Chapter 1

Introduction

1.1 Preliminaries

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• Student names and background

• Encourage participation, criticism, and suggestions

• Scope of the course and contents (see handout or web page)
  – Magnetospheric physics as a laboratory for complex plasma physics
  – Very simple basic configuration: Earth’s dipole with solar wind and ionospheric boundary conditions
  – Magnetospheric boundaries
  – Geomagnetic tail
  – Coupling to the ionosphere
  – Magnetic and electric fields, plasma physics of boundaries, coupling to a partially conducting boundary

• Conduct (see handout or web page)
  – Textbooks, some lecture notes on the web, but emphasis on lecture notes
– Homework: analytical with some numerical (simulation) examples
– A project will be part of the class
– Grading
– Midterm test and final exam

• Questions

1.2 History of the Earth’s magnetosphere

Figure 1.1: Woodcut of Aurora (Fridjof Nansen).

Aurora: Most easily observed effects of magnetospheric processes manifest themselves in the Aurora. Early historic notes:

• Aurora known from ancient times (documents from China and Greece).
• Name Aurora (roman goddess) introduced by Galileo Galilei (1564-1642).
• Many myths and mysteries around Aurora.
• Aurora is known to be located at great heights because it appears the same from very different locations (Pierre Gassendi - French mathematician, 1592-1655).
• Rene Descartes (french philosopher and mathematician, 1596-1650) speculates that it is caused by ice crystals.
Galilei hypothesizes that Aurora is air rising into the sunlight

De Mairan (French philosopher and geophysicist, ~1731) hypothesizes a connection of the Aurora to sunspots.

**Magnetic field:** The Earth’s magnetic field is the cause for the magnetospheric cavity. The compass to measure magnetic fields is known early in China (Shan Kan, 1030-1093) and later also in Europe (Alexander Neekan, 1157-1217). Historical progress of field measurements [Russell, 1995]:

- Declination (difference between magnetic and geographic north), 1540.
- Inclination, 1576.
- Dipole field character + Terrela (William Gilbert, chief physician to Queen Elizabeth), 1600.
- Temporal changes in declination (Henri Gellibrand, astronomer), 1635.
- Theory and accurate measurements of the magnetic field by Halley, 1698, 1700.
- Magnetic Perturbations (activity) by George Graham (clockmaker), 1722.
- Diurnal variations detected (Hiorter, astronomer Sweden), 1740.

**Observations converge:**

- Correlation between magnetic and auroral activity (Hiorter), 1741.
- Auroral rays extend along magnetic field lines (Wilcke), 1770.
- Aurora Australis (southern hemispheric Aurora, captain James Cook), 1770
- Auroral altitude 52 to 71 miles (Henry Cavendish, british philosopher and scientist), 1790.
- Network of magnetic observatories (Johann Carl Friedrich Gauss), 1800’s.
- Correlation between sunspot cycle (sunspots known since 1600’s) and auroral activity (Edward Sabine, astronomer and explorer), 1851.

**Moving into a new science:**

September 1, 1859: Richard Carrington observed a great flare (duration of only a minute) and almost at the same time magnetic perturbations are recorded. 18 hours later one of the largest magnetic storms ever recorded developed. The immediate response (we now know) is caused by the increase in UV radiation and a corresponding increase in ionospheric conductance. The delay of 18 hours imply that the information of the large flare traveled with approximately 2300 km/s toward Earth. Abrupt changes indicate a rather thin discontinuity in the medium which carries the signal of the flare. Further key developments:

- 1878: Becquerel and Goldstein suggest that particles shoot from the sun and are guided by the Earth’s magnetic field.
- Sir William Cooke finds that cathode rays are bent by magnetic fields.
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Figure 1.2: Sketch of the interaction of the magnetosphere with and infinitely conducting solar wind (Chapman and Bartels, 1940).

- 1882 Balfour Stewart concludes that the upper atmosphere is most likely a location of electric currents that produce the solar controlled variation of the magnetic field on the surface of the Earth.

