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ERNEST HARRY VESTINE

1906—1968

A Biographical Memoir by
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Biographical Memoir

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ERNEST HARRY VESTINE

May 9, 1906—July 18, 1968

BY SCOTT E. FORBUSH

ERNEST HARRY VESTINE was born in Minneapolis, Minnesota on May 9, 1906, the son of Swedish parents, Frida Christine (Lund) and Olaf Vestine, who left the United States to live near Edmonton, Alberta. Here he received all his early education and a B.Sc. degree from the University of Alberta in 1931. In 1932 he joined the Canadian Meteorological Office in Toronto, where he was occupied with meteorological and geomagnetic measurements.

During the Second International Polar Year (1932–33), Vestine led the Canadian expedition to Meanook in northern Alberta, Canada, where he established and operated a new magnetic observatory, an installation which continues to provide important magnetic data from the auroral region. While at Meanook, he made some of the most significant observations of noctilucent clouds—authoritatively described in his comprehensive 1934 review article.

In September 1934 he left the Canadian Meteorological Office for graduate study in England, and in 1937 received a Ph.D. and a Diploma of the Imperial College of Science and Technology from the University of London. His Ph.D. thesis, done under Professor Sydney Chapman, dealt with the electric current-systems responsible for geomagnetic field variations during magnetic storms. There is no doubt that

this association with Professor Chapman profoundly influenced Dr. Vestine, who greatly admired Chapman's numerous classical contributions to geomagnetism and related subjects. Both had the greatest respect for thoroughness and objectivity, and each devoted his entire life to active research. There was even some similarity in their psychologically calm and logically objective approaches to problems.

Between July 1937 and January 1938, Dr. Vestine again became associated with the Canadian Meteorological Office in Toronto and later lectured in physics at the University of Toronto. In January 1938 he joined the Carnegie Institution of Washington's Department of Terrestrial Magnetism.

On May 20, 1943 Dr. Vestine married Lois Anne Reid. Their only child, Henry Charles Vestine, is a successful popular musician. Dr. Vestine was a persistent reader of scientific literature with a keen interest in history and biography. He and his wife often enjoyed cruising and fishing on the Chesapeake Bay in their comfortably equipped forty-foot motor launch. Dr. Vestine was quite proficient in maintaining his boat in excellent condition. He never appeared perturbed by ordinary misfortunes and, like his wife, was always interesting, courteous, and affable.

At the Department of Terrestrial Magnetism he made numerous outstanding, comprehensive contributions to the understanding of the earth's magnetic field, its secular, diurnal, storm-time, and other variations and related phenomena in the Earth's interior and in the aura and the ionosphere. In recognition of these accomplishments, he was given the sixth John A. Fleming Award in April, 1957 by the American Geophysical Union of The National Academy of Sciences-National Research Council. In his citation, Professor Chapman, world authority on geomagnetism and related subjects, characterized Dr. Vestine as a world leader in geomagnetism and auroral science.

The association of Dr. Vestine with the Department of

Terrestrial Magnetism of the Carnegie Institution of Washington was extremely fortunate and beneficial for both. This Department was established in 1904, two years before Dr. Vestine's birth. Since its founding, the Department had completed an extensive world-wide survey comprising an enormous number of measurements of the earth's magnetic field on land and sea. At many points, these measurements were repeated at intervals to provide data for secular variation, while the observatories of many countries provided continuous data and additional land survey information.

The prodigious task of systematically organizing practically all of the useful aspects from this multitude of data covering a period of four decades into reliable, comprehensive, and usable forms was carried out under the direction of Dr. Vestine, who effected many original, comprehensive analyses of the results. Those who assisted him in this exacting task were so devoted to him—because of his humane and considerate appreciation of the involved details and reliability required—that all contributed their diligent, enthusiastic and vigorous cooperation. Thus, in 1947 the Department of Terrestrial Magnetism published the resulting two volumes, described by Professor Chapman as “two great collections of modern geomagnetic data, including brief but cogent analyses and discussions of the data.” The two large volumes, containing over 900 pages, are *The Description of the Earth's Main Magnetic Field and Its Secular Change, 1905–1945* and *The Geomagnetic Field, Its Description and Analysis*.

