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(*b*. Frankfurt am Main, Germany, 9 October 1873: *d*. Potsdam, Germany, 11 May 1916)

astronomy.

Schwarzschild was the eldest of five sons and one daughter born to Moses Martin Schwarzschild and his wife Henrietta Sabel. His father was a prosperous member of the business community in Frankfurt, with Jewish forebears in that city who can be traced back to Liebmann “of the Black Shield” (died 1594), and possibly even further, to one Elieser, also known as Liebmann, who came to Frankfurt from Cologne in 1450.

From his mother, a vivacious, warm person, Schwarzschild undoubtedly inherited his happy, outgoing personality; from his father, a capacity for sustained hard work. His childhood was spent in comfortable circumstances among a large circle of relatives, whose interests included art and music; he was the first to become a scientist.

After attending a Jewish primary school, Schwarzschild entered the municipal Gymnasium in Frankfurt at the age of eleven. His curiosity about the heavens was first manifested then: he saved his allowance and bought lenses to make a telescope. Indulging this interest, his father introduced him to a friend, J. Epstein, a mathematician who had a private observatory. With Epstein’s son (later professor of mathematics in the University of Strasbourg), Schwarzschild learned to use a telescope and studied mathematics of a more advanced type than he was getting in school. His precocious mastery of celestial mechanics resulted in two papers on double star orbits, written when he was barely sixteen. They appeared in the *Astronomische Nachrichten* (1890).

In 1891 Schwarzschild began two years of study at the University of Strasbourg, where Ernst Becker, director of the observatory, guided the development of his skills in practical astronomy—skills that later were to form a solid underpinning for his masterful mathematical abilities.

At age twenty Schwarzschild went to the University of Munich. Three years later, in 1896, he obtained his Ph.D., *summa cum laude*. His dissertation, written under the direction of Hugo von Seeliger, was an application of Poincare’s theory of stable configurations in rotating bodies to several astronomical problems, including tidal deformation in satellites and the validity of Laplace’s suggestion as to how the solar system had originated. Before graduating, Schwarzschild also found time to do some practical work: having read about Michelson’s interferometer with two slits variably spaced, he devised a multislit instrument for himself. This instrument consisted of a coarse wire grating at a variable angle above the objective lens of a ten-inch telescope. He used it to measure the separation of close double stars; with a micrometer he found the distance between the tiny first-order spectra that resulted, and was able to detect separations as small as 0.88” of arc. Later workers, notably Comstock and Hertzsprung, used this device to find the “effective wavelengths” of individual stars and so a clue to stellar surface temperatures.

After graduating, Schwarzschild became assistant at the Kuffner observatory in Ottakring (a western suburb of Vienna), where Leo de Ball was then director. Here Schwarzschild remained from October 1896 until June 1899, and here he began what became a lifetime avocation-giving lectures that conveyed to nonastronomers his own feelings about the excitement and significance astronomy holds for everyone.

During this period Schwarzschild published several papers on celestial mechanics, dealing with special cases of the three-body problem. But the main thrust of his work now became a coordinated attack on one of astronomy’s most fundamental problems; stellar photometry. Measurement of the radiant energy reaching us from the stars was then still being done by eye, in principle just as Hipparchus had done two millennia earlier. Schwarzschild decided to try substituting a photographic plate for the human eye at the telescope. The many advantages of photography had been recognized (permanent record: coverage of a whole field of stars at once, and of invisible stars merely by increasing the time of exposure), but much work remained to be done before photography could even equal the eye of a trained observer. This work, both theoretical and practical. Schwarzschild now began. It culminated with the publication of his “Aktinometrie,” so called because light producing a photochemical effect was then referred to as “actinic.” Part A of “Aktinometrie,” published in 1910, contains the earliest catalog of photographic magnitudes; it preceded Parkhurst’s “Yerkes Actinometry” by several years.

