EXPLORING THE SECRETS OF THE AURORA

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EXPLORING THE SECRETS OF THE AURORA

Second Edition

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Springer

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Preface to the Second Edition

In the first edition, I described the evolution of magnetospheric physics from my own personal point of view (I used the word "evolution" rather than "development" because, unlike development, evolution can go right or wrong). However, I was not interested in simply relating a history of magnetospheric physics. I wanted to emphasize the fact that we still have many long-standing, unsolved problems from the early days and to suggest that there is a possibility that the present paradigm may not be headed in the right direction. We have to recognize that several fundamental problems remain; what is needed is not just improvements to traditional theories or a mopping-up of residual problems. I am convinced that new thinking is needed to solve long-standing unsolved problems. What I suggest in this book may be far from the correct way to understand them, but I hope that my suggestions will serve the readers to recognize that many unsolved problems exist and that different ways of thinking are needed to solve them. It is for this very reason that I emphasized in the first edition that a successful scientist must be able to conceive new ideas that do not fit established theories. Obviously, new ideas will encounter confrontations; the scientific community does not want to see the framework it has already built collapsed by new ideas; it is bound to reject the new ideas. In that first edition, I tried to describe how one might overcome such difficulties based on my experience.

In the Epilogue of the first edition, I reached the conclusion that a different way of thinking, paradigm change, namely the conception of a new idea, is an act of synthesis based on a set of facts, including other researchers' viewpoints and theories. In this age of infinite specialization, the importance of synthesis should be emphasized more now than ever. This is because we have to deal with systems, and a study of systems must be based on either integration or synthesis. This is why I emphasize the importance of synthesis in the second edition.

Unfortunately, synthesis is foreign to most scientists, because they are trained to focus on a narrow subject of ever-increasing specialization. Nevertheless, synthesis could produce an important epoch-making advance in science. In 1981, I was honored to be chosen as one of the 1000 most quoted scientists in all fields of science. Looking back on my contributions in science, my work that has endured the longest and has been quoted the most has been synthesis work, rather than my topical work. Thus, I believe that synthesis is an important task in science, because it can often lead to a paradigm change.

My dream of a grand synthesis is to bring solar physics, interplanetary physics, magnetospheric physics, and upper atmospheric physics together in terms of space weather research. Although undoubtedly incomplete, I tried to synthesize the results from the four disciplines in a new Chapter 4 and also in Chapter 8 in the second edition. It is my hope that these provide some idea of the synthesis process.

As mentioned in the Preface in the first edition, this book is intended to be neither a textbook nor the standard monograph on solar-terrestrial physics. In this book, I wanted to emphasize three points:

(1) The first is that readers should appreciate how much effort is required for new findings to become common knowledge. The contents of one chapter in this book may be condensed into one sentence or one page in a standard textbook. On the other hand, this book describes how science actually evolves. This cannot be learned in a textbook.
(2) The second is that readers will learn that a major advance in a scientific field requires a new synthesis of observed facts. The second edition emphasizes this point in the new Chapters 4 and 8.
(3) The third point is that there are many long-standing, unsolved problems in advancing solar-terrestrial physics that are waiting for new ways of thinking by young researchers. When readers find my own views strongly expressed on the present paradigms, they might infer that the problems are not yet solved, although the standard textbooks may imply they are understood as basic knowledge. My views are only intended to initiate new ways of thinking.

I am also hoping that this book would have a narrative feel rather than a textbook “drowned-by-equations” feel, and that it will be read like a history book. Nevertheless, I hoped it would still provide younger researchers an accurate portrayal of the background required to pursue magnetospheric physics and solar physics.

For all these reasons, as those also mentioned in the Preface in the first edition, this book should not be considered as one of the standard textbooks, monographs, or reference books. It is for this reason that references are not given in this book. The year that follows quoted authors refers to the period when their works were written. A list of some of the standard monographs is provided at the end of the book.

I would like to thank many colleagues who are mentioned in this book and others for their advice and discussion throughout my research career. In a way, this book is a joint product with my colleagues, in particular Yasha Feldstein, Ghee Fry, Kazuyuki Hakamada, Tony Lui, Ching Meng, Takao Saito, and Lee Snyder. We have worked together for three decades or more. I would like to also thank Mrs. Kimberly Hayes for her most dedicated work in completing both the first and second editions of this book.

Preface to the First Edition

My purpose in writing this book is to describe my own experiences, from my graduate student days in the 1950s to the present (2001), when I came upon phenomena or facts that did not support the prevailing ideas and theories, or even contradicted them. In some instances, the encounters began with nothing more than the naïve questions I posed as a graduate student to my professors regarding a well-established fact. Others were the result of questions my graduate students asked me. Essentially, this is an account of my personal encounters with some of the ideas and theories that once prevailed but were later eliminated in the history of auroral science.

I believe that young researcher's success as scientists depends on how they deal with new phenomena or facts that do not fit established theories. One cannot be a researcher unless he/she can address such a problem, because such an encounter is the very first step for new progress. Some may put the discordant facts on the shelf or sweep them under the rug, so to speak. Others may try hard to shoehorn new facts into prevailing ideas by modifying or improving them. Yet others may try to establish a new idea, scheme, or theory by adapting their findings, and those of others, by abandoning the prevailing dogma or interpretation of the phenomena or facts. It has been my experience that it is the people in this last group who produce epoch-making progress in science.

The choice of what to do when facing this situation is not easy and depends on many factors. First of all, researchers have to know where they stand at that point in the history of their scientific discipline. It is therefore crucial to have a deep historical knowledge of the background of a prevailing idea or the established interpretation of a phenomenon. To choose a course of action without knowing the background would be like starting to run in the dark without a sense of direction or of the surroundings. Unfortunately, I see too many young scientists doing just that, particularly those who believe that technological advance is everything. Often, a mentor provides the history, not necessarily in a classroom setting, but through daily interactions. I was fortunate to have a very good mentor, Sydney Chapman, who guided me during my early days.

