EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 92 NUMBER 34
23 AUGUST 2011
PAGES 281–288

# The Scientific Legacy of Sydney Chapman

PAGES 281–282

Sydney Chapman (1888–1970) was arguably one of the greatest scientists of the twentieth century. His comprehensive work on the kinetic theory of gases and solar-terrestrial physics, as well as on the mechanisms behind the formation of Earth's ozone layer, has inspired a wide swath of research spanning several generations [*Van Allen*, 1970].

Chapman, a member of the Royal Society, in London, and president of the International Geophysical Year (IGY), also was a recipient of AGU's William Bowie Medal. Young AGU members today may recognize Chapman from the topical conferences that carry his name. Although his biography has so far not been published, he gave three talks on his life: two at the National Center for Atmospheric Research, Boulder, Colo., in 1965 and 1966, and one at the Geophysical Institute, University of Alaska Fairbanks, in 1967 (see Figure 1). All three are transcribed and included in a book, *Sydney Chapman, Eighty: From His Friends* [*Akasofu et al.*, 1968]. These talks, combined with other sources, shed light on this insightful and discerning scientist.

## *Early Days*

Chapman was born in Eccles, a suburb of Manchester, England, in 1888. When he was 14 years old, his father took him to a builder's merchant for advice concerning his career. The man suggested that he should be a plumber. Instead, Chapman enrolled in the Royal Technical Institute, Manchester. At that time, his county offered 15 university scholarships to local students to attend Manchester University. Chapman wrote an exam to compete for the scholarship and became the fifteenth recipient chosen. "I sometimes wonder," he reflected years later, "what would have happened if I'd hit one place lower" [*Akasofu et al.*, 1968, p. 161].

By S.-I. Akasofu

After graduating from Manchester with degrees in engineering and mathematics, he attended Cambridge University (1908–1911). There he studied the kinetic theory of gases and wrote his first paper [*Chapman*, 1911], under the advice of physicist Joseph Larmor, who was well established as a leader in the study of electricity and thermodynamics. The kinetic theory of gases proved to be Chapman's lifelong subject—for example, with his colleague T. G. Cowling, a professor at the University of Leeds, he published the fundamental treatise *The Mathematical Theory of Non-Uniform Gases* [*Chapman and Cowling*, 1953], which lays out the basic properties of gases, such as thermal diffusion, thermal conductivity, and viscosity.

## *First Job and Exposure to Geomagnetism*

Before graduating from Cambridge University, Chapman received an unexpected visit from Frank Dyson, the Astronomer Royal (the title of the Greenwich Observatory director). Dyson offered Chapman a job, and the 22-year-old student excitedly wrote to his parents about Dyson's visit. His first assignment, he told them, was to design a new magnetic observatory. At the Greenwich Observatory (now the Royal Observatory Greenwich), Chapman renewed his acquaintance with physicist Arthur Schuster, his former professor at Manchester University and a member of the board of visitors of the observatory.

Schuster told him about his idea of the "quiet day daily magnetic variation" [*Akasofu et al.*, 1968, p. 191]. The Earth experiences a fairly regular daily magnetic variation, called the *Sq* variation, caused by solar and lunar tidal forces in the ionized upper atmosphere (now called the ionosphere) across the geomagnetic field lines, inducing a dynamo. His curiosity piqued by Schuster, Chapman published his first major paper [*Chapman*, 1919], developing Schuster's hypothesis on *Sq* variation, entitled "Solar and lunar diurnal variations of terrestrial magnetism." His paper became the foundation for later developments on the Earth's daily background magnetic variation.

