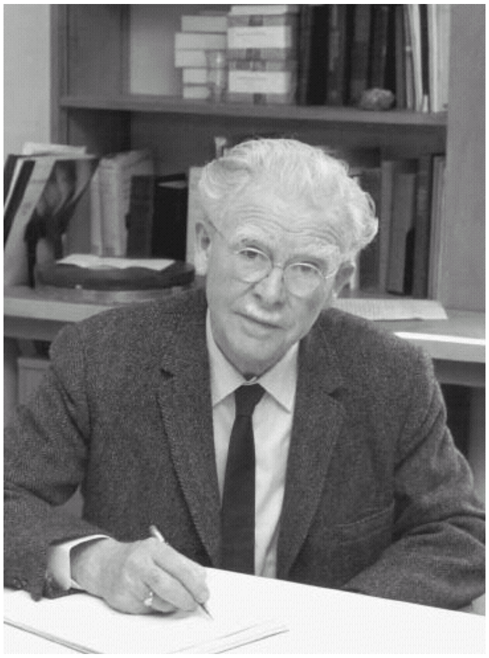

Scott Ellsworth Forbush

April 10, 1904 — April 4, 1984

By James A. Van Allen

SCOTT FORBUSH LAID THE observational foundations for many of the central features of the now huge field of solar-interplanetary-terrestrial physics. The heart of his research was the patiently meticulous and statistically sophisticated analysis of the temporal variations of cosmic-ray intensity, as measured by ground-based detectors at various latitudes and altitudes, and the correlation of such variations with presumptively causative or at least related geophysical and solar phenomena. Among the latter were magnetic storms, solar activity, rotation of the Earth, and rotation of the Sun.

Working almost alone with only technical assistance, Forbush either discovered or put on a reliable basis for the first time the following fundamental cosmic-ray effects:

- The quasi-persistent 27-day variation of intensity;
- The diurnal variation of intensity;
- The absence of a detectable sidereal diurnal variation of intensity;
- The sporadic emission of very energetic (up to several GeV) charged particles by solar flares;
- Worldwide impulsive decreases (Forbush decreases) of intensity followed by gradual recovery;
- The 11-year cyclic variation of intensity and its anticorrelation with the solar activity cycle as measured by sunspot numbers; and
- The 22-year cycle in the amplitude of the diurnal variation.

His pioneering work provided the empirical foundations and inspiration for an immense amount of subsequent research. For the most part, he made only tentative forays into the detailed theory of the relationships he established. Nonetheless he was thoroughly aware of the speculative interpretations of others and embraced them enthusiastically insofar as they were consistent with his perception of the facts. This characteristic of his work is well illustrated by his classical review article "Time-Variations of Cosmic Rays" in the *Handbuch der Physik* (1966).

EARLY YEARS

Forbush was born in 1904 on a farm near Hudson, Ohio. His boyhood was typical of the rural Midwest during that epoch, walking back and forth to a country school 2 miles from his home and taking over a progressively increasing share of the farm chores. His mother, a teacher, nurtured his curiosity and keen interest in learning and enrolled him in the nearby Western Reserve Academy, from which he graduated second in his class in 1920. A year later he entered the Case School of Applied Science in Cleveland and graduated in June 1925 with a major in physics. He then tried graduate study in physics at Ohio State University for a brief period, but he visualized observational geophysics as much more appealing than pure physics and sought employment in that field. He resumed formal graduate work later but with a fresh appreciation of its direct applicability to his research.

1926-32

After a year's employment by the National Bureau of Standards in Washington, D.C., Forbush joined the staff of the Department of Terrestrial Magnetism (DTM) of the Carnegie Institution of Washington (CIW) in September 1927. This appointment was the pivotal point in his professional life. His first job was as an observer at DTM's magnetic observatory at Huancayo, Peru, in the Andes about 100 miles east of Lima. Two years later he joined the staff of the famous nonmagnetic sailing ship *Carnegie*, a vessel built specifically for DTM's worldwide survey of the geomagnetic field. On November 29, 1929, an explosion and consequent fire destroyed the ship while she was at anchor about a mile offshore in the harbor of Apia, Western Samoa. Forbush was on board at the time, but by a quirk of fate, he escaped unscathed. He attributed his good fortune to having decided to take a daytime nap rather than return to work in the ship's photographic darkroom in a compartment near the explosion. He then returned to DTM, and ten months later was reassigned to Huancayo. In the autumn of 1931 he again returned to Washington, and was granted a year's leave of absence to take graduate courses in physics and mathematics at Johns Hopkins University.

