Introduction to Geomagnetically Trapped Radiation

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# 1

# The Earth's radiation belts

## Introduction

The discovery in 1958 that the Earth's magnetic field contains belts of energetic ions and electrons was a major milestone in geophysics and astronomy. This discovery can be viewed as the birth of magnetospheric physics since an enormous quantity of new knowledge concerning our planet's outer environment rapidly followed the first measurements of these radiation belts. Furthermore, the interpretation of many well-known phenomena, such as the aurora, magnetic storms and ionospheric structure, required major revisions in the light of this new information. Thus, our view of planet Earth was changed and enlarged by these new discoveries, nourished by the availability of space technology.

A thin upper atmosphere and ionosphere surrounded by an empty magnetic field were no longer seen as the outer envelope of the near-Earth region. Instead, the magnetic field was found to contain a population of ions and electrons of varied origin and having a rich, dynamic behavior. The geomagnetic field in the region between the ionosphere and the solar plasma accepts charged particles from both of these sources. The electric and magnetic fields accelerate, store and transport these particles, eventually returning them to the source regions. The complexity of the processes experienced by charged particles in the geomagnetic field is truly bewildering, such that, after 30 years of sustained effort, important phenomena are still only dimly perceived. Many features that have been observed repeatedly still lack a quantitative explanation, and new discoveries will, no doubt, continue to be made.

The remainder of this introduction will be a brief, qualitative review of our knowledge of space plasmas in the region near the Earth. This overview is intended to give the reader a sense of the role of radiation belts in space science and in space technology, and to make the reader aware of the scope and variety of the phenomena to be considered. Thus, this chapter will lay the groundwork for the more detailed development of radiation belt physics presented in the body of the book.

## The magnetosphere

The Earth's magnetosphere is the region of space containing magnetic fields of terrestrial origin. Electric currents in the Earth's core produce a magnetic field (about $6 \times 10^{-5}$ tesla at the Earth's surface near the poles). Above the surface the geometrical pattern of the field is approximately a dipole within distances of several Earth radii from the Earth's center. The solar wind, a plasma of electrons and ions moving radially outward from the sun, impinges on the Earth's field at a velocity of 300–500 $\mathrm{km\,s^{-1}}$. The moving plasma compresses the field on the sunward side, flows around the magnetic barrier, and distends the field lines into a tail extending several million kilometers down-wind from the Earth. The interaction of the solar wind and the geomagnetic field is complex and the processes that control many of the characteristics are not yet understood. Nevertheless, satellite experiments conducted over the past 30 years have identified the principal features of the magnetosphere, and these are illustrated schematically in Figure 1.1.

The solar wind flow is supersonic, that is, its speed is greater than the speed of any plasma wave which can propagate in the upstream direction and warn incoming ions and electrons that an obstacle, the geomagnetic field, is about to be encountered. One might therefore expect that particles of the solar wind would impact the geomagnetic field directly and not flow more or less smoothly around the flanks. Indeed, nature solves this problem by forming a shock wave 2–3 Earth radii ($R_E$; $1R_E = 6.37 \times 10^3$ km is the mean radius of the solid earth) ahead of the magnetic barrier. This shock wave converts some of the directed energy of ions and electrons into thermal motion and reduces the bulk flow velocity to a value below the plasma wave speed. Thus, the plasma, after passing through the shock, is subsonic and can flow around the magnetic obstacle in much the same way that air flows around a subsonic airplane wing. The shell-like region between the shock and the magnetic barrier is called the magnetosheath. The magnetosheath is bounded on the upstream side by the shock and on the downstream side by the geomagnetic field. This inner boundary, called the magnetopause, separates the plasma and magnetic field of solar origin from the plasma and magnetic field associ-