It is also my hope for this book that young researchers will learn that even a simple, one-line statement in a standard textbook, such as "The aurora lies along an oval-shaped belt." endured a decade of struggle before acceptance by the scientific community. My point here is that it is important to learn how to proceed during the period of controversy and struggle, which requires skills not taught in a textbook. However, it is not the intent of this book to provide a general methodology, even if one existed, on how to overcome such problems. I show several examples, right or wrong. The creative approach taken by individual researchers is crucial at this point. In science, we may eventually reach the same or a similar conclusion, but the creative approach taken depends greatly on the individual, as the history of science proves. Science is a human endeavor and is not a dry subject at all.

It is obvious, first of all, that new ideas or theories in science should explain more observational facts than the old ones did. However, that an idea is great (or better) does not guarantee its immediate acceptance by the scientific community. Scientific accuracy is a necessary condition for acceptance, but is not in itself a sufficient condition for it. The readers of this book will see examples, not a methodology, of how such situations were dealt with in the history of auroral science by researchers who made significant advances in understanding auroral phenomena. The most serious problem in a scientific discipline occurs when a given idea or theory dominates utterly. The longer a particular prevailing idea dominates, the more damage it does, retarding progress as researchers, young and old, begin to feel that there is nothing major left to be done.

Looking back at the history of auroral science, one can find that our pioneers had dreams. Our generation also has dreams. Some of the recent advances have made their and our dreams a reality. In order to make this book a little more than just my own ramblings, I have added several highlights concerning those advances in some of the chapters.

Despite the considerable progress in the disciplines of solar-terrestrial physics, a number of long-standing fundamental problems have remained unsolved for many decades. It is my belief that some of these problems remain unsolved because no doubt has been cast on the guiding concept behind the prevailing ideas, not because we presently lack the technology to solve them. In order to stimulate new or different ways of thinking, I have decided to provide some unconventional ideas, although they will certainly be criticized or ignored by those who believe that they are on the right track and that their difficulties are only technical in nature. However, it must be noted that all the materials used here were at least accepted and published in standard scientific journals; many of my unsuccessful geophysical research projects will be described elsewhere.

Space physics must evolve. The future of space physics depends on the creativity of the young generation with a wide range of interests in other fields of science. With a solid background in space physics and at least one other field, the young generation should be able to create a new field of science. I have suggested the exploration for life on planets of distant stars by searching for oxygen emissions in their aurora. That is just an example, and there may be many new unexpected fields of science.

Obviously, this book is not a textbook, or an autobiography, or a treatise of facts and theories for a particular prevailing idea or two. It is a sort of reflection on my research endeavor during the last 40 years or so. Since I have an instinctive tendency to avoid prevailing ideas and theories, I am perhaps not a normal scientist, but I hope nevertheless that this book will be useful, particularly for graduate students and young scientists, especially in helping them think beyond the box of accepted wisdom.

I thank my senior and junior colleagues in many countries, and my former graduate students, who participated in my research activities and helped guide me. Without their close interaction over my research career, I would not have written this book. Those who are not mentioned in the main text are acknowledged in the figure captions. I have also worked with many other close colleagues who are not mentioned in this book, but could not mention them in order to focus on the subject areas specifically dealt with in this book.

Note: At the end of the book, further readings are listed for those who are interested in the history of auroral science, but this is not a reference list. The names of authors with the year in parentheses may look like citations, but instead they indicate the year their papers were published. I have used the full first name of those authors with whom I had at least some acquaintance. For all the rest, I have given only their initials.

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Prologue

The story in this book had a fascinating beginning that can best be described by R.C. Carrington (1860) with his own words:

> While engaged in the forenoon of Thursday, September 1, in taking my customary observations of the forms and positions of the solar spots, an appearance was witnessed, which I believe to be exceedingly rare – two patches of intensely bright and white light broke out . . .

Simultaneous with this first sighting of what is now called a white-light solar flare (a most intense type of solar activity), the terrestrial magnetic field record made at the Kew Magnetic Observatory in Greenwich, England, showed a distinct magnetic variation.[1] About 16 hours after this remarkable event, a great geomagnetic storm began and a brilliant auroral display appeared over northern Europe and many other places. Carrington suspected that the geomagnetic storm was related to what he had observed on the Sun, but hesitated to assert the connection. The footnote in Carrington's report to a meeting of the Royal Astronomical Society reads:

> While the contemporary occurrence may deserve noting he would not have it supposed that he even leans towards hastily connecting them. "One swallow does not make a summer."

It is in this way that solar-terrestrial physics was born. Lord Kelvin (1892) took up Carrington's extremely modest suggestion of the solar-terrestrial connection during the Anniversary Meeting of the Royal Society of London, England, in 1892.

Kelvin, then the president of the society, attempted to explain the observed geomagnetic variations in terms of the solar magnetic changes observed at a distance of 200 solar radii and found that the expected changes of the dipole moment of the Sun were too large to be reasonable. Thus, he concluded:

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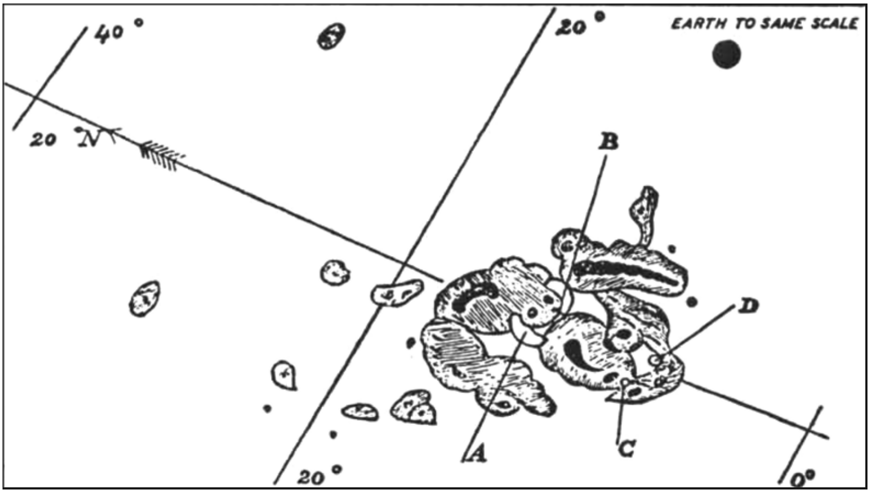
[1] This magnetic change is a result of *augmentation* of the ionospheric current by an enhanced conductivity of the Earth's ionosphere (Sqa), which is caused by the flare's radiations.