- 1902 Kristian Birkeland concludes that large magnetic field-aligned currents must be present in the Aurora.
  - Birkeland (1867-1917): general expression for Poynting flux (1895) still used; first general solution of Maxwell’s equations; experiments with cathode rays->suggestion for auroral model due to energetic particle ejected from sunspots and guided by the magnetic field; Terrella experiments to prove his theory; theoretical solution of charged particle motion in a unipolar magnetic field (with Poincare); first auroral observatories (1899); categorizes magnetic perturbations (first finding of geomagnetic storms and auroral substorms); identified ionospheric current as responsible for magnetic perturbations; concludes the presence of field-aligned currents.

- The invention of the camera allows Carl Stormer to measure and triangulate the Aurora precisely. He also calculates the trajectories of charged particles in the Earth’s dipole field.

- Lord Kelvin (1892, president of the royal astronomical society): “that the supposed connection between magnetic storms and sunspots is unreal”

- 1918 Sydney Chapman revives the idea of a singly charged beam of particles from the sun to cause the magnetic disturbances.
  - Chapman (1888-1970): gifted mathematician; theories on geomagnetic disturbances based on (equivalent) currents confined to a spherical shell (1918, 1927) driven by atmospheric motion; attempt to find exact mathematical solutions; views dominated the field from 1925 - 1970; Chapman-Ferraro theory of currents and the compression of the magnetosphere (the first idea of a magnetopause - boundary between the magnetosphere and the ambient medium); hypothesis of a closed magnetosphere and different attempts to explain the solar wind penetration into the magnetosphere.

- Lindeman suggests a beam of particles with both charges (i.e., a neutral beam).

- 1925 Appleton detects the previously expected ionosphere using radio waves.
• 1920-1957 Stormer continues some of Birkeland’s works most noteworthy work on classification of different types of Aurorae and measurement and triangulation of tens of thousand’s of auroral rays.

![Birkeland’s Terrella experiment and pioneers of space physics.](image)

**Figure 1.3:** Birkeland’s Terrella experiment and pioneers of space physics.

Development of space plasma physics:

• 1951 Biermann predicts a continuous solar wind consisting of charged particles.

• 1957 Alfvén suggests that the solar wind particles are magnetized.
  
  – Alfvén: Revival of Birkeland’s idea of field-aligned currents and ongoing controversy with Chapman; development of plasma fluid equations (plasma theory, and various other major contributions); dualism of fields and sources and corresponding controversy.

• 1962 Quantitative theory of the solar wind by Parker.

Solar wind - magnetosphere interaction:

• 1957 Sweet and Parker develop the first theory of magnetic reconnection

• 1961 Dungey applies the theory to the magnetospheric boundary and suggest the concept of an open magnetosphere.

• 1963 Petschek develops the first theory of fast magnetic reconnection.

• 1961/62 Furth, Killeen, and Rosenbluth develop the theory of tearing modes

• 1960 Axford and Hines suggest viscous solar wind - magnetosphere interaction.

• 1964 Description and theory of the auroral substorm by Akasofu.
1.3 Structure of the Magnetosphere

The magnetosphere is a large plasma cavity generated by the Earth’s magnetic field and the solar wind plasma. The streaming solar wind compresses the dayside portion of the Earth’s field and generates a tail which is many hundreds of Earth radii ($R_E = 6370$ km) long. The basic mechanism for the formation of the magnetosphere is extremely simple, i.e., it is a magnetic dipole exposed to a stream of charged particles. The entire magnetosphere is subject to only two boundary conditions, explicitly the boundary between the magnetosphere on the streaming solar wind and the boundary of the plasma in the ionosphere. The basic elements of the magnetosphere are

- **The Bow Shock and the Magnetosheath**
  
  While not part of the magnetosphere proper the magnetosheath is an outer layer embedding the magnetosphere. The solar wind plasma travels usually at super-fast speeds relative to the magnetosphere. Therefore a standing shock wave forms around the magnetosphere just as in front of an aircraft traveling at supersonic speeds. The bow shock is the shock in front of the magnetosphere and the magnetosheath is the shocked solar wind plasma. Therefore it is not directly the solar wind plasma which constitutes the boundary of the magnetosphere but the strongly heated and compressed plasma behind the bow shock. The region is rich in various wave phenomena, boundaries and shocks are often treated as discontinuities.