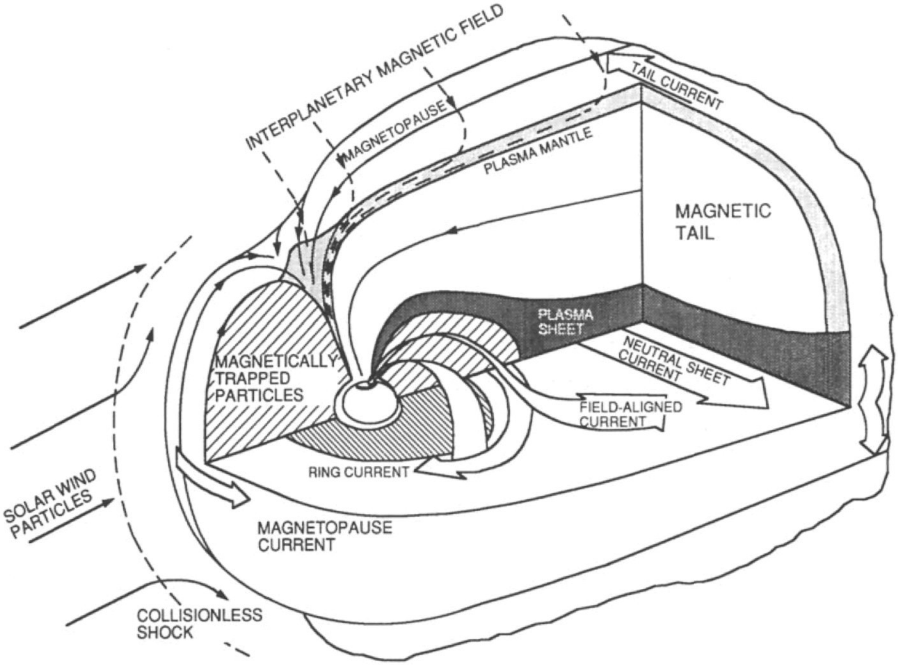

Figure 1.1. Schematic representation of Earth's magnetosphere indicating the locations and shapes of the various features.

ated with Earth. A straightforward but oversimplified calculation balancing plasma and magnetic pressures on both sides of the magnetopause predicts the location of the magnetopause in the region facing the Sun.

On the downstream side of the Earth this pressure balance approach fails. In fact, all theoretical approaches to calculating the properties of the geomagnetic tail have limitations and the picture of Figure 1.1 is largely empirical. It is clear from experiments that the geomagnetic field is drawn downstream into two great lobes, the field lines in the northern lobe pointing towards the Earth (and the Sun), while those in the southern lobe are directed away from the Earth (and the Sun). Such a magnetic configuration requires a current sheet flowing across the tail in the dawn-to-dusk direction in the equatorial plane. Other current systems must flow on the surface of the magnetosphere to separate the internal field of geomagnetic origin from the solar magnetic field carried by the solar wind. The separation of solar and Earth generated magnetic fields is not complete, however, and field lines originating in the Earth can become topologically connected to solar field lines. This process of field line merging is believed to be important for the dynamic behavior of the magnetosphere.

Figure 1.1 is an idealized illustration of the Earth's magnetic configuration and plasma regions and is intended to illustrate the location and extent of various features. These features are distinguished by magnetic field topologies, by the characteristics of the plasmas found there, by the presence of electric currents and fields, or by the presence of certain types of plasma waves.

The Earth's magnetosphere as described by Figure 1.1 is not in a steady state. The overall size of the magnetosphere varies with solar wind velocity and density, and internal instabilities cause changes in the tail structure. Also, the direction of the magnetic field carried by the solar wind affects the character of the connections between solar and terrestrial field lines.

## The radiation belts

Well inside the magnetosphere lie the radiation belts, regions where energetic ions and electrons experience long-term magnetic trapping. In general, such trapping requires stable magnetic fields, and near the magnetopause the magnetic field fluctuations induced by solar wind variability prevent long-term trapping. On the low-altitude side the atmosphere limits the radiation belt particles to regions above 200–1000 km because collisions between trapped particles and atmospheric constituents slow down the trapped particles or deflect them into the denser atmosphere. Thus, in the study of trapped radiation the region of prime interest is the volume of stable magnetic field above ~200 km and below about 7 $R_E$ at the equator. The magnetic geometry limits this volume to magnetic latitudes equatorward of about 65°. However, it is as well to remember that neighboring regions (in fact the entire magnetosphere) are involved in radiation belt phenomena. These regions supply particles for the belts and produce electric and magnetic fields that accelerate, deflect or transport the trapped particles.

## The importance of trapped radiation in space science and technology

The magnetically contained ions and electrons surrounding the Earth are an integral part of the Earth's environment and play an important role in many geophysical processes. This plasma is a reservoir of energy that on occasion is released into the atmosphere producing transient aurora, airglow and ionization. The trapped ions and electrons exchange energy with plasma waves. Hence, this region of space teems with various types of waves that may be amplified, damped, refracted or reflected by the associated plasmas. The trapped particles also produce electric currents that in turn generate magnetic fields. Measurements of this variable component of the geomagnetic field have been made for decades, but many aspects were fully understood only after the discovery of trapped radiation. For example, during the main phase of a magnetic storm the depression of the magnetic field observed at the Earth's surface is caused by increased numbers of trapped ions and electrons whose motion produces a magnetic field opposing the field of the Earth's core.