R.C. Carrington's sketch of a sunspot group. He was the first to witness a solar flare (A, B, C, D).
Source: Carrington, R.C., *Mon. Not. Roy. Astronom. Soc.,* **20**, 1860

Lord Kelvin (1824–1907)
Source: Terr. Magn. Geoelect

. . . Guided by Maxwell's "electro-magnetic theory of light," and the adulatory theory of propagation of magnetic force which it includes, we might hope to perfectly overcome a fifty years' outstanding difficulty in the way of believing the Sun to be the direct cause of magnetic storms in the Earth, though hitherto every effort in this direction has been disappointing. It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and Sunspots is unreal, and that the seeming agreement between the periods has been mere coincidence.

E.W. Maunder (1851–1928)
Source: Courtesy of R.H. Eather

His difficulty is understandable. Without the concept of a medium (which now is known as solar plasma flow) that carries the effects of solar disturbances out into interplanetary space, it is not possible for the Sun to cause the magnetic changes recorded on the Earth.

E.W. Maunder (1905) made a new approach to this problem by noting that geomagnetic disturbances generally reoccur every 27 days, the so-called 27-day recurrence tendency. After an extensive study of magnetic and solar records, he concluded:

First: The origin of our magnetic disturbances lies in the Sun: not any body or bodies affecting both. This is clear from the manner in which those disturbances mark out the solar rotation period . . .

Second: The areas of the Sun giving rise to our magnetic disturbances are definite and restricted areas . . . not due to a general action or influence diffuse over the whole solar surface.

Third: The areas of the Sun, wherein the magnetically active areas are situated, rotate with the speed of the chief spot-bearing zones, viz., latitudes 0° to 30°.

Ninth: . . . though Sunspots and magnetic disturbances are intimately connected, large Sunspots will often be observed when no disturbances are experienced, whilst sometimes disturbances will be experienced when no spots with which they can be associated are visible . . .

The first statement was the most definitive in history in suggesting that the sun is responsible for geomagnetic disturbances. The other remarks are also remarkably accurate in spite of the very limited amount of data available to Maunder at that time. The spot-free region he referred to is what we now call a coronal hole. In his concluding remark, Maunder noted:

> That, therefore, which Lord Kelvin spoke of twelve years ago as "the fifty years outstanding difficulty" is now rendered clear . . .

A. Schuster (1905) immediately criticized Maunder's conclusion by an argument similar to that presented by Kelvin:

> . . . I cannot, therefore, agree with his somewhat boastful claim that he has rendered clear what Lord Kelvin has called a "fifty years' outstanding difficulty." He has, no doubt, added a new fact and made an important contribution to the subject. He has given a renewed interest to it and brought out the urgent importance of further investigation, but the mystery is left more mysterious than ever. The facts have become harder to understand and more difficult to explain.

In the history of solar-terrestrial physics, as in any other field of science, such controversies among experimenters, observers, and theorists have been a common occurrence. However, through such controversies, their efforts have been interwoven, resulting eventually in a better understanding of natural phenomena.

After such exciting beginnings, the concept of the Earth's electromagnetic environments has evolved dramatically (Figure I). K. Birkeland viewed the interaction between the solar gas and the Earth's magnetic field in terms of motions of solitary charged particles in a dipole field. He set up an elaborate discharge chamber to study the trajectories of electrons around what he called a *terrella*. Stimulated by Birkeland, C. Störmer began his lifelong study of trajectories of charged particles in a dipole field. His life work was summarized in his book, *The Polar Aurora* (1955). In their studies, both Birkeland and Störmer assumed that the Earth's magnetic field was unaffected by the advancing solar gas.

In order for this particular field of science to make substantial progress, however, we had to wait for Sydney Chapman and Vincenzo Ferraro (1931) to introduce the concept of confinement of the Earth's magnetic field in a cavity carved in the solar gas flow. Chapman and Ferraro considered the solar gas to be consisting of an equal number of positive and negative particles (plasma in present terminology) and attempted to understand the behavior of the plasma flow as it approached a dipole field. They inferred that the solar plasma flow forms a comet-like structure around the Earth, extending in the anti-solar direction and confining the Earth and its magnetic field in it. Chapman and Julius Bartels summarized the development of the field in their classic treatise *Geomagnetism* in 1940.

The discipline of geomagnetism evolved into magnetospheric physics after the International Geophysical Year (IGY), the historic geoscience enterprise in 1957–1958, namely during the beginning of the space age. Tomy Gold (1959) coined the term *magnetosphere* by defining it as "*the region above the ionosphere in which the magnetic field of the Earth has a dominant control over the motions of gas and fast charged particles.*"

The Earth's electromagnetic environment is continuously monitored by recording changes of the Earth's magnetic field. The record shows from time to time characteristic changes $\Delta\boldsymbol{B}$ of the Earth's magnetic field. At a low-latitude observatory, the magnetic variations begin with a step-like increase for a few hours, which is then followed by a decrease of a larger magnitude for a day or so. The upper diagram of Figure II shows magnetic records of the north-south