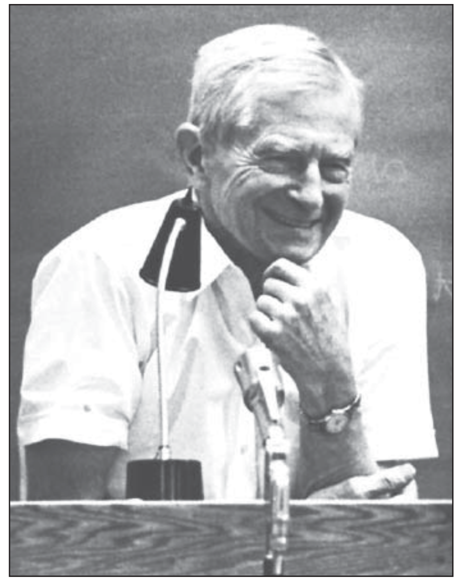

*Fig. 1. Sydney Chapman, delivering his third public lecture, at the Geophysical Institute, University of Alaska Fairbanks, on 30 June 1967.*

## *Early Study of Geomagnetic Storms*

As Astronomer Royal, Dyson roused Chapman to study geomagnetic storms by referring to an earlier statistical study of magnetic disturbances by then observatory assistant E. Walter Maunder [*Akasofu et al.*, 1968, p. 191], in which *Maunder* [1905] concluded that a stream of solar gas is responsible for geomagnetic disturbances. Chapman, interested in the physical processes of what Maunder had observed, published his first major paper on that subject, "An outline of a theory of magnetic storms" [*Chapman*, 1918]. The paper consists of two parts: an analysis of geomagnetic storm fields and a hypothesis on their formation. In the first part he analyzed geomagnetic storm fields as a function of latitude and local time. The fundamentals of his method are still used today; the geomagnetic storm index *Dst* is based on this analysis. In the theoretical part he considered a stream of charged particles (in those days called corpuscles) of either protons or electrons from the Sun, entering the Earth's ionized upper atmosphere and causing its motions. The resulting dynamo process, he hypothesized, would produce a system of currents, and thus magnetic fields, that would add to the Earth's main geomagnetic field. In later life, Chapman mentioned several times that "the observational part was useful, the theory was quite phony" [*Akasofu et al.,* 1968, p. 191].

After his paper was published, Chapman was immediately criticized by physicist F. A. Lindemann [*Lindemann,* 1919], who noted that a stream of one sign, positive or negative, will disperse itself by its electrostatic repulsive force. However, Lindemann made a helpful suggestion in his critique: that the solar stream becomes almost fully ionized (now called plasma) on its way to the Earth. Taking Lindemann's suggestion seriously, Chapman, with his first graduate student, V. C. A. Ferraro, showed that the Earth is engulfed in a comet-shaped cavity in the solar plasma stream [*Chapman and Ferraro,* 1931], which we call the magnetosphere.

Referring to the Chapman-Ferraro theory, Chapman reflected in one of his lectures that "for a long time people didn't believe in it, they were dubious about it" [*Akasofu et al.,* 1968, p. 199]. Although their paper became the foundation of magnetospheric physics after the late 1950s, there were competing theories in those days, including the ultraviolet light theory of geomagnetic storms, as promoted by physicist E. O. Hulburt [*Hulburt,* 1930], who proposed that auroras and geomagnetic storms are caused by an increase in the ionization of the upper atmosphere by solar flares. Astrophysicist and plasma physicist Hannes Alfvén proposed [*Alfvén,* 1950] that electricity is discharged from neutral points that are formed by the interaction between the geomagnetic field and the interplanetary magnetic field; these discharges cause auroras and geomagnetic storms.

In the history of the development of geomagnetic theories, the great ongoing debate between Chapman and Alfvén on theories of geomagnetic storms was a memorable event [*Alfvén,* 1951; *Chapman,* 1951; see also *Akasofu,* 2003]. It may be that both men were actually correct, in the sense that a pencil has two ends: Chapman emphasized one end, the plasma (nonmagnetic) aspect of the solar plasma stream, while Alfvén stressed the importance of the interplanetary magnetic field in it. Combining both yields the present concept of the magnetosphere [*Dungey,* 1961].

On 12 September 1961, the Explorer 12 satellite observed the magnetic field across the frontside of the boundary of the magnetosphere and recorded that the magnitude of the Earth's dipole field just inside the boundary is doubled because the Earth's magnetic field there is compressed by the advancing solar gas, exactly as predicted by the Chapman-Ferraro theory [*Cahill and Amazeen,* 1963]. The observation confirmed, beyond doubt, Chapman's most important contribution to magnetospheric physics. This news must have been a relief for him, for when he learned of Explorer's observations, he said, "It is rather rare that it takes 30 years for a theory to be confirmed" (S. Chapman, personal communication, 1961).

