Title: ***The Solar-Terrestrial Environment***
Author: J. Hargreaves
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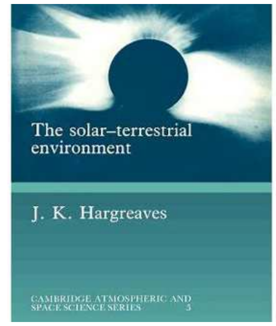

The Solar-Terrestrial Environment is part of a book series called *Cambridge Atmospheric and Space Science Series*. I often encounter references to the book and author in other books and papers I have studied on Earth's ionosphere and space weather. The author, J. Hargreaves, is a co-author with R. Hunsucker of another book in my library, ***The High-Latitude Ionosphere and Its Effects on Radio Propagation***, which also is part of the CASSS series and scheduled for review [Hunsucker].

The very first sentence in the book under review concisely and accurately says "This textbook describes the physical conditions in the upper atmosphere and magnetosphere of the Earth". This is called *geospace*, and is the environment that experiences *space weather* out to *many* Earth radii. The book was published almost 20 years ago, but I do not know of a more modern book that covers the same amount of material and is as easy to read as this one. Further, well-written books like this are closer to the development of the basic ideas and knowledge on which the field now stands and are far easier to understand than most modern works.

Although ***The Solar-Terrestrial Environment*** was published in 1992, the basic principles and interpretations discussed in it have not changed much since then. Sure, there have been many, many refinements, better understanding and new discoveries. However, there were (and still are) many gaps in our knowledge, and a lot of them have been filled since 1992. The author does a good job of identifying outstanding problems that existed at the time he wrote the book, so a reader may be able to resolve at least some of them through current research publications and online seminars such as the *Magnetosphere Online Seminar Series* recorded in 2020 [MagOnline].

The book is designed as a textbook for advanced physics undergraduates and new postgraduates, but it does not include any problems such as are found in most textbooks. From the standpoint of clarity of presentation, any student of upper atmospheric, ionospheric or magnetospheric physics will find this book very useful. By student I do not mean only those engaged in formal academia; I mean any person wishing to understand more about the natural systems surrounding Earth and controlled by the Sun (I am such a student). For amateur radio astronomers, there are many aspects of this book that are of interest including effects on terrestrial-to-terrestrial and celestial-to-terrestrial radio propagation. If nothing else, this book will increase one's knowledge, and the fact that it is very easy to read is a bonus.

The author's writing style is always remarkably clear and even amusing at times. A book on magnetospheric and ionospheric physics cannot be written without equations. The author purposely does not derive any of the many equations in his book, and he usually shows versions based on simplified assumptions so the reader can more quickly understand the important aspects and variables. He also provides many *back-of-the-envelope* calculations that put complicated concepts into perspective and magnitude.

The author shows many equations in both the CGS (Centimeter, Gram, Second) units system and SI (International System) units system. This recognizes the enormous amount of prior research that uses the CGS unit system and makes it easier for someone to move between the two without having to think "do I multiply or divide by 4π or some other factor here or not?". The illustrations all are black-white line drawings, well-explained, and usually taken from a reference. These characteristics really make the book accessible and understandable to even a casual (but technical) reader.

All of the phenomena described in ***The Solar-Terrestrial Environment*** are inter-related, so it often is necessary to refer backward or forward to an explanation. What makes this book different from many technical books is that, rather than simply saying "this was previously discussed" or "this will be discussed later", the author gives the actual section number for the referenced discussion. This makes it very easy to go back and forth when one wishes to be refreshed about the fine details of the subject.

The book's progression through its ten chapters is logical – it starts with an overview and then quickly goes into Earth's atmosphere, magnetosphere and ionosphere and then to follow-on subjects including magnetospheric waves (both electromagnetic and magnetic) and the technological applications of geospace science. In the remainder of this review I describe each chapter in turn.

The book starts in chapter 1, *The Earth in Space*, by first generalizing the Sun and solar wind, Earth's atmosphere and ionosphere, the geomagnetic field and magnetosphere. The physics are then summarized in chapter 2, The *Physics of Space*, by describing the properties of gases, magnetoplasma, and waves (phase and group velocity, refractive index, polarization and so on). Details are given of radio waves and their propagation in an ionized medium such as the ionosphere. The author introduces more types of waves in plasma, such as hydromagnetic and magnetosonic waves, *whistlers* (lightning-induced radio waves that propagate along geomagnetic field lines between the northern and southern hemispheres) and ion-cyclotron waves, among others. These all are relatively brief introductions that are discussed in greater detail in later chapters.