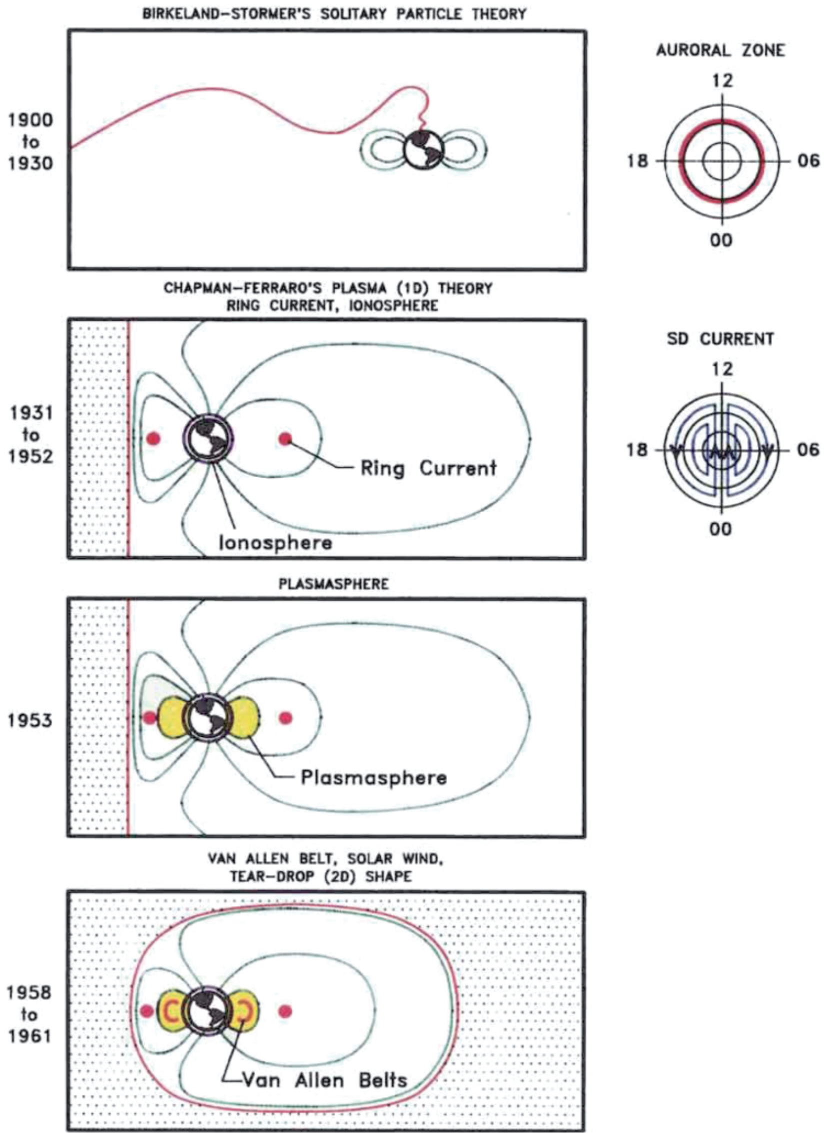


FIGURE I.

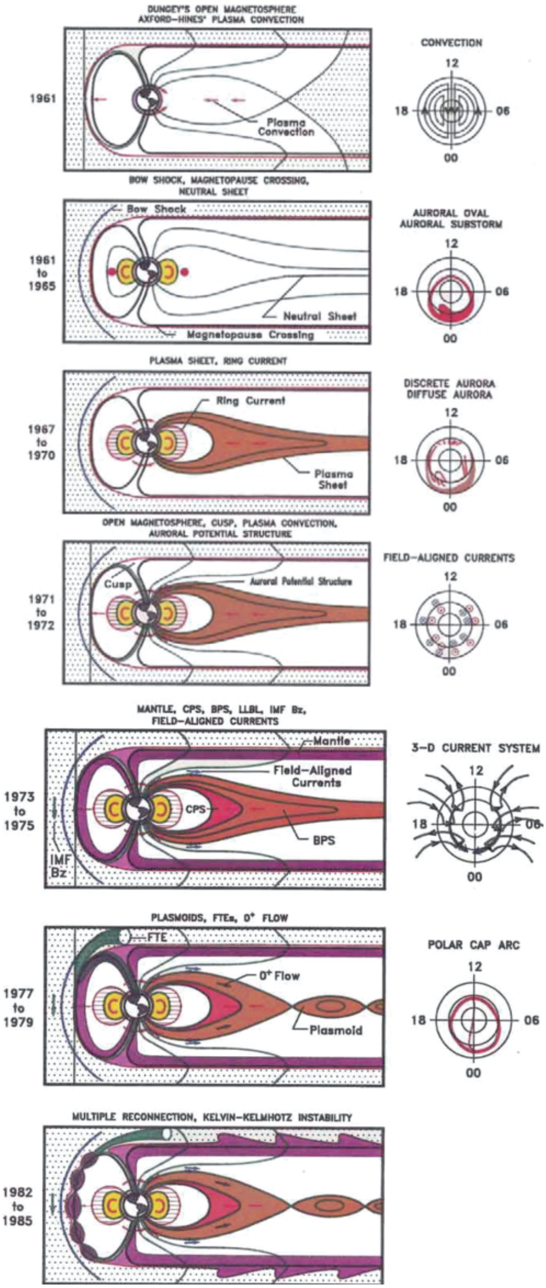


FIGURE I. (*Continued*) Schematic presentation of the development of the concept of the magnetosphere.