The contribution of these two volumes is best summarized in the following principal parts a and b of the two corresponding prefaces by Dr. Vestine. These show not only that he was thorough and most competent, but also charmingly modest and self-effacing:

a) The present volume summarizes a descriptive study of the Earth's main field and its secular change. It is the result of a very considerable outlay of persistent effort, with much attention to detail, on the part of

those who have tried to fit the many published observations of magnetic surveys into a consistent picture.

Perhaps students of geophysics will welcome most the comprehensive new world-charts descriptive of secular change. These have been drawn complete in all magnetic elements for the first time. They are also, we believe, the first set of isoporic charts reasonably consistent with all available carefully assessed measurements with each other and with the known character of electromagnetic fields. Since they are drawn at four epochs a decade apart, the phenomenon is apparent with good continuity for almost half a century. A new and rich store of information is thus afforded respecting deep-seated, rapid, and mysterious physical processes of the Earth's interior which to the best of our present knowledge are not reflected in any other way.

The new charts of secular change have permitted the use of the great majority of survey-measurements made since the beginning of the present century in constructing isomagnetic charts in seven elements for the epoch 1945.0. The rather successful use of older as well as more recent data has thereby increased by a thousand or more the number of observational points that would ordinarily determine the isomagnetic lines. In this way, a somewhat more detailed description of the Earth's main field is afforded, bringing into a little sharper focus a major geophysical phenomenon of unknown cause.

It is not implied that this new series of charts represents an accurate description of the geomagnetic field. There are many regions in which magnetic measurements have never been made. Much use was made of uncertain interpolations, particularly across polar and ocean areas.

I have not troubled the reader with the multitudinous details incidental to a project of this kind. To have done so would have extended the present book to many volumes. The aim rather has been that of providing a condensed readable account highlighting features of importance and interest.

b) This book continues a descriptive study of geomagnetism begun with Carnegie Institution of Washington Publication 578, which was principally concerned with the description of the Earth's main magnetic field and its secular change. The present volume extends this work to the various known geomagnetic variations, with inclusion of some analyses.

To a considerable extent, the present book is actually a by-product of Publication 578, since extensive information on geomagnetic variations was required for the improving of estimates therein of geomagnetic secular change for the period 1905 to 1945. Because the latter required descriptive

information respecting shorter-period time-variations on a world-wide scale and over these many years, the general scope of coverage is considerable. Moreover, the emphasis has been upon the description rather than upon the interpretation of results.

It is believed that the two volumes together comprise the first convenient detailed compendium of geomagnetic data especially suited to the needs of those engineering workers who are mainly concerned with the practical applications of geomagnetism. The wide use of illustrative diagrams (many initially drawn as a training exercise for the draftsmen who drew the maps of the first volume) enhances the effective description of geomagnetic phenomena of our environment. The books emerge therefore as a kind of picture supplement to the standard treatise *Geomagnetism*; the writer hopes that his teacher, Professor Chapman, senior author of that treatise, will not object to such suggestion, provided he be not held at fault for any mistakes we may have made.

In the course of pursuing the major descriptive objectives of this war project, the writers could not resist the temptation to undertake some serious investigations of the extensive new data available. Hence attempts at explanation of certain phenomena will be found at intervals, between the stacks of figures and tables, along with some short discussions linking the present with previous work. The writers hope that in this way a more interesting and readable account has been provided.

Dr. Vestine's logical, objective, and imperturbable approach to perplexing problems characterized all his activities and his attitude in personal discussions of scientific questions with colleagues. He always searched for independent tests of conclusions, which he made without personal bias or preferences. This accounted for the many fruitful, pleasant, and profitable discussions enjoyed by his colleagues. From his many investigations throughout his career of the secular change of the geomagnetic field and its rate of change with time, Dr. Vestine made several fundamental contributions. His improved determination of the westward drift showed this to be correlated with the previously unexplained variations in the rate of the earth's rotation. When he considered independent geophysical evidence on the rigidity of the earth, Dr. Vestine concluded that "the source of the geo-