Of the two likely ways of converting from black dots on a photographic plate to actual stellar magnitudes, Schwarzschild rejected measuring diameters of the images as inaccurate. He had investigated the theory of diffraction patterns as produced at various angular distances patterns as produced at various angular distances from the optic axis and found that the distribution of intensity in the concentric rings was not constant over an extended field. He therefore decided to smear out the images by putting his plate inside the focal plane, and then to measure the density of the resulting blurs with a photometer. This technique had been suggested by Janssen in 1895, but Schwarzschild was actually the first to use it.

Next Schwarzschild investigated the response of the photographic emulsion in order to determine whether photographs taken at different exposure times could be directly compared. According to the photochemical law enunciated by Bunsen and Roscoe in 1862, the image of a given star should be identical with that produced for a star half as bright when exposed for twice the time. But other workers, such as Abney, noted deviations from such strict reciprocity. Schwarzschild was the first to quantify the particular "failure of reciprocity" that occurs under low levels of illumination such as from faint stars. He performed a series of laboratory experiments and concluded that the law must be modified by raising the exposure time to the power p, with p less than unity but a constant for any given combination of emulsion and development process. This relation is still known as Schwarzschild's law, and p as Schwarzschild's exponent, although subsequent work has shown that p is not as unvarying as Schwarzschild had thought.

Now Schwarzschild was ready to try out his techniques on the sky over Vienna. He photographed an aggregate of 367 stars, which included two that were known to vary in brightness. In following one of the variables, eta Aquilae, through several of its cycles, Schwarzschild found that its changes covered a considerably larger range of magnitude photographically than visually. He correctly attributed this difference to a rhythmic change in surface temperature and was therefore the first both to observe and to explain this phenomenon. It is one that occurs in all similar stars—the Cepheids.

These photometric results were presented to the University of Munich as Schwarzschild's monograph qualifying him to teach. He returned to Munich and served as *Privatdozent* for two years.

At a meeting of the German Astronomical Society held in Heidelberg in August 1900, Schwarzschild–once more under Seeliger's influence–discussed quite a different aspect of astronomy, namely the possibility that the geometry of space was non-Euclidean. He suggested two kinds of curvature: elliptic (positively curved and finite, like the surface of a sphere but with antipodal points considered identical) and hyperbolic (negatively curved and infinite). After considering he astronomical evidence then available, he concluded that, if space were curved, the radius of curvature of the universe must exceed the earthsun distance by at least four million time for a hyperbolic universe, and by a hundred million time for an elliptic. The latter case carried the proviso that space absorption of about forty stellar magnitudes must occur, otherwise the returning light emitted from the far side of outsun would refocus into a visible countersunk in the sky. These estimates of size, even as lower how small a universe Schwarzchild thought he lived in, it also demonstrates the unlimited boldness of his thought.

In other publication dating from this period, Scwarzchild considered the suggestion, published by Arrhenius a few months previously, that the tails of comtes point way from the sun because the repulsive pressure of solar radiation ourweighs gravity. Assuming that the tails were made up of a reasonable density, he found that the pressure of radiation could just barely exceed the gravitational attraction by the necessary twenty times, if the particles had diameters between 0.07 and 1.5 mocrons: below that size scatting would predominate. He remarked that occasional tail n which even greater repulsion seemed to be present could not be shaped by radiation pressure alone, Such is still belived to be the case.

In the fall 1901 Scwarzchild was named associate professor at the University of Göttingten abs also director of its observatory. Thr observatory. with the director's living quarters in one wing. had been built and equipped eighty years earlier by Gauss.

Less than a year later, at the age of twenty-eight, Scwarzchild was promoted to full professor, He remained eight years in Göttigen, the most productive and probably the happiest time in his life. He sharpened his ideas in discussions with a brilliant circle of colleageuesl for example, during the summer semester of 1904 he was one of four men in charge of the mathematical-phycial seminar, the other three being Klein, Hibert, and Minkowski. He caried a heavy teaching load but each year managed to include a course entailed "Popular Astronomy." The observatory soon became a center for young intellectuals of all disciplines. But it did not at first Schwarzchild the instruments he needed to pursue his observational work.