Source: Akasofu, S.-I., *Magnetospheric Substorms*, ed. by J.R. Kan, et al., AGU Monograph, 64, p. 3, Washington D.C., 1991

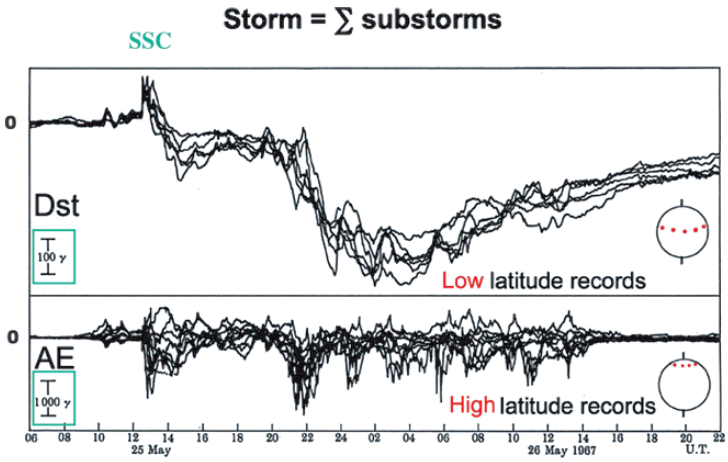


FIGURE II. Upper – Superimposed magnetic records (the north-south component) on May 25–26, 1967, from six low-latitude observatories separated widely in longitude. Lower – Superimposed magnetic records on the same dates from nine high-latitude observatories separated widely in longitude. Note the difference of the scale between the upper and lower diagrams.
Source: Akasofu, S.-I. and S. Chapman, *Solar-Terrestrial Physics*, p. 542, Oxford University Press, Oxford, 1972

component from several low-latitude stations widely separated in longitude; northward changes are recorded as positive changes, while southward changes are recorded as negative changes. The first increase and the subsequent larger decrease are observed at all stations, indicating that those changes occurred on a global scale. This phenomenon is called the *geomagnetic storm*. The development of the study of geomagnetic storms is one of the important subjects of this book. It may be noted that the term magnetic storm was coined by A. Von Humboldt in his treatise *Cosmos* (1871).

The geomagnetic storm field $\Delta \boldsymbol{B}$ is produced by various electric current systems that develop around the Earth when solar disturbances reach the Earth. The field $\Delta \boldsymbol{B}$ is thus superposed on the Earth's main field $\boldsymbol{B}_o$, which does not change in days or months.

During a geomagnetism storm, at high-latitude observatories, fluctuations of a much greater magnitude than those seen in low latitudes, consisting of a number of simultaneous impulsive changes, can be observed. In the lower diagram of Figure II, magnetic records from a number of high-latitude stations are shown; note the difference of the scale for the low- and high-latitude records. Those impulsive changes are magnetic manifestations of what we now know as *magnetospheric substorms*. During a geomagnetic storm, a number of such intense impulsive disturbances occur.

Birkeland classified fluctuations of the Earth's magnetic field in terms of equatorial positive/negative and polar positive/negative changes. As far as I am aware, Chapman was the first who established the present concept of the geomagnetic storm. It consists of the *storm sudden commencement* (SSC), a step-function-like increase in the horizontal (north-south) component and the *main phase*, a larger decrease that follows the SSC. There is often a relatively steady period of a few hours after the SSC, which is followed by the main phase; this period is called the *initial phase*. The SSC is caused by the impact of the shock wave on the magnetosphere; the shock wave is generated by a solar plasma/magnetic cloud advancing in the solar wind after being ejected during solar activities. The main phase is caused by the formation of a belt of energetic particles that surround the Earth. This belt is called the *ring current belt*.

After reaching the maximum decrease during the main phase, the storm tends to recover slowly; this phase is called the *recovery phase*. In the book *Geomagnetism*, by Chapman and J. Bartels (1940), an early account of the development of a study of geomagnetic storms is outlined. Chapman told me that there was great difficulty in publishing it, as world tension was mounting before World War II.

K. Birkeland (1867–1917)
Source: Courtesy of University of Oslo

Sydney Chapman (1888–1970)
Source: Courtesy of Geophysical Institute

After World War II, in the 1950s and 1960s, there were several important developments in a study of the electromagnetic environment between the Sun and the Earth and beyond. First of all, until that time, interplanetary space was thought to be practically a vacuum, except for the streams suggested by Maunder and clouds ejected by solar flare activity. Thus, the Chapman–Ferraro cavity was thought to form only *occasionally*, as the solar plasma engulfed the Earth. Meanwhile, Ludwig Biermann (1951, 1953) suggested a continuous flow of solar plasma. Gene parker (1958) theorized that the Sun blows out plasma continuously with a supersonic speed from the whole solar surface under a certain temperature profile in the corona; he coined the term "*solar wind*." The subsequent detection of the solar wind by the Mariner 2 spacecraft in 1962 brought about a significant change in the concept of the magnetosphere. The magnetosphere is now considered a permanent feature of the Earth, so long as the solar wind blows, rather than forming only occasionally when the Earth is engulfed by intermittent solar plasma flows.

Second, an extensive tail of the magnetosphere was first revealed by the IMP-1 satellite, reported by Norman Ness and his colleagues (1965), as had been suggested by Jack Piddington (1960) . It was found later by space probes on their way to outer planets that the magnetotail extends to a distance of about 1000 Earth radii and perhaps farther.

Third, it was found that the Earth is surrounded by an extensive atmosphere of ionized gases. Based on the study of atmospherics (radio emissions generated by thunderstorm lightning), L.R.O. Storey (1953) found that atmospherics can propagate approximately along the geomagnetic field lines from one hemisphere to the other. The propagation requires an extensive ionized atmosphere to a distance of several Earth radii. This ionized atmosphere has been named the *plasmasphere*. The ionosphere feeds the ionized gases to the plasmasphere.

The Space Age and space research by rockets and satellites were initiated by James Van Allen. In his effort to explore the origin of auroral electrons and cosmic rays, his first attempt was to study auroral electrons near Greenland by *rockoons*, a combination of a rocket and a balloon. It is worth noting that the space age was initiated by the curiosity of scientists like him, who were pursuing the causes of auroral and geomagnetic phenomena. It was his pursuit of auroral electrons by satellites, which led him to the discovery of the Van Allen radiation belts. Subsequently, the ground-based discipline of geomagnetism, together with satellite-based studies, developed into magnetospheric physics. In theoretical space research, Hannes Alfvén stimulated my generation most by introducing many creative concepts, including the concept of the guiding center, magneto-hydrodynamics (MHD), Alfvén waves, dusty plasmas, and many others.