## *Chapman's Contributions to Ionospheric Physics and Aeronomy*

In 1927, radio scientist Edward V. Appleton confirmed the existence of the ionosphere. Chapman subsequently published the first hypothesis about how the ionosphere is formed through solar ultraviolet radiation and deduced a vertical profile of electron density in the ionosphere. This theoretical profile, called the Chapman layer, laid the foundation for later developments in ionospheric physics [*Chapman,* 1931a].

In aeronomy, his theory of ozone molecule formation—in which one oxygen atom (O), one oxygen molecule ($O_2$), and any other molecule collide simultaneously to form an ozone molecule ($O_3$)—still holds today [*Chapman,* 1931b]. Additionally, in the early years of World War II, Chapman and Julius Bartels, a close German colleague, managed to publish a major treatise on geomagnetism and ionospheric physics entitled *Geomagnetism* [*Chapman and Bartels,* 1940a, 1940b]. Because of its comprehensive summaries of all major efforts to understand the near-Earth space environment up to that point, it was the standard textbook on geomagnetism and the ionosphere for at least 2 decades.

## *Chapman and the Solar Wind*

In the late 1950s, Chapman became interested in zodiacal light—the faint glow of the night sky along the ecliptic—and the possible relationship between the high temperature of the solar corona and the high temperature of the upper ionosphere, which averages about 2000 K or more. On the basis of this possible relationship, he developed a theoretical model of a static solar corona that extends beyond the distance of the Earth. He submitted his paper to one journal, which rejected it, and to a second journal, which published it [*Chapman,* 1957].

This paper drew the attention of American solar physicist and astrophysicist Eugene N. Parker, who published a thermal expansion theory of the solar corona [*Parker,* 1958]; he coined the term "solar wind." It is interesting to note that the beginning of the study of the solar wind, one of the most fundamental aspects in solar-terrestrial physics, was initiated in some sense by Chapman's interest in the solar corona.

## *Chapman and the Aurora*

In 1951, the first major conference after World War II on auroras [*Gerson et al.,* 1954] was held in Canada, at the University of Western Ontario, London. In a session on geomagnetic storms and auroras, Carl Störmer, one of the pioneers in auroral study, showed his calculations of trajectories of single electrons in the vicinity of a dipole field. Störmer claimed that he could explain the formation of the auroral zone and thinness of the curtain-like auroral arc structure. Chapman, also a presenter at the session, could offer only the Chapman-Ferraro theory, not any concrete explanation of the aurora, despite the title of his paper, "The theory of magnetic storms and auroras." After their presentations, the participants had a lengthy discussion (fortunately, well transcribed in the conference proceedings) in which Störmer argued in essence that Chapman could not explain the aurora as he himself had.

A short time after this conference and his retirement from Oxford, Chapman went to Alaska and to several other universities, including the University of Colorado, to learn about the aurora and the Sun. In addition to being the president of the International Geophysical Year, he became a leader of its all-sky camera project with Christian T. Elvey, who was then director of the Geophysical Institute. Elvey's and Chapman's enthusiasm made it possible for many younger researchers to learn about simultaneous auroral activities over the entire polar region, with a time resolution of 1 minute, for the first time in the history of auroral science.

## *A Pioneer in Solar-Terrestrial Physics*

As a rigorous mathematical physicist, Chapman contributed substantially to establishing the modern solar-terrestrial sciences, inspiring many scientists throughout his research life in fields related to the kinetic theory of gases, ionospheric physics, magnetospheric physics, solar physics, and heliophysics.

In science, most hypotheses fail or become obsolete as time passes and new insight is gained. By contrast, Chapman's work has stood the test of time, becoming the foundation of modern solar-terrestrial physics. Even today, students learn about the Chapman layer, the Chapman-Ferraro theory, and Chapman's theory of the ozone molecule formation process. Further, in a time when research is becoming increasingly more specialized, Chapman's life and legacy serve as a reminder of the value of broad, cross-disciplinary thinking, which can lead not just to new discoveries but also to entire new fields of science.