In many ways, some only vaguely understood, the trapped population acts as a coupling agent transferring energy, momentum and mass between the interplanetary medium and the Earth's atmosphere. This transfer is many-faceted, sometimes occurring by the direct transport of particles, and sometimes through the intermediary of stresses in the geomagnetic field, electric currents and plasma waves. Unraveling these dynamic interactions is one of the principal immediate goals of magnetosphere research.

In spacecraft technology the energetic trapped particles have always been an important, sometimes dominant, concern. Satellite components such as solar cells, integrated circuits and sensors can be damaged by radiation, or their performance may be degraded by an increased background resulting from the passage of charged particles through the electrically active volume. A dramatic example of this vulnerability occurred in 1962 when several satellites ceased to operate after their solar cells were damaged by the enhanced radiation belt from a high-altitude nuclear explosion. At present, considerable effort is devoted to manufacturing radiation resistant electronic components for satellite equipment, primarily in order that it may survive the trapped radiation environment.

Trapped particles may also disrupt satellite operation in more subtle ways. On occasion the electrons and ions may deposit unequal charges on satellite surfaces leading to differences in the electric potential of various satellite segments. The resulting electric discharges can damage electronic components or produce spurious signals which give false instructions to spacecraft computers. These satellite 'anomalies' are often associated with unusual conditions in space such as magnetic storms.

Over the past 30 years radiation belt characteristics have been mapped extensively, and the radiation hardness of electronic components has been greatly improved. Nevertheless, the effects of the radiation belts on satellites remains a major factor in satellite lifetimes. The miniaturization of electronics and the digitization of logic circuits has made satellite instrumentation more susceptible to radiation because the energy deposited by an incoming ion may be as large as the charge representing a binary digit in the circuit. Also, the greater sophistication and efficiency of sensors has resulted in an increased sensitivity to background radiation. The Hubble Space Telescope, a major space science instrument launched in 1990, routinely has some of its sensors turned off during passage through the most intense radiation regions.

## Implications for astrophysics

It is now recognized that energetic ions and electrons are a ubiquitous feature of nature, occurring wherever large-scale, fluctuating magnetic fields exist in the presence of ions and electrons. The outer planets of the solar system have radiation belts analogous to that of the Earth but with some distinctions characteristic of each planet. The Sun, whose magnetic field geometry does not support long-term, stably trapped radiation belts, nevertheless produces high-energy ions and electrons. These particles, which are accelerated by rapidly changing magnetic fields in solar active regions may reach several BeV in energy for ions and several MeV for electrons. The magnetic field configurations near active regions on the Sun probably contain these particles for several minutes, and the extended solar magnetic field throughout the solar system can hold such particles for many hours. In addition, the magnetic structures that originate on the Sun and extend through interplanetary space also accelerate ions and electrons to several MeV. Although the geometries involved in the acceleration of solar plasma and the creation of planetary radiation belts are dissimilar, some of the fundamental processes are the same. Thus, study of particle acceleration in the near-Earth region has led to improved insight into solar acceleration processes. In turn, studies of solar particles have advanced our knowledge of magnetospheric physics.

On the larger scale of galactic dimensions, energetic charged particles are also of profound importance. Best known are the cosmic rays, very high-energy particles (up to $10^{14}$ MeV) that permeate the galaxy. These particles can be measured directly and their energy and composition are clues to the formation, structure and evolution of the galaxy. Even when such cosmic particles cannot be detected directly, the electromagnetic radiation they produce is often observed. Thus, synchrotron radiation and X-rays from high-energy electrons reveal the presence of spinning neutron stars and even more exotic objects such as quasars and black holes. Again, while phenomena have vastly different scales than the Earth's magnetosphere, the insight obtained by the relatively advanced understanding of Earth's plasma environment has been valuable. For the foreseeable future, solar system plasmas will be the only astrophysical plasma populations in which local measurements can be made. At present, the Earth's plasma is the only region for which comprehensive, long-term data are available. The Earth is also unique in that observations have been made over most of the volume containing the energetic plasma, thereby giving a relatively complete picture of the entire structure, including the all-important boundaries. Thus a thorough understanding of the Earth's radiation belt suggests ideas and concepts which aid astronomers in the interpretation of less complete astrophysical data.