magnetic field lies within a large-scale fluid-circulation inside the central core of the earth and that this fluid circulation in the core (relative to the mantle) must be considered established as real, since no other adequate large source needed to conserve the total angular momentum (core plus mantle) is apparently available.”* Over a period of about 120 years, the geomagnetic field pattern was found to have drifted (with variations in the rate of drift) about 3300 km west and about 2900 km north. He also showed that surface fluid motions of the earth’s core that can closely approximate secular change also show features compatible with four of the generator models that might account for the geomagnetic field—but that these comparisons did not indicate a preferred choice among these models. Such tests of models for secular change are presently of much interest, since they provide some basis for reliable estimation of the time scale for reversals of the earth’s dipole field. This reversal time is a useful tool in geological investigations involving plate movements and related phenomena. Thus, as in the nature of most research, the studies initiated by Dr. Vestine have come to have important consequences for other phenomena.

The phenomena of secular change was only one of Dr. Vestine’s many interests. He reliably located the northern and southern auroral zones and showed the dependence of their morphology upon the geomagnetic field. Related investigations provided estimates on the maximum total energy of particles in the Van Allen trapped radiation belts.

In 1944 and 1945, Dr. Vestine published the results of a thorough, comprehensive investigation of the geographical incidence of aurora and magnetic disturbances in the northern and southern hemispheres respectively. The study derived detailed curves showing the three geomagnetic com-

* Ernest Vestine, “On Variations of the Geomagnetic Field, Fluid Motions, and Rate of the Earth’s Rotation,” *Journal of Geophysical Research*, 58 (1953):127.

ponents of the disturbance diurnal variation, S_D (difference for magnetically disturbed, less that for quiet days), and the variation from pole to pole of the maxima and minima of S_D . These outstanding, authoritative studies indicate the thoroughness and reliability for which Dr. Vestine's work was regarded with the highest esteem by geophysicists everywhere.

Dr. Vestine contributed much to the mathematical methodology of techniques for analyses of the geomagnetic field. In addition, he developed theoretical models for aspects of magnetic storms and for the geomagnetic control of the aurora. His investigations included the effect of solar influences on magnetic storms and other geomagnetic phenomena. His analytical investigation of seismic waves and waves from blasts was most useful in seismology.

In addition to his research contributions, Dr. Vestine wrote many excellent survey articles on geomagnetism and related phenomena for encyclopedias, handbooks, dictionaries, and some survey books.

After he joined the Rand Corporation in January 1959, Dr. Vestine's interests were logically extended to include the use of rockets for measuring the geomagnetic field at great heights and for determining the lunar magnetic field. His later work in space science included scientific uses of satellites, astronautics and its applications, space vehicle environment, and the evolution and nature of the lunar atmosphere.

A most fitting tribute to the memory of Dr. Vestine is the dedication to him of the publication *World Magnetic Survey 1957-1969*, published in 1971 as IAGA Bulletin No. 28 of the International Union of Geodesy and Geophysics International Association of Geomagnetism and Aeronomy World Magnetic Survey Board. Dr. Vestine served as secretary general of the World Magnetic Survey Board and formed the center for planning and guidance of the activities of this

international enterprise. *World Magnetic Survey* was edited by the late Dr. Alfred J. Zmuda, a very close friend of Dr. Vestine. This interesting, authoritative volume describes geomagnetic surveys by land, sea, air, and satellite, and presents charts, discussions of survey results, theories for the origin of the geomagnetic field, discussion of the interpretation of magnetic anomalies, and comments on seafloor spreading. It is an outstanding monument to the memory of Dr. Vestine.

To foster investigation on a national and international scale in his own and related fields, he unselfishly contributed the benefits of his knowledge, experience, and judgment to the work of numerous committees. As a participant in the International Geophysical Year, Dr. Vestine was an alternate member of the Executive Committee of the U.S. National Committee for the IGY, a member of the Committee on Aurora and Airglow, and a member of the Committee on Geomagnetism. As a member of the National Academy of Sciences, he served as a member of the Committee on Particles and Fields, the Committee on International Relations, the Space Science Board, and U.S. Commission IV to the Union Radio Scientifique Internationale, as chairman of the U.S. Panel on World Magnetic Survey, as a member of the Committee on Polar Research, and as a member of the U.S. Committee for the Year of the Quiet Sun. Dr. Vestine's involvement with the International Union of Geodesy and Geophysics included terms as chairman of the Committee on Magnetic Secular Variation Stations, chairman of the Committee on World Magnetic Survey and Magnetic Charts, chairman of Commission II, Magnetic Charts, and secretary general of the World Magnetic Survey Board, International Association of Geomagnetism and Aeronomy. For the American Geophysical Union, Dr. Vestine served as a member of Working Group II, Committee on Space Research, as chairman of the Committee on Cosmic Terrestrial Relationships,

as a member of the Committee on Planetary Sciences, president of the Section on Geomagnetism and Aeronomy, and as a member of the Council.