Gauss's original meridian circle was obsolete, while the other main piece of equipment, a Repsold heliometer, was unsuitable. In 1904, however, A. Schobloch donated a seven-inch refractor. Schwarxchild and his collaborators used this telescope to photograph 3,522 stars, data on which appeared in the "Aktinometrie."

For this enterprise Scwarzchild has a new idea, Instead of using extrafocal images as before, he decided to use a special plateholder— his "Schraffierkassette" — held in the focal plane but moved mechanically during a three-minute exposure so that all the images came out as squares 0.25mm. on a side, This plateholder, revised several times, was effective but cumbersome and was not used by subsequent investigators, The methods or reducing the plates were also refined. The final publication, *Akinometrie, Teil B* (1912), constrain for each star its fully corrected photographic magnitude and an indication of its surface temperature in the form if its color index (photographic minus visual magnitude). Scwarzchild used the Potsdam visual manitude and also those obtained at Harvard, for comparison.

To the tradition of geodetic measurements at Göttingen, initiated by Gauss, Scwarzchild contributed in 1903 a suspended Zenith camera of his own design, to be used for photographic latitude determination. He also became interested in ballooning— in balloons filled with gas the city plant, making it is hazardous a sport as Schwarschild's other favorites, mountain climbingand skiing. To simplify the problem of navigating while in the swinging basket of a balloon, Schwerzschild developed a form of bubble sextant, with ancillary tables and nomograms.

While in Götingen, Schwarschild also became interested in the sun. He obtained a small grant and went by freighter from Hamburg to Algeria for the total solar eclips of 30 August 1905. His companions were Carl Runge, an applied mathematician at the University of Göttingen, and Robbert Emden, a physicist, then teaching in Muncih, and Schwarxschild's brother-in-law. Their modest equipment, pictured in the published report (and including a rare photograph of Shcwarzschild himself), was set up on the ruined stage of an old Roman amphitheater in Guelma, with a makeshift darkroom nearby. The ambient tempertaure was 108° F., but the planned program was carried out to the last detail. Of greatest interest were Schwarschild's flash spectura; unsing a camera fitted with an objective prism (all the glass being transparent to near ultraviolet light) and roll film pulled through by hand, he got sixteen photographs of the solar spectrum in a period of thirty seconds, beginning ten seconds before second contact. Since the speed with which the moon passed across the solar disc was known, these spectrograms could be analyzed to give the chemical composition, both qualitative and quantitative, of regions at various heights on the sun. This ingenious method was later revived by Menzel in his jumping film spectrograph.

Returning to Germany, Schwarzschild enlisted the aid of his old friend Villiger (who had helped him to measure double star separations in 1896) to investigate how the intensity of ultraviolet light varied across the disc of the sun. The observations were made at Jena, in the Zeiss factory, using a thin film of silver on the objective of the telescope, to screen out all radiation longer than 3,200 A. They found that the drop-off between center and limb was even more pronounced at these short wavelengths than in either the visible or the infrared.

In 1906 Schwarzschild published a theoretical work on the transfer of energy at and near the surface of the sun. In discussing the results of the 1905 eclipse he had assumed that equlibria in the different modes of energy transfer could occur simulataneously and therefore be treated separately. He had also remarked that the rapid decrease in density necessary to explain the observed sharpness of the solar disc favored the predominance of radiative over convective (adiabatic) transfer near the photosphere. He now developed a theory of radiative exchange and equilibrium that was quantitative, and therefore susceptible to experimental verification. He assumed that near its surface the sun was horizontally layered into regions, each of which received radiation from below and reemitted it outward. His first approximation to a solution of the integral equations involved was similar to one proposed by Schuster in 1905. It is therefore usuallyl referred to as the Schuster-Schwarzschild model for a gray atmospherd, althought they arrived at it independently. It represented a major steptoward understanding stellar structure, but as it did not predict the correct flux it was superseded by Eddington's model, which did.