In July 1932 Forbush married Clara Lundell, a concert pianist and former teacher of piano and organ at the University of Michigan. The couple had no children. Their marriage was a model of mutual support and harmony for thirty-five years before her death in 1967. Indeed, she inspired her husband to a new level of purposeful and productive professional work, as he later wrote.

1932-40

This period set the tone of Forbush's subsequent career. Back at DTM in Washington, he undertook the reduction and analysis of gravity observations by the *Carnegie* and the detailed study of the characteristics of magnetic instruments as related to data from observatories and field surveys. He developed a passion for sorting out significant effects in large bodies of geophysical data in the face of inevitable instrumental errors and irrelevant natural fluctuations. And he pursued a rigorous program of after-hours courses in physics, statistics, and applied mathematics at George Washington University, the U.S. Department of Agriculture, and the National Bureau of Standards.

In response to a 1932 recommendation by Robert A. Millikan and Arthur H. Compton, the CIW sponsored the development of a network of detectors for the continuous recording of cosmic-ray intensity. Such an undertaking was judged broadly supportive of DTM's mission of investigating all aspects of the Earth's magnetic field. Appropriate detectors were developed under Compton's direction and became known as Compton-Wollan-Bennett ionization chambers or simply as model C cosmic-ray meters. The central element of each of these devices was a spherical steel shell of 19.3 liters volume filled with highly purified argon at a pressure of 50 atmospheres. A carefully controlled electrical potential between the outer shell and a central electrode caused the collection of a current as penetrating cosmic rays ionized the fill gas. Ingenious auxiliary devices were used to balance out this collected current and record the departures from its mean value on a photographic strip chart with an electrometer.

These meters measured charged secondaries (principally μ-mesons, as was later realized) of the primary cosmic radiation after its traversal of the Earth's external magnetic field and its interaction with the overlying atmosphere. Forbush made a detailed study of the technical characteristics of the meters and the effects of temperature and barometric pressure. The latter effect was particularly important because of its diurnal, seasonal, and other variations. He became a master of the calibration and maintenance of these meters and of the necessary corrections. He was then responsible for establishing the initial network of the model C meters in collaboration with national research groups in the several countries in which they were located. The first meter was placed in operation in Cheltenham, Maryland (geomagnetic latitude 50.1° N, altitude 72 meters) in March 1935. The second and third meters of the network were placed in operation in June 1936 in Huancayo, Peru (0.6° S, 3,350 m) and Christchurch, New Zealand (48.6° S, 8 m). Others were added later.

The data from these meters were central to Forbush's subsequent research for many years. In scaling the photographic traces and converting them to numerical tables he had the dedicated technical assistance of Isabelle Lange until 1957 and then of Lisellote Beach until the latter's retirement in 1975. Otherwise Forbush led a largely solitary but never lonely professional life searching the cosmic-ray data for periodicities, trends, impulsive events, and associations with related geomagnetic and solar data. This was a challenging task in the face of statistical fluctuations and variability due to multiple and perhaps unrelated physical causes. Following in the footsteps of the German geophysicist Julius Bartels, he became a master of this process, often depending on Bartels' concept of the harmonic dial in searching for periodicities and assessing their validity. The harmonic dial consists of a vector whose length represents the amplitude of the periodic variation and whose direction corresponds to the phase as displayed, for example, as a hand on a 24-hour clock of Greenwich Mean Time. One test of validity was the carefully calculated statistical significance or insignificance of the relationships among harmonic dials for subdivisions of the data or for the data from different stations. Forbush benefited greatly from Bartels' visits to DTM and he enjoyed the durable encouragement and support of John A. Fleming, DTM's longtime director. Many of his preliminary findings appeared in the yearbooks of the CIW before formal publication.