Few investigators have enjoyed such a lifetime of extraordinarily fruitful research that has contributed so solidly to the understanding of so many phenomena in a wide field of geophysical interest. This achievement resulted from Dr. Vestine's sustained singleness of purpose and persistent effort, without deflection by irrelevant activities, toward his laudable goal.

BIOGRAPHICAL MEMOIRS
HONORS AND DISTINCTIONS

EDUCATION

University of Alberta, 1928–32; B.Sc., 1931

University of Toronto, 1933–34

Imperial College of Science and Technology, University of London, 1934–37; D.I.C. (Diploma of Imperial College) and Ph.D., 1937

PROFESSIONAL POSITIONS

Canadian Meteorological Office, 1937

University of Toronto, Instructor in Geophysics and Meteorology, 1937

Carnegie Institution of Washington, Department of Terrestrial Magnetism, 1938–56

Johns Hopkins University, Applied Physics Laboratory, Consultant on Missile Guidance, 1946–56

Battelle Memorial Institute, Consultant, 1956–59

National Aeronautics and Space Administration, Consultant, 1959–66

National Science Foundation, Consultant, 1960–66

The Rand Corporation, 1957–68

University of California, Los Angeles, Professor of Meteorology, 1966–68

PROFESSIONAL SOCIETIES

American Geophysical Union

American Seismological Society

Institute of Electrical and Electronics Engineering

Society of Terrestrial Magnetism and Electricity (Japan)

Washington Academy of Sciences

International Scientific Radio Union (URSI)

HONORS

National Academy of Sciences, Member, 1954

John A. Fleming Award by the American Geophysical Union of the National Academy of Sciences–National Research Council, 1967

Moon Crater named Crater Vestine by the International Astronomical Union

World Magnetic Survey Summary Volume of the International Union of Geodesy and Geophysics dedicated to the memory of Dr. Ernest Harry Vestine, 1971

BIBLIOGRAPHY

1932

With R. J. Lang. First spark spectrum of antimony. *Phys. Rev.*, 42:223-41.

1933

Observations in terrestrial magnetism, meteorology and aurora at Meanook, Polar Year, 1932-33. In: *Results of the Second International Polar Year, 1932-33*. Toronto: Meteorological Service of Canada.

1934

Noctilucent clouds. *J. R. Astron. Soc. Can.*, 28:249-72; 303-317.

1938

With S. Chapman. Electric current system of magnetic storms. *Terr. Magn. Atmos. Electr.*, 43:261-82.

1939

Solar relationships and magnetic storms. In: *Cinquième Rapport de la Commission Pour l'étude des Relations Entre les Phénomènes Solaires et Terrestres*, pp. 120-26. Edinburgh: Conseil Internatl. Unions Scientifiques, Firenze.

1940

Note on surface field analysis. *Trans. Am. Geophys. Union*, 21:291-97.

The potential of the Earth's magnetic secular variation. *Trans. Int. Union Geod. Geophys.*, Washington Assembly. IUGG Bull. no. 11:382-91.

With M. A. Tuve and E. A. Johnson. Various hypotheses regarding the origin and maintenance of the earth's magnetic field. *Trans. Int. Union. Geod. Geophys.*, Washington Assembly. IUGG Bull. no. 11:354-600.

The disturbance-field of magnetic storms. *Trans. Int. Union of Geod. Geophys.*, Washington Assembly. IUGG Bull. no. 11:360-81.

Magnetic secular variation in the Pacific area. In: *Proceedings of the Sixth Pacific Science Congress*, pp. 65-74. Los Angeles and Berkeley: Univ. of California Press.