In 1968, Sam Bame and his colleagues at Los Alamos National Laboratories discovered the most extensive region of plasma, called the *plasma sheet*, in the tail region of the magnetosphere. Thus, the magnetosphere has been found to be not an empty cavity, but to consist of several plasma domains. In the 1970s, solar wind-like plasmas were found well inside the boundary of the magnetosphere, and the region occupied by such plasmas is called the *plasma mantle*. The plasma in the plasma mantle flows in the anti-solar direction with a speed of about 100 km/sec, appreciably less than that of the solar wind. Certainly, the plasma in the plasma mantle is of solar wind origin. This finding indicates that the magnetospheric boundary does not exclude completely the solar wind from the magnetosphere, as Chapman and Ferraro originally envisioned in their theory.

Hannes Alfvén (1908–1995)
Source: Courtesy of H. Alfvén

James Van Allen with Carl McIlwain (left) and George Ludwig (right), giving a farewell kiss to their detector to be carried by one of the first U.S. satellites.
Source: Courtesy of J.A. Van Allen

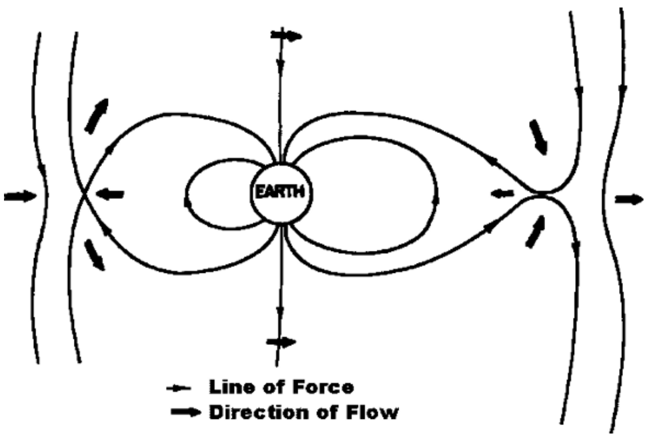
This was also a major change of the concept of the magnetosphere. Another unexpected finding by D.C. Hamilton and his colleagues in 1988 was that oxygen ions (O^+) of ionospheric origin, instead of solar wind protons, become the dominant ions in the ring current belt during intense geomagnetic storms.

Jim Dungey (1961) made the most drastic addition to, or more appropriately the most fundamental revision of, Chapman–Ferraro's original theory. He suggested that the magnetic field lines carried by the solar wind are connected with some of the geomagnetic field lines across the boundary of the magnetosphere. Such a magnetosphere is said to be *open*, while the Chapman–Ferraro model is called a *closed* magnetosphere. The difference between the two theories is that Dungey considered magnetized solar wind plasma, while Chapman and Ferraro considered it a diamagnetic plasma.

Dungey envisaged that the connection process, called *reconnection*, takes place on the dayside magnetopause and that the connected field lines are then transported in the anti-solar direction by the solar wind, resulting in the magnetotail. Subsequently, the field lines are reconnected there and then transported back to the dayside magnetosphere. Dungey's view was that this transport process may occur intermittently and that magnetospheric disturbances, such as magnetospheric substorms, are a manifestation of such a transient process.

In this book, we consider that this interaction between the magnetized solar wind and the magnetosphere constitutes a dynamo that converts a small fraction of the kinetic energy of the solar wind into electrical energy. Magnetospheric disturbances are various manifestations of the power generated by the *solar wind-magnetosphere dynamo*. Chapter 1 describes efforts toward this understanding based on my own experience.

The aurora can then be understood as the only visible manifestation of electrical discharge processes that are powered by the dynamo. Its output power is usually one million megawatts or more. The discharge takes place in an oval-shaped belt, called the *auroral oval*, in the polar upper atmosphere. On the basis of this finding, it could be expected that a magnetized planet with an atmosphere, such as Jupiter, Saturn, Uranus, and Neptune, would have a similar auroral oval, while a non-magnetized planet, such as Venus and Mars, would have no auroral oval. Indeed, the Hubble Space Telescope Project succeeded in imaging the auroral ovals of Jupiter and Saturn (see Figure 2.29), while the Venus and Mars orbiters could not image any indication of the auroral oval.



Dungey's open magnetosphere.
Source: Dungey, J.W., *Phys. Rev. Lett.*, **6**, 47, 1961

As mentioned earlier, geomagnetic disturbance fields $\Delta \boldsymbol{B}$ are the magnetic fields produced by the discharge currents generated by an enhanced solar wind-magnetosphere dynamo power. *Thus, auroral activity and geomagnetic disturbances are only different manifestations of an enhanced dynamo power.* Obviously, the two subjects cannot be discussed separately in understanding magnetospheric disturbances. One purpose of studying auroral phenomena and geomagnetic disturbances is, among other things, to infer the configuration of the discharge current system in the magnetosphere and the dynamo process that feeds the current. Chapters 2 and 3 describe our efforts in this endeavor during the early days of the space age.

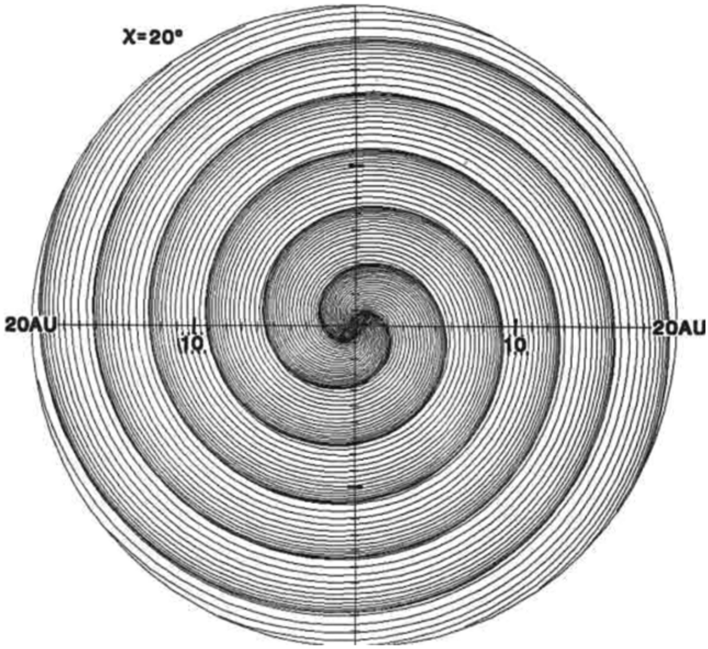
A typical geomagnetic disturbance field $\Delta\boldsymbol{B}$ undergoes a specific sequence of changes, as shown in Figure II. We now understand that a geomagnetic storm is the magnetic manifestation of what we call a *magnetospheric storm* that results from a large increase of the dynamo's power. Similarly, an auroral storm is its visible manifestation.