## Status of radiation belt knowledge

Our present knowledge of the Earth's radiation belts has reached an advanced state, having benefited from years of research and a rapidly improving technology for performing the necessary measurements. Virtually all regions of the Earth's magnetosphere have been explored. The various populations of trapped particles have been observed, their compositions and energy spectra measured, and a long history of changes in particle distributions caused by natural variations in the Earth's magnetic and electric fields has been recorded. Many, if not all, of the physical processes have been identified. The motion of individual particles in static magnetic and electric fields is completely understood and is the subject of the first half of this book. In the second half of the book the effects of changes in the large-scale magnetic and electric fields and the resulting diffusion and acceleration of particles is considered. This topic retains some of its mystery in that the time variations of the fields have not been measured sufficiently to support a complete verification of the theoretical formulations. Also, much of the theoretical foundation rests on approximations that are not always valid.

Knowledge of the influence of various types of waves on trapped particles is in a less satisfactory state, although there is no controversy over the general principles by which waves and particles interact. Various approximations have been applied successfully when the wave amplitudes are small. However, these simplifications cannot be used for strong waves. The general case where the waves and particles exchange appreciable energy has not been fully investigated within magnetospheric geometry and is an active area of current research.

In general, our knowledge of radiation belt processes decreases with increasing distance from the Earth. The inner radiation belt region, which was the first region to be explored by spacecraft and which is the most stable of the trapping regions, is rather well mapped and explained. Much of the well-established theory presented in this volume finds its application in the near-Earth radiation regions. As one moves outward through the magnetosphere, the belts become subject to larger variations and exhibit a wider variety of behavior. The regions connected by magnetic field lines to higher latitudes participate in the dumping of particles to sustain the aurora and are supplied with energetic ions drawn from the atmosphere. At the outer boundary of the radiation belts, time variations are large, and the magnetic field is greatly distorted by the solar wind pressure. The radiation belts' populations are fed by solar plasma and depleted by the escape of trapped particles into the magnetosheath. In this outer region much remains to be accomplished, both experimentally and theoretically.

It is generally correct to say that the exploratory phase of radiation belt research is ending, and we are now entering an era of detailed investigation in which theory will be confronted by more comprehensive and precise data. The data most needed now are simultaneous observations made from key locations throughout the magnetosphere. Such measurements will involve multispacecraft observations as well as multi-instrument measurement of particle fluxes, electric and magnetic fields, and the characteristics of waves over a broad frequency range. Only when such data are available and have been explained can one be confident that all the important processes in radiation belt physics have been identified.

## *Problems*

1. Assume that the solar wind has a number density of $5 \times 10^6$ ions and electrons $m^{-3}$ and a velocity of $400\,\mathrm{km\,s^{-1}}$. This moving plasma applies a dynamic pressure of $2\rho v^2$ to the magnetopause, where $\rho$ is the mass density and $v$ is the solar wind speed. This pressure is balanced by a magnetic field pressure of $B^2/2\mu_0$ inside the magnetopause at the subsolar point. What is the value of $B$ at that location?

2. About half the magnetic field just inside the magnetopause originates in the Earth's core and half is produced by currents along the magnetopause. If the core field at the subsolar point is given by $B_{\mathrm{eq}} = 3 \times 10^{-5}(\mathrm{R_E}/r)^3 T$, where $\mathrm{R_E}$ is the radius of the Earth and $r$ is the distance from the Earth's center to the point in question, what will be the distance from the center of the Earth to the subsolar magnetopause?

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3. The most energetic cosmic ray particles have energies of about $10^{14}$ MeV. This energy is equivalent to that of a $10^{-2}$ kg marble dropped from what height?

4. The solar constant, the amount of radiant energy striking a 1 $m^2$ surface at the Earth is $1.39 \times 10^3$ J $m^{-2}$ $s^{-1}$. Assuming that all this radiation is absorbed by the atmosphere, land or oceans, what is the total radiant power (in J $s^{-1}$) which the Sun can supply to the Earth. Using the data from problem 1 and assuming the frontal part of the Earth's magnetosphere is a half sphere 15 $R_E$ in radius, what is the total power of the solar wind striking the magnetosphere?