It is in chapter 2 that the author provides a very lucid discussion of a *frozen-in* magnetic field, a concept that was first introduced by H. Alfvén in 1942 [Alfvén] and not explained very well in other geospace books. The solar wind is an example (but not the only one) where the Sun's magnetic field lines are frozen-in with the moving plasma of charged particles and carried along with it. A frozen-in field depends on the very high conductivity of the plasma. There are two errors in equation (2.39), which relates the velocity (v) of a conducting medium (in this case a plasma) with respect to the magnetic field to the power dissipated (P), magnetic field flux density (B), conductivity (σ) of the medium and the length of a hypothetical circuit (l). The quantities B and l in the second part of the equation both should be squared, as in

$v^2 = P/B^2 \cdot \sigma \cdot l^2$ (corrected equation 2.39)

Errors like this infiltrate all works that involve equations (analogous to software and firmware bugs in computer code), and there are a few more of them in this book along with some misspellings (for example, *permiability* instead of permeability) and some obvious typographical errors. After discovery, errors often are handled by errata issued by the publisher. I did find the errata for this book on the publisher's book *Resources* webpage, but the errors in equation 2.39 are not listed. By the way, I did not discover the equation error by applying first principles (Maxwell's equations) or even Alfvén's concepts but by first noticing something that did not look right and then applying simple unit analysis.

Chapter 3, *Techniques for Observing Geospace*, is over 50 pages long and discusses the importance of observing and observing methods and instruments. It briefly reviews the sensors and also the physics that forms the basis for each type of instrument. Our knowledge of geospace progressed very quickly after spacecraft were launched into it, enabling direct measurements and what is called *topside* sounding or topside measurements.

Spacecraft used for direct measurements also allow indirect measurements of the upper atmosphere. For example, the air density can be determined from measurements of ejected falling spheres with built-in accelerometers and telemetry and by measuring satellite drag. Before the use of spacecraft, all measurement instruments were ground-based, or bottom side, except for some balloon-and rocket-borne measurements that produced limited results. The most familiar examples of ground-based instruments are geomagnetometers, which have been deployed globally for well over 100 years.

Sensing by means of radio waves, both topside and bottom, is covered quite extensively. For example, terrestrial HF ionosondes have been used for almost 100 years to probe the ionosphere. The extensive use of Global Positioning System (GPS) satellite transmissions in the L-band (~1.5 GHz) to determine total electron content between a satellite and receiver station is well known; satellite-mounted beacon transmitters also are used for topside measurements.

Other techniques described in chapter 3 are HF doppler measurements, which are used to investigate acoustic-gravity waves in the ionosphere. Ionospheric modification, for example, heat injection such as produced by HAARP experiments in Alaska, produces many phenomena that are used as diagnostics of the ionosphere. Examples are magnetic field aligned irregularities (FAI) and striations in the ionosphere, ionospheric *holes*, and low frequency emissions. Many other techniques are briefly described, and later chapters describe the results obtained from them.

The Neutral Atmosphere is covered in chapter 4. Here, the author details the vertical structure of the atmosphere, including the gas makeup, temperature and different wind regimes as altitude increases. As the chapter name indicates, the focus is on the neutral atmosphere – intact atoms and molecules such as oxygen and nitrogen and at higher altitudes hydrogen and helium – that coexists with ionized constituents described later.

Chapter 5, *The Solar Wind and the Magnetosphere*, defines the magnetosphere as "the region of the terrestrial environment where the geomagnetic field exerts the dominating influence". Without the solar wind the magnetosphere would be shaped like the field around a magnetic dipole. With the solar wind the magnetic field is compressed on the day side and stretched out on the night side of Earth; thus, the magnetosphere's boundary varies according to its interaction with the solar wind.

The solar wind itself does not penetrate the magnetosphere but flows around it; that is, it is *frozen-out*. This flow is not smooth and energy is transferred from the solar wind into the magnetosphere. The magnetosphere circulates as two regions, an inner region rotating daily with the Earth and an outer region circulating under the influence of the solar wind.