- **The Magnetopause**
  
  The magnetopause is the actual boundary between the shocked solar wind and the magnetospheric plasma. However, the magnetosphere is not closed in terms of the magnetic field but there is considerable magnetic flux crossing the magnetopause. Thus it is not easy to define this boundary precisely. Also the boundary does permit a certain amount of solar wind plasma entry. This entry is easier along magnetic field lines. The magnetopause is an highly important region because the physical processes at this boundary control the entry of plasma, momentum, energy and the redistribution of geomagnetic flux. Essential
instabilities are reconnection (tearing modes) and Kelvin Helmholtz modes in addition to various micro-instabilities.

- **Cusp and Mantle**

  - The cusp and mantle regions are directly adjacent and inward of the magnetopause. The cusp is the region where dipolar field lines converge and in a two-dimensional case represents a field line which goes into a singularity with $B = 0$. The mantle region represents a boundary to the magnetotail usually filled with solar wind plasma but with a stretched magnetospheric magnetic field. The role of the cusps is not fully understood but it is a region where highly energetic particle can be produced and it is very active in terms of turbulence and wave energy because the boundary field lines converge in the cusp and all waves which travel along the magnetic field are channeled into this region.

- **The Quiet Magnetotail**

  - The magnetotail is the long tail-like extension of the magnetosphere on anti-sunward side of the magnetosphere. Since the magnetic field points toward the Earth in the northern lobe and away in the southern lobe there is a current in the westward direction. Because of its structure there is considerable energy stored in the magnetic field in the magnetotail. During magnetically quiet times convection is typically low and energy in the plasma flow is only a tiny fraction of the overall energy density.

- **The inner Magnetosphere**
The inner magnetosphere is different from most of the magnetosphere in that the magnetic field is mostly dipolar and perturbations of the field are small compared to the average dipole field. However, there can still be large amounts of energy stored in this region in particular during so-called storm times. During such times the ring current (current due to gradient curvature drifts of charged particles) intensifies strongly and is responsible for strong magnetic perturbations at low geomagnetic latitudes on the Earth.

- **Magnetosphere - Ionosphere Coupling**

  - The ionosphere is the region where the atmosphere is partially ionized and plasma and neutrals strongly interact. This interaction exerts a drag on the plasma. The plasma density can be very high but also strongly variable such that the ionospheric conductance can vary by orders of magnitude. Magnetospheric plasma motion is transmitted into the ionosphere and forces ionospheric convection. This also implies the existence of strong currents along magnetic field lines which close through the ionosphere. In particular at high latitudes these currents lead to magnetic perturbations during times of strong magnetospheric activity (fast convection and changes of the magnetospheric configuration).

**Magnetospheric Activity**

There are two basic types of geomagnetic activity:

- Magnetic storms
- Magnetospheric substorms

This terminology is misleading in that substorms are not small storms. Rather a storm can consist of several substorms but also of quiet periods. A storm is a large and long duration perturbation of the magnetosphere which leads to a strong compression and a contraction of the magnetosphere. Characteristic is a strong amplification of the ring current and the associated magnetic field measured at equatorial latitudes. Aurora is typically visible at much lower latitudes. Storms are associated with larger solar flares and/or coronal mass ejections and storm durations are many hours.

A substorm is characterized by a specific large scale auroral intensifications and corresponding magnetic perturbations at high latitudes typically close to magnetic midnight. Characteristic are also fast flows in the magnetotail, plasma ejection in the tailward direction, release of energy stored in the lobe magnetic field, energetic particle injections at geosynchronous distances, and strong intensifications of field-aligned current systems. A substorm consists of the growth phase, the (auroral) expansion phase, and the recovery phase. Substorms are clearly related to periods of southward interplanetary magnetic field (IMF) which leads to reconnection on the dayside, transport of magnetic flux from the dayside to the tail, and storage of magnetic energy in the tail during the growth phase. There is a rapid release of magnetic energy which is partly deposited in the the ionosphere through Joule heating and precipitation and in part ejected tailward through so-called plasmoids.