It also has been found that the magnetosphere has a specific response to an increased power of the solar wind-magnetosphere dynamo for a few hours. The results of these responses are called *magnetospheric substorms*, their manifestations being the *polar magnetic* and *auroral substorms*. It may be noted here that MHD-based magnetospheric physicists are interested in interpreting magnetospheric disturbances in terms of magnetic flux transfer, not in terms of the dynamo. A magnetospheric storm results from a frequent occurrence of intense magnetospheric substorms. That is to say, *the substorms are the basic elements of a storm*. This is because substorms are responsible for feeding oxygen ions (O^+) from the ionosphere into the ring current belt. During recent years, considerable progress has been made in studying the distribution of the injected oxygen ions, by using an imaging method, called the energetic neutral atom (ENA) imaging. In Chapter 4, we synthesize selected important facts in an attempt to understand processes associated with magnetospheric substorms.

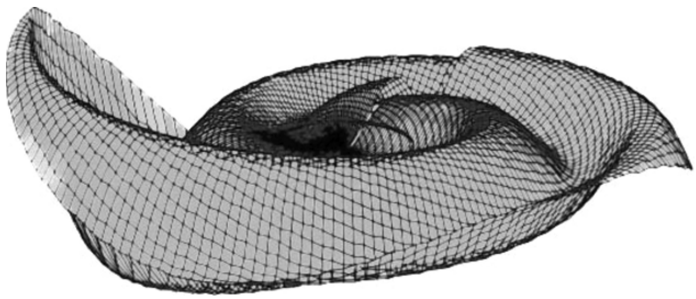
Planetary magnetism is an important subject for all geophysicists, solar physicists, and astrophysicists. It has been a great surprise that the dipole fields of both Uranus and Neptune appear to be inclined considerably with respect to their rotation axis and are greatly off-centered. So long as the generation of planetary magnetism relies on the planetary rotation, it is difficult to explain why the magnetic axis is inclined greatly from the rotation axis. Chapter 5 provides a nontraditional interpretation of planetary magnetic fields. In this attempt, it is assumed that the photosphere of the Sun corresponds to the core surface of the magnetized planets and a spherical surface of 3.5 solar radii, called the *source surface*, corresponds to the planetary surface, where the field is more or less dipolar. Thus, a study of the relationship between the magnetic fields of the photosphere and the source surface might provide a new way of interpreting the observed planetary magnetic field.

The solar wind stretches the dipolar field lines on the source surface all the way to the outer boundary of the heliosphere, where the solar wind interacts with interstellar gas. As the Sun rotates with a period of about 25 days, the stretched field develops a spiral structure. The heliospheric current sheet is formed as the extension of the magnetic equator of the Sun. The current sheet divides the stretched dipolar field lines (the interplanetary magnetic field lines) into two regimes, away and toward the Sun, in terms of the orientation. The axis of the dipolar field on the source surface is inclined with respect to the rotation axis. As a result, the heliospheric current sheet develops a wavy structure as the Sun rotates.

As the solar wind and its magnetic field are continuously changing, the power of the solar wind-magnetosphere dynamo varies as a result. In particular, after a few days of intense solar activities (including solar flares), coronal mass ejections, an intensified solar wind, together with its shock wave, reaches the

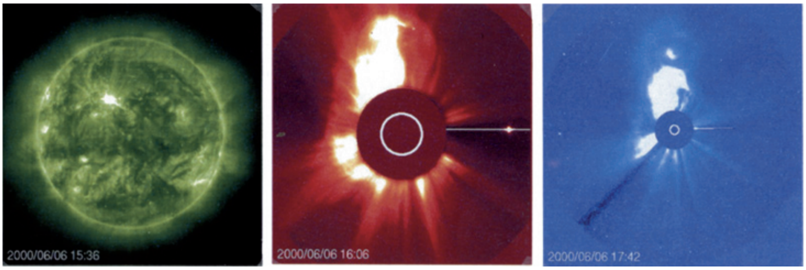


The spiral structure of the interplanetary magnetic field lines within a distance of 20 AU; the Sun is located at the center.
Source: Hakamada, K. and S.-I. Akasofu, *Space Sci. Rev.*, **31**, 3, 1982

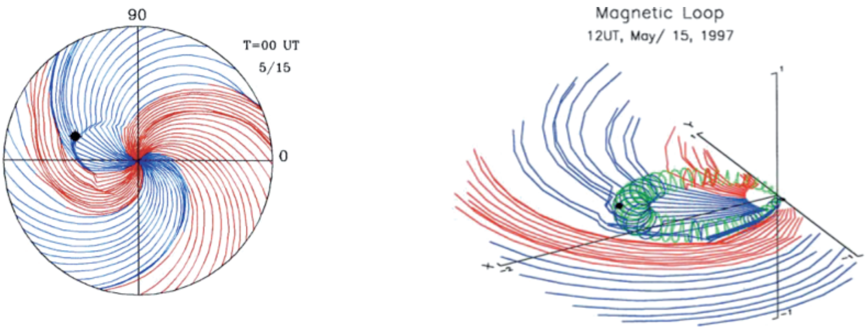


Heliospheric current sheet that extends from the Sun for Carrington Rotation 1654. The Earth's orbit is also shown.
Source: Akasofu, S.-I. and C.D. Fry, *J. Geophys. Res.*, **91**, 13, 679, 1986

magnetosphere. The shock wave compresses the magnetosphere. As a result, the Alfvén waves are generated at the front of the magnetosphere and propagate into the magnetosphere, causing the SSC. The intensified solar wind in the form of plasmoids or magnetic flux ropes are thought to generate the shock wave