The solar wind is a permanent feature of the Sun consisting of matter – charged particles, mostly a plasma of electrons and hydrogen and helium ions – that continuously leaves the Sun. It is assumed the solar wind is caused by convective acceleration outward from the hot corona that exceeds the inward gravitational acceleration. However, to this day (July 2020) the origin, release and acceleration of the wind are three of the top nine outstanding questions of solar wind physics [Viall].

The speed of the solar wind from the undisturbed Sun as measured near Earth is in the neighborhood of 300 to 350 km s^{-1} but solar activity such as coronal mass ejections (CME) near the peak of the 11-year solar cycle can temporarily increase it to as high as 2000 km s^{-1}. The solar wind is not a simple motion of matter through space. Since the Sun's magnetic field is frozen-in, any solar activity will affect the interplanetary magnetic field (IMF), and these variations in-turn affect Earth's magnetosphere. The interactions with the magnetosphere have been intensely studied since the discovery of the solar wind as permanent feature in the early 1960s. The results of these studies (through 1990) are well and interestingly described in chapter 5.

The lower altitude boundary discussed in ***The Solar-Terrestrial Environment*** is about 60 km above Earth's surface. This is considered the lower boundary of the ionosphere's D-region (it actually is variable), a region up to around 90 km that has a certain range of electron density characteristics. This region can help or hinder radio propagation depending on the frequency and space weather conditions, but there also are other ionospheric regions that affect radio propagation.

The regions of the ionosphere – D, E, F1 and F2 – are briefly mentioned in chapter 6, *Principles of the Ionosphere at Middle and Low Latitudes* but only generally. The ionosphere is significantly influenced by Earth's magnetic field, and these natural influences affect the low and middle latitude ionosphere (between 0° and approximately 60° north and south) in different ways than higher latitudes. Therefore, the author has split more detailed discussions of ionospheric phenomena in these latitude ranges into the two chapters that follow chapter 6.

The ionosphere is so called because of its significant numbers of free electrons and positive ions. The ionization is caused by radiation from the Sun at extreme ultraviolet and x-ray wavelengths. Although the ionospheric medium contains charged particles, it is electrically neutral in any given volume and called a plasma. The charged particles are mixed with a much larger number of neutral atoms and molecules, but radio propagation is controlled by the charged particles in concert with Earth's magnetic field.

The concentration of charged particles varies with altitude and increases when there are solar outbursts such as flares and other increases in solar radiation; thus, the ionosphere broadly changes with the solar cycle. The movement and concentration of charged particles and their interaction with Earth's magnetic field heavily influence the electrical properties of the ionosphere. As a result, radio propagation also is affected, particularly in the HF band but in other bands as well. In broad general terms, the ionosphere varies in a regular and predictive manner at all time and distance scales, but perturbations and irregularities can and do occur that defy predictability. To this day, our theoretical understanding of the ionosphere is incomplete.

The magnetosphere rotates with the Earth and its interaction with the solar wind and ionosphere causes currents to circulate in different ways at low and middle latitudes than at high latitudes. Chapter 7, *Ionospheric Phenomena at Middle and Low Latitudes*, discusses the first situation. At low latitudes, from 0° to 20° or 30° either side of the magnetic equator, Earth's magnetic field lines are horizontal and strongly influence the electromagnetic forces on the upper atmosphere. A consequence is the very high conductivity of the ionosphere. A large ring current flows around the Earth at these latitudes, synchronized with Earth's rotation as the Sun's radiation ionizes the atoms and molecules in the upper atmosphere.

The middle latitudes, approximately 30° to 60° north and south of the magnetic equator, have been studied the most since the beginning of radio. The ionization at middle latitudes is controlled almost entirely by the Sun's radiation, and is removed again by chemical recombination processes that involve both the neutral atmosphere and ionized particles. The balance between ion production and loss are affected by winds in the neutral atmosphere. Although the processes in the middle latitudes also take place at low and high latitudes, other processes also are important.

The ionization at all latitudes varies with altitude and develops into more or less distinct regions. Chapter 7 is where the author first discusses the ionosphere's regions in any detail, starting with the E-region and sporadic-E and moving upward to the F1- and F2-regions and finally downward to the lowest region, the D-region. These regions vary with the sunspot cycle and are affected by solar flares and other solar activity, leading to a wide range of ionospheric disturbances including the *shortwave fadeout*, *sudden cosmic noise absorption*, *sudden phase anomaly*, *sudden enhancement of atmospherics*, *magnetic solar flare effects*, and *sudden frequency deviations*. There are many other effects and irregularities discussed in chapter 7 including storms in the various ionospheric regions and equatorial anomalies.