## *Acknowledgments*

I thank Mary Tessler, Sydney Chapman's daughter, for her careful review of this article. I also thank the reviewers for their helpful suggestions on early versions.

## *References*

Akasofu, S.-I. (2003), Chapman and Alfvén: A rigorous mathematical physicist versus an inspira-

tional experimental physicist, *Eos Trans. AGU, 84*(29), 269, 274, doi:10.1029/2003EO290002.
Akasofu, S.-I., B. Fogle, and B. Haurwitz (1968), *Sydney Chapman, Eighty: From His Friends,* 230 pp., Natl. Cent. for Atmos. Res., Boulder, Colo.
Alfvén, H. (1950), *Cosmical Electrodynamics*, 237 pp., Oxford Univ. Press, Oxford, U. K.
Alfvén, H. (1951), The theory of magnetic storms and auroras, *Nature, 167,* 984–985.
Cahill, L. J., and P. G. Amazeen (1963), The boundary of the geomagnetic field, *J. Geophys. Res., 68,* 1835–1843.
Chapman, S. (1911), The kinetic theory of gas constituted of spherically symmetrical molecules, *Proc. R. Soc., 86,* 411–442.
Chapman, S. (1918), An outline of a theory of magnetic storms, *Proc. R. Soc., 97,* 61–83.
Chapman, S. (1919), Solar and lunar diurnal variations of terrestrial magnetism, *Philos. Trans. R. Soc., 218,* 1–118.
Chapman, S. (1931a), The absorption and dissociative or ionizing effect of monochromatic radiation of an atmosphere on a rotating Earth, *Proc. Phys. Soc., 43,* 26–45.
Chapman, S. (1931b), Bakerian Lecture—Some phenomena of the upper atmosphere, *Proc. R. Soc., 132,* 353–374.
Chapman, S. (1951), The theory of magnetic storms and auroras, *Nature, 168,* 86.
Chapman, S. (1957), Notes on the solar corona and the terrestrial ionosphere, *Smithson. Contrib. Astrophys., 2,* 1–11.
Chapman, S., and J. Bartels (1940a), *Geomagnetism,* vol. I, *Geomagnetic and Related Phenomena,* Oxford Univ. Press, Oxford, U. K.
Chapman, S., and J. Bartels (1940b), *Geomagnetism,* vol. II, *Analysis and Physical Interpretation of the Phenomena,* Oxford Univ. Press, Oxford, U. K.
Chapman, S., and T. G. Cowling (1953), *The Mathematical Theory of Non-Uniform Gases*, 431 pp., Cambridge Univ. Press, Cambridge, U. K.
Chapman, S., and V. C. A. Ferraro (1931), A new theory of magnetic storms, Part I. The initial phase, *Terr. Magn. Atmos. Electr., 36,* 77–97.
Dungey, J. W. (1961), Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett., 6,* 47–48.
Gerson, N. C., T. J. Keneshea, and R. J. Donaldson Jr. (Eds.) (1954), *Proceedings of the Conference on Auroral Physics*, *Geophys. Res. Pap., 30, AFCRC-TR-54-203,* Dep. of Phys., Univ. of West. Ont., London, and Geophys. Res. Dir., Air Force Cambridge Res. Cent., Cambridge, Mass.
Hulburt, E. O. (1930), The ultra-violet light theory of aurorae and magnetic storms, *Phys. Rev., 36,* 1560–1569.
Lindemann, F. A. (1919), Note on the theory of magnetic storms, *Philos. Mag., 38,* 669–684.
Maunder, E. M. (1905), Magnetic disturbances, 1882 to 1903, as recorded at the Royal Observatory, Greenwich, and their association with sunspots, *Mon. Not. R. Astron. Soc., 65,* 2–34.
Parker, E. N. (1958), Dynamics of the interplanetary gas and magnetic fields, *Astrophys. J.,* 664–676.
Van Allen, J. A. (1970), Sydney Chapman, *Phys. Today, 23*(9), 83.

## Author Information

Syun-Ichi Akasofu, Professor Emeritus, International Arctic Research Center, University of Alaska Fairbanks; E-mail: sakasofu@iarc.uaf.edu