Other theoretical work that Schwarzschild did at Göttingen includes three papers on electrodynamics, written in 1903. In them he attempted to formulate the fundamental equations in terms of direct action at a distance, using Hamilton's principle of least action. This approach has been used again at least once, by Wheeler and Feynmann in 1945.

In 1905 Schwarzschild published three papers on geometrical optics. dealing exhaustively with the aberrations encountered in optical systems. Here he used Hamilton's "characteristic function" (called the "eikonal by Bruns). In the first paper he showed how spherical aberrations originate, including those of higher order. In the second paper he demonstrated how, by combining two mirrors with aspherical surfces, a telescope free of aberrations would result. In the third paper he provided formulas for computing a variety of compound optical systems. Max Born, writing 1955, acknowledge that these papers formed the backbone of his own "Optik," first published in 1932.

Schwarzschild also mde contributions to stellar statistics, at a time when the structure of our galaxy and the way it rotates were still mysterious. He considered, in two articles published in 1907 and 1908, the motions of nearby stars through space as related to estimates of their distances. The sparse observational material then available, including proper motions as tabulated in the Groombrige-Greenwich catalog, had already been analyzed by Kapteyn, who was surprised to find that peculiar motions (obtained from proper motions of the stars by correcting for the motion of the sun) were not random but seemed to favor two preferential directions. Kapteyn derived from this his "two stream hypothesis," which had stars moving past each other from opposite directions. Such a picture was intellectually unacceptable to Schwarzschild, who developed instead what he called a unitary picture, which he showed would fit the observed facts equally well. A third article, published in 1911 after he had left Göttingen, gave details of his methods and compard his results to those of Seeliger, Kapteyn, and Hertzsprung.

Schwarzschild's cosmological thoughts are available in a collection of four popular lectures, entitled "On the System of Fixed Stars." Perhaps of the greatest interest is the lecture read before the Scientific Society of Göttingen on 9 November 1907, dealing with Lambert's cosmological letters. Schwarzschild discussed the type of teleological arguments used (successfully) by Lambert to reach many of the same conclusions about the universe—including the plurality of inhabited worlds—that are adhered to even by those physicla scientist to whom telecological arguments are anathema. Schwarzschild includes a wry comment that teleology is still fruitful in biological sciences, in the theory of evolution.

In 1909 Schwarzschild's life changed. He was appointed successor to Vogel as director of the Astrophysical Observatory in Potsdam. This was the most prestigious post available to an astronomer in Germany, but accepting it meant increased administrative burdens, and also giving up the academic surroundings so congenial to him. Potsdam had been an army town since the time of Frederick the Great, and the University of Berlin would be fully fifteen miles away. Nevertheless, he decided to go, and took up his duties on Telegraph Hill (where the observatory was located) late in 1909. With him he brought Else Rosenbach, the daughter of a professor of surgery at Gottingen, whom he had married on 22 October 1909. Their marriage was successful despite initial family misgivings (she was not Jewish) and was blessed with three children: Agathe, Martin (professor of astronomy in Princeton University), and Alfred.

Also making the move to Potsdam at this time was Ejnar Hertzsprung, who had come to Göttingen at Schwarzschild,s invitation in April 1909.

In August 1910 Schwarzschild went to California to attend the Fourth Meeting of the International Union for Cooperative Solar Research, stopping off along the way to visit the major observatories in the United States. The published account of this trip sheds an interesting light on the differences between American and European astronomy just before World War 1. Notwithstanding the better skies and the larger instruments, Schwarz schilds' envy was directed mainly toward the installations both Harvard and Lick had in the Southern hemisphere. He came home ready to push for a German observatory south of the equator, and suggested Windhoek, then in German Southwest Africa,as a possible site.