As mentioned above, many attributes of the low and middle latitude ionosphere, including solar flare effects, also apply to high latitudes, from about 60° to the poles. However, the high latitude ionosphere is connected through the geomagnetic field lines to the outer region of the magnetosphere where it is directly influenced by the solar wind. In this way, the so-called *polar ionosphere* is accessible to particles that have been energized within the magnetosphere or have come from the Sun, thus providing another source of ionization and producing different patterns and anomalies unique to high latitudes.

Chapter 8, *The Ionosphere at High Latitudes*, discusses these anomalous characteristics, which includes *ionospheric blobs*, *enhancements* and *patches*. Experiments with incoherent scatter radar shows patches as small as 50 km and as large as 1000 km wide with electron densities at night that are similar to the daytime ionosphere at mid-latitudes. Radars have been used to probe the high-latitude E-region and have detected density irregularities that drift with speeds of hundreds of kilometers per second.

The aurora is manifested in the magnetosphere at high latitudes. In addition to the spectacular visual displays, there are auroras detected at radio frequencies that do not always have visual counterparts. Auroral absorption is a phenomenon that sometimes prevents ionosondes at high latitudes from showing the expected results, so riometers are used for absorption measurements. High-latitude phenomena also include whistlers and ULF (ultralow frequency, 3 Hz to 3 kHz) and VLF (very low frequency, 3 to 30 kHz) emissions.

In addition to these radio phenomena, high latitudes also experience magnetic storms in different ways. As opposed to low-latitude terrestrial magnetometers, magnetometers at high latitudes always indicate higher amplitude changes in the magnetic flux density that result from a magnetic disturbance. The circulation of the high-latitude magnetosphere produces the *auroral electrojet*, which is a current system at higher latitudes that not only flows horizontally but vertically. These and many other effects are described in chapter 8 with enough detail to be very illuminating and interesting but not so much that the reader becomes bogged down.

Chapter 9, *Magnetospheric Waves*, is about the electromagnetic waves or emissions generated within the magnetosphere by oscillating charges. A low frequency natural radio listening enthusiast will find plenty to read about in this chapter. Magnetospheric waves involve energy that is coupled from a particle to a wave or from a wave to a particle. Resonance is required for efficient energy transfer. For example, an energetic electron spiraling around a magnetic field line and producing Doppler shifted radiation may resonate with a whistler-mode wave generated by lightning. Observations of these frequencies reveal information about the magnetic field and electron density.

Although these phenomena are electromagnetic, some have frequencies in the audio range. When detected they are easily converted to sound. Whistlers are easy to recognize from their falling tone. Some emissions in this category have a short duration and discrete spectrum, while others are unstructured and have the sound of a *hiss* or *chorus* when detected. Magnetic measurements with ground instruments also show wave phenomena. Examples are micropulsations, which have amplitudes that are a tiny fraction of the magnetic field and periods ranging from a fraction of a second to hundreds of seconds.

The phenomena described above are observed from the ground with the appropriate receivers and antennas. Similar observations by satellite-borne instruments complement ground measurements and also provide measurements not possible from the ground because of absorption or because the emissions may not propagate to the ground. Space observations have resulted in the discovery of a multitude of emissions in the magnetosphere that serve as diagnostics, and ***The Solar-Terrestrial Environment*** provides a brief description of each. It is clear that for every question that has been answered by these measurements, many more questions are produced.

The question arises, what are the uses of the knowledge gained through scientific investigation of the solar-terrestrial environment? The book attempts to answer this question in chapter 10, *Technological Applications of Geospace Science*. It is well understood that bad space weather in the solar-terrestrial environment can affect our technology including metallic pipelines, electric powerlines, radio communications over wide frequency ranges, satellite operations, polar flights at high altitudes and human spaceflight and travel. This chapter is 20 pages long and provides only a very brief summary of technological applications and how our understanding of both the science and technologies helps us mitigate the deleterious effects. Nevertheless, it provides a good springboard for readers interested in space weather, who may wish to pursue the subject with the many current books now available.

The number of different but related physical processes that occur in geospace is quite surprising and perhaps daunting at first. However, ***The Solar-Terrestrial Environment*** summarizes them fluently and successfully and is written in such a way that a reader can pick and choose only those subjects of interest. The author's expertise, and the expertise of many others, all well referenced and cited, shows in this book.

Citations:

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