1941

On the analysis of surface magnetic fields by integrals. *Terr. Magn. Atmos. Electr.*, 46:27-41.

1942

With H. C. Silsbee. Geomagnetic bays, their frequency and current system. *Terr. Magn. Atmos. Electr.*, 47:195-208.

The reduction of magnetic observations to epoch, Part 1. *Terr. Magn. Atmos. Electr.*, 47:97-113.

1943

Remarkable auroral forms. *Terr. Magn. Atmos. Electr.*, 48:233-36.

1944

Geographic incidence of aurora and magnetic disturbance, northern hemisphere. *Terr. Magn. Atmos. Electr.*, 49:77-102.

Preliminary summary, auroral observations, Meanook, Canada, December 1, 1932 to June 30, 1933. *Terr. Magn. Atmos. Electr.*, 49:25-36.

1945

With E. J. Snyder. Geographic incidence of aurora and magnetic disturbance, southern hemisphere. *Terr. Magn. Atmos. Electr.*, 50:105-24.

1946

With L. Laporte and C. Cooper. Geomagnetic secular change during past epochs. *Trans. Am. Geophys. Union*, 27:814-22.

1947

With L. Laporte, C. Cooper, I. Lange, and W. C. Hendrix. *Description of the Earth's Main Magnetic Field and its Secular Change, 1905-1945*. Wash., D.C.: Carnegie Inst. Publ. 578.

With L. Laporte, I. Lange, and W. E. Scott. *The Geo-Magnetic Field—Its Description and Analysis*. Wash., D.C.: Carnegie Inst. Publ. 580.

1948

- The rocket technique applied to exploration of the geomagnetic field to great heights within the atmosphere. Applied Physics Laboratory Report CM-480, The Johns Hopkins University.
- The variation with sunspot cycle of the annual means of geomagnetism. In: *Sixième Rapport de la Commission Pour l'étude des Relations Entre les Phénomènes Solaires et Terrestres*, pp. 121-22, Conseil Internatl. Unions Scientifiques, Orleans.

1952

- On variations of the geomagnetic field, fluid motions, and rate of the earth's rotation. *Proc. Natl. Acad. Sci. USA*, 38:1030-38.

1953

- On variations of the geomagnetic field, fluid motions, and rate of the earth's rotation (more detailed). *J. Geophys. Res.*, 58:127-45.
- Note on geomagnetic disturbance as an atmospheric phenomenon. *J. Geophys. Res.*, 58:539-41.
- The immediate source of the field of magnetic storms. *J. Geophys. Res.*, 58:650-62.
- With S. E. Forbush. Statistical study of waves from blasts recorded in the United States. *J. Geophys. Res.*, 58:381-400.
- Note on analytical tests for distinguishing types of seismic waves. *J. Geophys. Res.*, 58:401-4.

1954

- With D. G. Knapp. Smithsonian Physical Tables 495-511. In: *Elements of Geomagnetism*, 9th rev. ed. *Smithson. Misc. Collect.*, 120:468-501.
- With S. E. Forbush. Ionospheric magnetic fields during marked decreases in cosmic rays. *Indian J. Meteorol. Geophys.*, 5:113-16.
- The earth's core. *Trans. Am. Geophys. Union*, 35:63-72.
- Report of committee on magnetic secular variation stations. *Trans. Brussels Meeting, August 21-September 1, 1951, Int. Assoc. Terrest. Magnetism Electr. IATME Bull. no. 14:225-63.*
- Report of committee on magnetic charts. *Trans. Brussels Meeting August 21-September 1, 1951, Int. Assoc. Terrest. Magnetism Electr. IATME Bull. no. 14:263-64.*

1955

Relations between fluctuations in the earth's rotation, the variation of latitude, and geomagnetism. *Ann. Geophys.*, 11:103. Also in: IAGA Bull. no. 15a.

1956

Some theoretical problems in geomagnetism. *J. Geophys. Res.*, 61:368-69.

Theoretical geophysics. *Science*, 124:234-36.

Exploring the atmosphere with a satellite-borne magnetometer. In: *Scientific Uses of Earth Satellites*, ed. J. A. Van Allen, pp. 198-214. Ann Arbor: Univ. of Michigan Press.