The year 1910 also brought a return of Halley's comet. Schwarzschild, with E. Kron, measured photographs of this comet, taken by a potsdam expedition to Tenerife. In their discussion of how the brightness diminished outward, there appeared for the first time the suggestion that fluorescent radiation occurs in comet tails (later amplyverified).

At Potsdam, Schwarzschild's interests turned more toward spectroscopy. He designed a spectrographic objective, which was built by Zeiss. Appreciating the need for a quick and reliable way to determine the radial velocities of stars (to supplement proper motions for work in stellar statistics), he expanded, in 1913, upon the way E.C. Pickering had used an objective prism for this purpose. In 1914, anticipating his own later work in general relativity, Schwarzschild attempted—unsuccessfully, as it turned out—to observe a gravitational red shift in the spectrum of the sun.

When World War I began in August 1914, Schwarzschild carried over into political life the unitary concepts that guided his scientific life. He volunteered for military service, feeling that loyalty to Germany should come ahead of professionalties and his personal background as a jew. After an initial delay, because of his high government position, he was accepted and placed in charge of a weather station in Namur, Belgium. Subsequently he was commissioned as a lieutenant and attached to the headquarters staff of an artillery unit, serving first in France and later on the Eastern front. His assignment was to calculate trajectories for long-range missiles; a communication to the berlin Academy in 1915 (not published until 1920 for security reasons) dealt with the effect of wind and air density on projectiles.

While serving in Russia, Schwarzschild wrote two papers on general relativity, presented to the Berlin Academy for him by Einstein, and published in 1916. The first paper, dealing with the gravitational field of a point mass in empty space, was the first exact solution of Einstein's field equations; Schwarzschild's comment is that this work of his "permits Mr. Einstein's result to shine with increased purity.

The well-known "Schwarzschild radius" appears in the second of these papers, which treated the gravitational field of a fluid sphere with constant density throughout. Such a simplification cannot, of course, represent any real star, but it does permit of an exact solution. This solution has a singularity at $R = 2MG/c^2$, where R is the (Schwarzschild) radius for an object of mass M, G the universal constant of gravitation, and c the velocity of light. Should a star, undergoing gravitational collapse, shrink down inside this radius, it becomes a "black hole" that emits no radiation and can be detected only by its gravitational effects. (As an example of how far a star has to shrink, R for our sun is less than two miles.) The black holes resulting from Schwarzschild's solution differ from those of Kerr's 1963 solution in that they have no angular momentum.

For sometime—dating back to his studies of the solar atmosphers—Schwarzschild had been interested in the problem of relating spectral lines to the underlying structure of the atoms producing them. His last paper was an attempt to enlarge upon several recent papers on the quantum theory written by Planck and by Sommerfeld. This subject, Schwarzschild said, awaits a Kepler—but he did not live to see who it would be.

While serving at the front in Russia, Schwarzschild developed symptoms of a rare, painful, and at the time incurable, malady called pemphigus. This is a metabolic disease of the skin, tentatively believed today to have an "auto-immune" mechanism. Schwarzschild was invalided home in March 1916 and spent the last two months of his life in a hospital. He was buried, according to his own wish, in the central cemetery in Göttingen.

The honors Schwarzschild received before he died at age forty-two were few, considering his accomplishments. He was elected to the Scientific Society of Göttingen in 1905, became a foreign associate of the Royal Astronomical Society of London in 1909, and a member of the German Academy of Science in Berlin in 1913. For his war work he was awarded an Iron Cross. In 1960 the Berlin Academy dedicated to him, as "the greatest German astronomer of the last hundred years," the Karl Schwarzchild telescope, a seventy-nine-inch reflector located at Tautenburg, a few miles from Jena, where the optical parts were made. In 1959 the German Astronomical Society established the Karl Schwarzchild lectureship in his honor, with invited lectures to be given by distinguished astronomers.

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Author’s Note: I am indebted to Professor Martin Schwarzschild for a number of facts about his parents that are not available in print.

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