**Giant Magnetospheres:**

Typical examples are the magnetospheres of Jupiter and Saturn. The main differences to Earth’s and similar/smaller sized magnetospheres are:

- Size
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Figure 1.6: Sketch of the magnetic field and different region of a giant magnetosphere. Red arrows represent convection and blue lines indication the magnetic field.

- Internal mass and plasma source (Jupiter and Saturn ~ 100 to 500 kg/s)
- Fast rotation

Here size is important because the typical time it takes for the solar wind to stream past the dayside magnetosphere is 30 minutes to 5 hours. This is important because the correlation time of solar wind properties is 20 to 30 minutes. The internal mass source in giant magnetospheres necessitates a dominant outward transport of plasma. This is opposite to Earth’s magnetosphere where the dominant source of plasma is the solar wind implying a balance between in- and outward transport of plasma. The mass source is provided by satellites of the planets and also causes auroral spots associated with the processes of plasma acceleration in the vicinity of these satellites. Although there are several proposed mechanisms (reconnection must play an important role) the physics of the outward plasma transport is not well understood. This is in part because of the rapid rotation of the giant magnetospheres. In all magnetospheres the inner part is corotating with the planet. The giant magnetosphere have a middle magnetosphere where the magnetic field is significantly stretched similar to the magnetotail magnetic field in the terrestrial magnetosphere. In this magnetodisc region, convection is still fast but can significantly deviate from corotation. In this fast rotating disc inertial forces are important. Outside of the disc region and in the dayside magnetosphere can be a so-called cushion region with a strong magnetic field in the equatorial plane (typical for Jupiter but only sometimes observed for Saturn). On the nightside the magnetodisc transitions into the magnetotail. The giant magnetosphere show significant auroral activity at all times which further intensifies for strong changes of the solar wind dynamic pressure.
1.4 Coordinate Systems

1.4.1 Geographic Coordinates (GEO)

These are the most common coordinates in use and usual are measured in geographic latitude and longitude. The coordinate axes have the following orientation.

- x in equatorial plane through the Greenwich meridian.
- z rotation axis.
- y completes coordinate system.

![Illustrations of GEI and GSE coordinates](image)

Figure 1.7: Illustrations of GEI and GSE coordinates.

1.4.2 Geocentric Equatorial Inertial (GEI) Coordinates:

For astronomical use a coordinate system is desirable which maintain (mostly) stellar coordinates such that it should not rotate with the Earth and it should not change orientation with the Earth’s orbit around the sun.

- x intersection of the equatorial and the ecliptic planes toward the sun at spring equinox (First point of Aries).
- z parallel to the rotation axis of the Earth.
- y completes coordinate system.

1.4.3 Geocentric Solar Ecliptic (GSE)

To measure effects of solar origin such as radiation or impinging solar wind it is useful to choose a coordinate system with an axis pointing toward the sun:

- x toward the sun.
- z perpendicular to the ecliptic plane.
- y in the ecliptic plane perpendicular to x.
1.4.4 Geomagnetic Coordinates (MAG)

A coordinate system which uses the magnetic dipole as a reference is useful for all research that depends on the terrestrial magnetic field and a corresponding coordinate system makes it much easier to model corresponding effects:

- z parallel to the magnetic dipole axis.
- x in the dipole equatorial plane pointing toward geographic North Pole.
- y in the dipole equatorial plane perpendicular to x.

The magnetic dipole axis shifts as the magnetic north and south poles drift (currently with velocities of 50 km/year for the north and 10 km/year for the south pole).

1.4.5 Geocentric Solar Magnetic (GSM)

Physical processes which are related to the interaction of solar effects and the terrestrial magnetic field are most easily described and understood in a system which uses both, the Earth magnetic field orientation and the sun as references.

- x toward the sun.
- z in the plane determined by x and the magnetic North Pole pointing toward the North Pole.
- y in the magnetic equator perpendicular to z.