His short (one figure plus one page of text) 1937 paper entitled "On the Effects in Cosmic-Ray Intensity Observed During a Recent Magnetic Storm" showed a convincing association between simultaneous impulsive decreases and subsequent recoveries of cosmic-ray intensity at both Cheltenham and Huancayo and the magnitude of the horizontal component of the geomagnetic field. Such impulsive decreases of cosmic-ray intensity in a few hours at the times of geomagnetic sudden commencements and the subsequent slow (typically a few days to a few weeks) recovery of intensity thereafter received the durable designation of "Forbush decreases." He modestly accepted this term, remarking occasionally that he preferred it to "Forbush declines." It was already widely accepted that sporadic bursts of solar corpuscular radiation (plasma) caused magnetic storms whose main phase was plausibly attributable to a westward-flowing equatorial ring current (Störmer ring current) whose radius was of about six Earth radii. The similar time signatures of the decreases of cosmic-ray intensity and of the main phases of magnetic storms led Forbush and others to suggest that the hypothetical ring current was also the direct cause of the cosmic-ray effect. This seductive although only qualitative explanation became known as the local or geocentric hypothesis.

In comprehensive follow-on papers in 1938 and 1939, Forbush used cosmic-ray and magnetic-storm data from Cheltenham (United States), Huancayo (Peru), Hafelekar (Germany), Christchurch (New Zealand), and Teoloyucan (Mexico) to establish the occurrence of worldwide decreases in cosmic-ray intensity in association with magnetic storms. This impressive body of data further encouraged Forbush to continue to espouse a common geocentric cause for both effects although he gave a full description of one example to the contrary, namely a large magnetic storm during which there was no perceptible change in cosmic-ray intensity.

Over two decades elapsed before the physical causes of Forbush decreases were convincingly identified. Further remarks on this matter are included in the 1958-84 section of this memoir.

In two other important 1937 papers Forbush used the harmonic dial technique to report (a) the absence of a sidereal diurnal variation of cosmic-ray intensity and hence the isotropy of the radiation within the galaxy and the absence of detectable extragalactic contributions and (b) the clear presence of a 24-hour diurnal variation and its implication of a solar-interplanetary cause.

In a short 1939 paper he gave reasons for doubting the hypothesis that cosmic-ray decreases could be caused by variations in a general dipolar magnetic field of the Sun.

1940-45

As the early phases of World War II spread in other parts of the world and threatened to engulf the United States, Forbush temporarily laid aside his own beloved research. From October 1940 to December 1945, he was on leave from DTM heading a division on mathematical analysis at the Naval Ordnance Laboratory (NOL) and in 1944-45 a related section of the Office of Scientific Research and Development. His work at NOL contributed importantly to the development of degaussing techniques for ships and submarines (i.e., the use of systems of electrical current-carrying coils to annul or at least greatly reduce the external magnetic field of a seagoing vessel and thereby reduce its susceptibility to magnetic mines). On the complementary side of the problem, he guided the development of airborne magnetometers for the detection of submerged submarines.

1945-57

After return to DTM following World War II, Forbush quickly made another seminal discovery by retrospective study of ionization chamber data from Cheltenham, Godhavn (Greenland), Christchurch, and Huancayo. In the records of the three high- and mid-latitude stations, he found large impulsive increases in cosmic-ray intensity on February 28 and March 7, 1942, and on July 25, 1946, each following an exceptionally large solar flare. No increase was observed at the equatorial station, Huancayo. The brief (hours) increases were precursory to large Forbush decreases at all four stations. He identified the increases as establishing the solar origin of impulsive emission of energetic particles having energies up to at least 3 GeV, but less than the geomagnetic cutoff at Huancayo, about 15 GeV. Study of the sporadic solar emission of energetic protons and heavier ions and of electrons has subsequently become a major field of research in solar and interplanetary physics as the energy and intensity thresholds for their detection have been progressively lowered, especially by instruments on spacecraft. Hundreds of such events are documented in the recent literature on the subject.

Forbush's geophysical program was again interrupted for about a year from July 1951 to August 1952 by the Korean War. During this period, he directed a mathematical analysis division of an operations research office based at Johns Hopkins University.

One of his most celebrated papers was completed and published in 1954 under the title "Worldwide Cosmic-Ray Variations, 1937-1952." In it he demonstrated that the intensity of galactic cosmic rays varied synchronously with the previously well known 11-year cycle of solar activity, being anti-correlated with sunspot numbers (i.e., greatest when solar activity was the least and vice versa). The following is quoted from the abstract of that paper:

> Annual means from continuous registration of cosmic-ray ionization at four stations from 1937 to 1952 show a variation of nearly four per cent, which is similar at all

> stations and which is negatively correlated with sunspot numbers. This variation in cosmic-ray intensity is quite similar for the annual means of all days, international magnetic quiet days, and international magnetic disturbed days, which indicates that it is not due to transient decreases accompanying some magnetic storms. . . .

