herman O. Minkowski, together with seven grandchildren, survive them in California.

In summary, Rudolph Minkowski was an outstanding observational astronomer and astrophysicist. His life was devoted to science. His work added greatly to our knowledge of planetary nebulae, supernovae and their remnants, radio sources, and galaxies; present research in these fields is along lines shaped in no small measure by his results.

THIS MEMOIR is based largely on the written record of Rudolph Minkowski's research, published in the papers listed in his bibliography, and on my personal conversations with him and with his wife Luise over the years since 1953, when I went to Caltech as a young faculty member and began working closely with him. I have also been able to use clippings, articles, news releases, letters, documents, and reminiscences provided through the kindness of his children, Eva M. Thomas and Herman O. Minkowski, and of many of his friends, colleagues, and fellow scientists. I am deeply indebted to all of them for their help.

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