The aurora australis and related phenomena. In: *Antarctica in the International Geophysical Year* (Geophysical Monograph 1), ed. A. P. Crary, L. M. Gould, E. O. Hulbert, H. Odishaw, and W. E. Smith, pp. 91-106. Washington, D.C.: American Geophysical Union.

John Adam Fleming. *Trans. Am. Geophys. Union*, 37:531-33.

1957

Observational and theoretical aspects of magnetic and ionospheric storms. *Proc. Natl. Acad. Sci. USA*, 43:81-92.

Report on Committee No. 3. Committee on magnetic secular variation stations. *Trans. Rome Meeting Assoc. Terrest. Magnetism Electr.* IAGA Bull. no. 15:285-93.

Atmospheric electricity. *Trans. Rome Meeting Assoc. Terrest. Magnetism Electr.* IAGA Bull. no. 15: 238.

U.S. National Report, Part D, Department of Terrestrial Magnetism, CIW. *Trans. Rome Meeting Assoc. Terrest. Magnetism Electr.* IAGA Bull. no. 15:233-35.

Magnetic storms as an atmospheric phenomenon. *Trans. Rome Meeting Assoc. Terrest. Magnetism Electr.* IAGA Bull. no. 15: 384-85.

Utilization of a moon-rocket system for measurement of the lunar magnetic field. The Rand Corp. Report RM-1933.

1958

With R. W. Buchheim, S. Herrick, and A. G. Wilson. Some aspects of astronautics. *IRE Trans. Mil. Electron.*, 2:8-19.

With R. Buchheim and others of the staff of The Rand Corp. *Space Handbook: Astronautics and its Applications*. N.Y.: Random House. Evolution and nature of the lunar atmosphere. The Rand Corp. Report RM-2106.

Seasonal changes in day-to-day variability of upper air winds near the 100-km level of the atmosphere. *Trans. Am. Geophys. Union*, 39:213-23.

1959

With C. Gazley and W. W. Kellogg. Space vehicle environment. *J. Aerospace Sci.*, 26:770-83.

Note on conjugate points of geomagnetic field lines for some selected auroral and whistler stations of the IGY. *J. Geophys. Res.*, 64:1411-14.

With W. L. Sibley. Lines of force of the geomagnetic field in space. *Planet. Space Sci.*, 1:285-90.

With D. Deirmendjian. Some remarks on the nature and origin of noctilucent cloud particles. *Planet. Space Sci.*, 1:146-53.

With Committee on Cosmic-Terrestrial Relationships. Chairman's Report of the Committee on Cosmic-Terrestrial Relationships 1957-1959. *J. Geophys. Res.*, 64:1077-91.

Physics of solar-terrestrial space: lunar flight. The Rand Corp. Report P-1344.

With W. L. Sibley. Remarks on auroral isochasms. *J. Geophys. Res.*, 64:1338-39.

Some preliminary findings of the International Geophysical Year. The Rand Corp. Report P-1626.

1960

With T. Nagata. Ionospheric electric current systems VI. *Ann. Int. Geophys. Year.*, 1:343-81.

Polar magnetic, auroral, and ionospheric phenomena, *Rev. Mod. Phys.*, 32:1020-25.

The upper atmosphere and geomagnetism. In: *Physics of Upper Atmosphere*, ed. J. A. Ratcliffe, pp. 471-512. N.Y.: Academic Press.

The survey of the geomagnetic field in space. *Trans. Am. Geophys. Union*, 41:4-21.

Aeronomy. In: *Encyclopedia of Science and Technology*, vol. 1, pp. 98-99. N.Y.: McGraw-Hill.

- With W. L. Sibley. Geomagnetic field lines in space. The Rand Corp. Report R-368.
- Geomagnetic control of auroral phenomena. In: *Proceedings of the Symposium on Physical Processes in the Sun-Earth Environment*, 20–21 July, pp. 157–164. Ottawa: DRTE Publication no. 1025.
- Note on the direction of high auroral arcs. *J. Geophys. Res.*, 65: 3169–78.
- Polar auroral, geomagnetic and ionospheric disturbances. *J. Geophys. Res.*, 65:360–62.
- With J. W. Chamberlain and J. W. Kern. Some consequences of local acceleration of auroral primaries. *J. Geophys. Res.*, 65:2535–37.
- With A. J. Dessler. Maximum total energy of the Van Allen radiation belt. *J. Geophys. Res.*, 65:1069–71.
- Evolution and nature of the lunar atmosphere. *Proc. Lunar Planetary Exploration Colloquium*, May 13, 1958 to April 25, 1959, vol. 1, pp. 19–23. Los Angeles: Aerospace Laboratories, North American Aviation, Inc.