Solar activity (solar flare) and a coronal phenomenon called "coronal mass ejection (CME)", observed by the Solar and Heliospheric Observatory (SOHO).
Source: SOHO/(Instrument) consortium. SOHO is a project of international cooperation between ESA and NASA

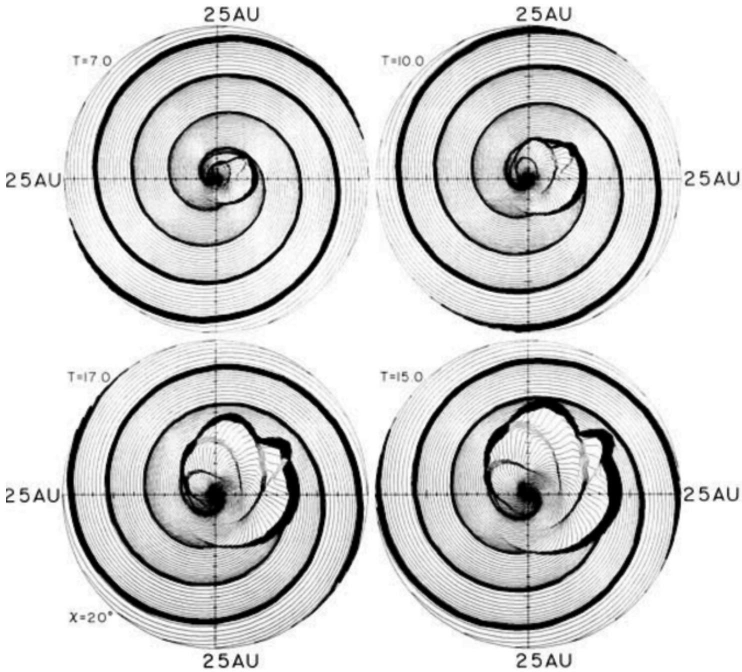


Left: The propagating of a shock wave during the May 1977 event. Right: An advancing magnetic flux rope with a helical structure.
Source: Saito, Takao, W. Sun, C.S. Deehr, and S.-I. Akasofu, *JGR*, Accepted, 2006

in the background solar wind and arrive at the front of the magnetosphere. When the magnetic field in the plasma cloud has an intense southward component, it increases the dynamo power, causing a frequent occurrence of magnetospheric substorms and thus subsequently generating the ring current belt and the magnetospheric storm.

The ultimate cause of magnetospheric storms is thus a variety of transient solar activities. In spite of more than a half-century of intense research, however, the causes of sunspots, solar flares still remain as long-standing unsolved problems. The nature of coronal mass ejections is still in debate. Most solar physicists consider that solar activities are directly related to hypothetical thin magnetic flux tubes beneath the photosphere, their uplift by buoyancy and magnetic reconnection among them after their uplift. In Chapter 7, it will be pointed out that magnetic flux tubes are nothing but a hypothesis, perhaps an unworkable one. It will also be pointed out that a dynamo process in the solar photosphere must generate the source of energy for solar activities, since solar activities are basically electromagnetic phenomena. In this book, I offer a non-traditional idea about the sunspot formation and causes of solar activity.

In this short review on the progress of solar-terrestrial physics, one can see that investigators of the four disciplines (solar physics, interplanetary physics, magnetospheric physics, and aeronomy) have made considerable progress in the twentieth century after Carrington's finding. However, for these disciplines to progress further, in particular in terms of space weather research, it is important for solar physicists, interplanetary physicists, magnetospheric physicists, and upper atmospheric physicists to work together. There are many missing links among the four disciplines that will only be noticed if one attempts to synthesize space weather research. Chapter 8 is devoted to the integration of the four fields.



Interplanetary disturbances caused by a series of solar flares.
Source: Akasofu, S.-I., K. Hakamada, and C.D. Fry, *Planet. Space. Sci.*, **31**, 1435, 1983

The disturbed solar wind caused by various solar activities advances into the interplanetary structure, well beyond the distance of the Earth. It is quite exciting that both Jupiter and Saturn appear to show auroral activities. It is hoped that what we learn about the Earth's magnetosphere will be useful in studying their magnetosphere and vice versa. Shock waves also form a barrier for cosmic ray particles that enter from the outer boundary of the heliosphere, causing a reduction of the cosmic ray intensity in the heliosphere. This phenomenon was discovered by Scott Forbush and is called the *Forbush effect*. It is likely that the so-called "11-year cycle variations" of cosmic ray intensity result from an accumulated effect of the shock waves. Chapter 9 describes the magnetic field structure of the heliosphere and how it is disturbed by solar activities.

It is hoped that the readers of this book will find a number of long-standing unsolved problems in the four disciplines and that my non-traditional ideas stimulate better ideas than mine. I believe that many of the difficulties the present generation is facing are not due to the lack of basic knowledge and technical problems (for example, the capability of a supercomputer), but to our inability to recognize fundamental flaws in the presently prevailing concepts, namely paradigms. The Epilogue is devoted to discussing this issue. The new generation of scientists are encouraged to challenge the present paradigms and advance our understanding of electromagnetic phenomena around the Earth, in interplanetary space, and the heliosphere.

PLATE 1. An active auroral curtain near the zenith. This form is sometimes referred to as the corona-type display. Photographed by Jan Curtis.

Source: Photographed by Jan Curtis