Once again Forbush led the way for scores of others who, as of 1997, continue to investigate the solar modulation of cosmic-ray intensity.

Other related solar effects that Forbush first placed on a firm statistical foundation were the 27-day quasi-persistent variation of cosmic-ray intensity, identified with the synodic rotational period of the Sun, and the diurnal variation of intensity, earlier work on which was noted above.

1957-58

In 1957 Forbush was named chairman of a section on theoretical geophysics at DTM, then directed by Fleming's successor Merle A. Tuve. At about the same time he became chairman of the Panel on Cosmic Rays of the U.S. National Committee for the 1957-58 International Geophysical Year (IGY). As such, he played an important role in organizing and coordinating both national and international efforts in the observation of cosmic-ray intensity on a worldwide basis, especially by the use of neutron monitors developed by John A. Simpson. Networks of these monitors proved to be an important part of the IGY, and they continue to provide valuable data up to the present date and probably far into the future.

1958-84

During the IGY and thereafter Forbush fleshed out and extended his earlier seminal work on the relationships among solar activity, geomagnetic storms, and cosmic-ray intensity. Also he traveled extensively to lecture at international meetings and expanded his personal research style to include more collaboration with other investigators.

In several years encompassing the IGY the physical causes of Forbush decreases and the solar modulation of cosmic-ray intensity were finally placed on a convincing basis. The geocentric hypothesis for Forbush decreases has been described above. It was favored on phenomenological grounds by Forbush and was supported on theoretical considerations by Eugene N. Parker in 1956. An alternative hypothesis was proposed and argued persuasively by Philip Morrison, also in 1956. In it he visualized sporadic emission of clouds of magnetized plasma (or solar corpuscular streams) from active regions on the Sun. Such clouds would modulate the cosmic-ray intensity in interplanetary space *and* produce terrestrial magnetic storms. In Morrison's scenario, both effects had a common cause, but magnetic storms did *not* cause Forbush decreases.

In a series of theoretical papers, 1953-56, Ernest C. Ray discussed the quantitative effect of a ring current on geomagnetic cutoff energies for cosmic rays. He found that a ring current of appropriate magnitude and radius to produce the main phase of a large magnetic storm was inadequate to cause a significant change in mid- and low-latitude cutoffs. Moreover, the effect was of the opposite algebraic sign to that required to explain a Forbush decrease. In retrospect it is most remarkable that these papers did not come to the attention of the proponents of the geocentric hypothesis.

In early space experiments in 1959 and more convincingly in 1960, Simpson and his collaborators Charles Y. Fan and Peter Meyer observed a Forbush decrease in interplanetary space far from the Earth and Paul J. Coleman, Jr., et al. observed, also on the same 1960 spacecraft the simultaneous passage of a large increase (factor of ten) in the interplanetary magnetic field. These observations were widely accepted as confirming the Morrison hypothesis and disposing of the geocentric hypothesis. Forbush, who had continued to be somewhat uneasy about the latter, was delighted to embrace those new findings, as was Parker, who soon became the foremost developer of the interplanetary hypothesis and its extension to encompass the 11-year cyclic variation as well.

As of 1997, scores of Forbush decreases have been observed by instruments on spacecraft near the Earth and by those very remote from the Earth. The most noteworthy Forbush decrease in the history of the subject was observed at the Earth on June 12, 1991, at Pioneer 11 on August 21 at 34 AU from the Sun, and at Pioneer 10 on September 30 at 53 AU, the progressively greater delay being attributed to the outward propagation of the burst of solar plasma.

The solar cycle variation of cosmic-ray intensity has also been massively confirmed and greatly illuminated by ground-based neutron monitors and space-based detectors, both much more sensitive to the lower-energy portion of the spectrum of primary cosmic rays than were the ionization chambers whose data Forbush used. There is little doubt that this effect is also encompassed by some form of the Morrison hypothesis. There remains the unsolved issue of the radial extent of the solar modulation, now known by direct observation to extend beyond 67 AU from the Sun.

In 1959 Forbush gave a series of lectures entitled "Geomagnetism, Cosmic Radiation and Statistical Procedures for Geophysicists" at the Peruvian National Universities of San Marcos (Lima), San Agustin (Arequipa), and Cuzco. In 1960-61, as a visiting professor in the department of physics and astronomy at the University of Iowa, he repeated these lectures and was the senior author of two valuable papers on the variability of the trapped particle population of the Earth's newly discovered radiation belts. Also in 1961 he was a visiting investigator at the Royal Institute of Technology in Stockholm, Sweden, and in 1968 at Imperial College, London.