1961

- With J. W. Kern. Reply to some comments by Malville concerning the midnight auroral maximum. *J. Geophys. Res.*, 66:989–91.
- Solar influences on geomagnetic and related phenomena. *Ann. N.Y. Acad. Sci.*, 95:3–16.
- With J. W. Kern. Theory of auroral morphology. *J. Geophys. Res.*, 66:713–23.
- Instruction Manual for the World Magnetic Survey*. IUGG Monograph no. 11. Paris: International Union of Geodesy and Geophysics.
- Geomagnetism in relation to aeronomy. In: *Symposium d'Aeronomie*, IAGA Symposium no. 1, pp. 181–93. Paris: International Union of Geodesy and Geophysics.
- World Magnetic Survey (introductory remarks). In: *Space Research II, Proceedings of the Second International Space Science Symposium, Florence*, ed. H. C. van de Hulst, C. de Jager, and A. F. Moore, pp. 675–78. Amsterdam: North-Holland Publishing.
- Morphology of magnetic storms. *Intern. Conf. on Cosmic Rays and the Earth Storm*. *J. Phys. Soc. Japan*, 17 (Suppl. A-I–III): 61–62.

- Chairman's summary, papers on geomagnetic pulsations. Intern. Conf. on Cosmic Rays and the Earth Storm. J. Phys. Soc. Japan, 17 (Suppl. A-I-III):74-75.
- Chairman's summary, papers on magnetic storms. Intern. Conf. on Cosmic Ray and the Earth Storm, J. Phys. Soc. Japan, 17 (Suppl. A-I-III):59-60.
- With S. Chapman, T. Nagata, S. Hayakawa, T. Gold, K. Maeda, B. Rossi, S. F. Singer, and S. N. Vernov. II,6 Synthetic theory of the earth storm, magnetic effect. Intern. Conf. on Cosmic Rays and the Earth Storm. J. Phys. Soc. Japan, 17 (Suppl. A-I-III):607-25.
- With E. C. Ray, L. Wombolt, and W. L. Sibley. The adiabatic integral invariant in the geomagnetic field. The Rand Corp. Report RM-3347.
- Space geomagnetism, radiation belts, and auroral zones. In: *Earth Magnetism, Benedum Symposium*, University of Pittsburgh, March 12-13, 1962, pp. 11-29. Univ. of Pittsburgh Press.
- Influence of the earth's core upon the rate of the earth's rotation. *Earth Magnetism, Benedum Symposium*, University of Pittsburgh, March 12-13, 1962, pp. 58-57. Univ. of Pittsburgh Press.
- With J. W. Kern. Cause of the preliminary reverse impulse of storms. J. Geophys. Res., 67:2181-88.

1963

- With J. W. Kern. An extension of the Chapman-Ferraro theory of geomagnetic storms. The Rand Corp. Report RM-3839.
- With J. W. Kern. Magnetic field of the earth and planets. Space Sci. Revs., 2:136-51.
- Recent advances in space sciences. Trans. Am. Geophys. Union, 44:137-43.
- With A. B. Kahle. Analysis of surface magnetic fields by integrals. J. Geophys. Res., 68:5505-15.
- With W. L. Sibley, J. W. Kern, and J. L. Carlstadt. Integral and spherical-harmonic analyses of the geomagnetic field for 1955.0, Part I. J. Geomagn. Geoelectr., 15:47-72.
- With W. L. Sibley, J. W. Kern, and J. L. Carlstadt. Integral and spherical-harmonic analyses of the geomagnetic field for 1955.0, Part II. J. Geomagn. Geoelectr., 15:73-89.

Note on low-level geomagnetic ring-current effects. *J. Geophys. Res.*, 68:4897-4907.