His own version of much of his life's work and its relationship to the work of others is contained in an extended review article in *Handbuch der Physik* (1966) entitled "Time-Variations of Cosmic Rays," the most valuable single reference of the appended bibliography.

During the last few years of his life, he enjoyed a fruitful collaboration with Doraswamy Venkatesan and with Martin A. Pomerantz and others of the Bartol Research Foundation. A year before his death he was senior author of a paper in *Solar Physics* as a result of the latter collaboration. This work refined criteria for the statistical significance of results from the superposed epoch analysis of geophysical and solar data.

GENERAL COMMENTS

Scott Forbush was profoundly influenced by Julius Bartels, who was a research associate at the Department of Terrestrial Magnetism of the Carnegie Institution from 1936 to 1940, and by Sydney Chapman, who occasionally visited there. During this pre-World War II period, the latter was collaborating with Bartels on completing their classical two-volume monograph *Geomagnetism* (Oxford, 1940). Forbush often acknowledged Bartels' personal guidance and his published papers on statistical methods for analyzing geophysical data and he extended Bartels's techniques and applied them with conspicuous success to a variety of problems, especially those involving the temporal variations of cosmic-ray intensity. In his research, Forbush was patient, persistent, and as objectively critical of his own work as he was of the often less careful and less rigorous work of others.

He traveled widely and was a standard contributor to international conferences on cosmic rays and related subjects. He typified a statement of a colleague: "Study cosmic rays and see the world." He carried a battered leather briefcase for many years and took a quiet pride in the dozens of stubs from airlines, shops, and hotels that he allowed to accumulate on its handle, a kind of archaeological record of his travels.

In his personal life, Forbush was shaken by the death of his wife Clara in 1967. The two had very different professional careers, he in science and she in music. But they were devoted to each other and delighted in each other's achievements. She once described their marriage as a two-person mutual admiration society. Their home was in Chevy Chase, Maryland, a suburb of Washington, D.C. He retired from the DTM staff in 1969, but he continued his research there for many years.

A visitor to Forbush's office at DTM in the late 1970s would have found him seated at a large work table carefully reading and annotating a preliminary manuscript. At that time he depended on flip-down magnifying lens attached to his usual spectacles for reading. Also, he often would have a roll-your-own cigarette, either lighted or unlighted, bobbing up and down between his lips as he greeted the visitor.

Forbush was a member of the Washington Academy of Science, the Philosophical Society of Washington (president, 1953), a fellow of the American Geophysical Union and of the American Association for the Advancement of Science, and a member of the Cosmos Club.

Among his honors were the title of Catedratico Honorario of the Republica del Peru, Universidad Nacional Mayor de San Marcos de Lima (1959); the Sir Charles Cree Medal and Prize, eleventh award of the United Kingdom's Institute of Physics and the Physical Society for "distinguished research in terrestrial magnetism, atmospheric electricity, and related subjects . . . cosmic radiation" (1961); an honorary doctor of science degree from Case Institute of Technology (1962); and the Waring Prize of Western Reserve Academy (1974).

He was elected to membership in the National Academy of Sciences in 1962, and in 1966 he received the especially appropriate John Adam Fleming Award of the American Geophysical Union "in recognition of outstanding contribution to the description and understanding of electricity and magnetism of the Earth and its atmosphere."

THE WRITER OF THE present memoir, a friend and ardent admirer of Forbush for many years, edited his 1959-60 Peru/Iowa lectures, much of them handwritten, and assembled these and a compilation of his original published papers into a monograph entitled *Cosmic Rays, the Sun and Geomagnetism: The Works of Scott E. Forbush*, published in 1993 by the American Geophysical Union, Washington, D.C. This volume also includes a tribute by Pomerantz from which the writer has drawn some material.

In June 1970 Forbush married Julie Daves, a science writer and watercolor artist, who, among other achievements, founded and edited the monthly publication *Space Science News* of the Smithsonian Institution's National Air and Space Museum. In 1982 the couple moved to Charlottesville, Virginia, where Scott died of pneumonia in 1984, being survived by Julie and his sister Louise Boyd of Hudson, Ohio.

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