1964

With A. B. Kahle and J. W. Kern. Spherical harmonic analyses for spheroidal earth. *J. Geomagn. Geoelectr.*, 16:229-37.

A survey of magnetic storms. The Rand Corp. Report P-3270.

Some comments on the ionosphere and geomagnetism. In: *Progress in Radio Science 1960-1963, III, The Ionosphere*, ed. G. M. Brown, pp. 121-48. Amsterdam: Elsevier Publishing.

The World Magnetic Survey and the earth's interior. Proc. Intern. Symposium on Magnetism of the Earth's Interior. *J. Geomagn. Geoelectr.*, 17:165-71.

The World Magnetic Survey and the earth's interior (abstract). NATO Advanced Study Institute, Symposium on Planetary and Stellar Magnetism, Newcastle upon Tyne.

1966

With A. B. Kahle. On the small amplitude of magnetic secular change in the Pacific area. *J. Geophys. Res.*, 71:527-30.

With A. B. Kahle and J. W. Kern. Spherical harmonic analyses for the spheroidal earth (II). *J. Geomagn. Geoelectr.*, 18:349-54.

1967

Distribution of the southern auroral zone. Proc. Eleventh Pacific Science Congress, Tokyo, 1966. JARE Scientific Reports, Special Issue No. 1, 18-28.

With A. B. Kahle and R. H. Ball. Estimated fluid motion of the surface of the earth's core. *Trans. Am. Geophys. Union.*, 47:464(A).

With R. H. Ball and A. B. Kahle. Field distortion by surface flow of fluid at surface of earth's core. *Trans. Am. Geophys. Union.*, 47:464(A).

With R. H. Ball, A. B. Kahle, and J. W. Kern. Determination of surface velocity of the earth's core. *Trans. Am. Geophys. Union.*, 47:464(A).

With A. B. Kahle and R. H. Ball. Estimated surface motions of the earth's core. The Rand Corp. Report RM-5091-NASA, August 1966.

- Comparison of estimates of surface motions of the earth's core for various epochs. The Rand Corp. Report RM-5193-NASA, April 1967. Also in: *J. Geophys. Res.*, 72:4917-25.
- With R. H. Ball and A. B. Kahle. Nature of surface flow in the earth's central core. The Rand Corp. Report RM-5192-NASA, April 1967. Also in: *J. Geophys. Res.*, 72:4927-36.
- Main geomagnetic field, 1965. In: *Physics of Geomagnetic Phenomena*, ed. S. Matsushita and W. H. Campbell, pp. 181-234. N.Y.: Academic Press.
- With R. H. Ball and A. B. Kahle. Inferred axial motions of conducting fluid at the surface of the earth's core. Amer. Geophys. Union 48th Annual Meeting, Washington, D.C., April 1967. *Trans. Am. Geophys. Union*, 48:58(A).
- With World Magnetic Survey Board. *Instruction Manual on the World Magnetic Survey, No. II*, International Association of Geomagnetism and Aeronomy, July 1967.

1968

- With A. B. Kahle. The westward drift and geomagnetic secular change. The Rand Corporation Report P-3667, September 1967. Also in: *Geophys. J. R. Astron. Soc.*, 15:29-37.
- With R. H. Ball and A. B. Kahle. Fluid motions at the surface of the core. Amer. Geophys. Union 49th Annual Meeting, Washington, D.C., April 1968. *Trans. Am. Geophys. Union*, 40:151-52(A).
- With R. H. Ball and A. B. Kahle. Variations in the geomagnetic field and in the rate of the earth's rotation. Amer. Geophys. Union 49th Annual Meeting, Washington, D.C., April 1968. The Rand Corp. Report RM-5717-PR, October 1968. Also in: *Trans. Am. Geophys. Union*, 49:152(A).
- With R. H. Ball and A. B. Kahle. On the determination of surface motions of the earth's core. The Rand Corp. Report RM-5615-NASA, November 1968.
- Short review of geomagnetism. The Rand Corp. Report P-2996, 1965. Also in: *International Dictionary of Geophysics*, ed. K. Runcorn. N.Y.: Pergamon Press.
- Geomagnetism. In: *Encyclopaedia Britannica*, vol. 10, pp. 179-85. Chicago: Encyclopaedia Britannica.