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# PLASMA PHYSICS GROUP

UNIVERSITY OF CALIFORNIA
LOS ANGELES

ENGINEERING

PHYSICS

METEOROLOGY

# THE EARTH'S MAGNETOSPHERE

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## I. General Structure

The magnetosphere is formed by the interaction of the earth's magnetic field and the solar wind, which is the supersonic, super-Alfvénic, and magnetized plasma expansion of the solar corona. The geomagnetic field presents a blunt obstacle to the solar wind so that a hydromagnetic bow shock forms to divert the flow around the magnetosphere. The location of the magnetopause, which separates the solar wind and magnetosphere, is determined by balancing the solar wind dynamic pressure with the magnetic pressure $B_M^2/2\mu_o$ of the magnetospheric field $\underline{B}_M$. The various magnetospheric boundaries and regions are depicted in Figure I; spatial scales are listed in Table I, and typical thermal plasma parameters are given in Table II. We will now discuss several dynamical processes which determine the basic magnetospheric structure.

## II. Magnetic Field Merging and Magnetospheric Convection

The magnetosphere is a driven hydromagnetic system whose internal dynamics are controlled by the input solar wind energy through magnetic field merging As the post-shock magnetosheath solar wind impacts the dayside magnetopause, the solar wind magnetic field $\underline{B}_{sw}$ comes into contact with $\underline{B}_M$. Unless $\underline{B}_{sw}$ is parallel to $\underline{B}_M$, the two fields can merge by resistive diffusion at a magnetic neutral line so that $\underline{B}_M$ becomes connected to $\underline{B}_{sw}$ (Figure II); clearly a large southward component of $\underline{B}_{sw}$ maximizes the merging interaction.

In hydromagnetics the magnetic field moves with the plasma so that the Lorentz force $\underline{E} + \underline{v} \times \underline{B} = 0$ in the laboratory frame. The solar wind flow around the magnetosphere stretches the merged field lines into a long magnetic tail of open flux behind the earth. About $3 \times 10^{15}$ Joules of solar wind flow energy is stored as magnetic energy in the tail. In steady state the motional electric field $\underline{E} = -\underline{v} \times \underline{B}$ (out of page in Figure II) appears throughout the magnetosphere and corresponds to a potential drop of 50 - 200 KV across the system. In the tail the open field lines flow toward the plane of symmetry, where they reconnect at the tail neutral line. The reconnected, but stretched, field lines accelerate the plasma back toward the earth's nightside thus injecting plasma into the inner magnetosphere. As the flow penetrates the dipole region it decelerates and the plasma is heated by adiabatic compression. The field lines then flow around the earth and return to the dayside magnetopause, thus completing the internal hydromagnetic convection or circulation system. Typical circulation times are 1 - 3 hours.

Not all of the earth's field lines participate in the convection system. Near the earth the field lines are forced to corotate by the ionosphere and do not generally become open to the solar wind. These plasmaspheric field lines fill with cool, dense plasma which diffuses upward from the ionosphere. The plasmapause separates the corotating and convecting field lines.

## III. Time-Varying Convection and Magnetospheric Substorms

In steady state the dayside merging rate equals the tail reconnection rate. However $\underline{B}_{sw}$ is rarely steady in direction. When $\underline{B}_{sw}$ has zero southward or a northward component for several hours, the magnetosphere is relatively quiet and convection is slow. Occasionally $\underline{B}_{sw}$ shifts and stays strongly southward for about an hour The enhanced dayside merging rate produces a transient change in the convection state and structure of the magnetosphere which culminates in the magnetosphere's most striking phenomenon--the magnetospheric substorm.

For about 10 - 60 minutes following the southward shift the dayside merging rate exceeds the tail reconnection rate, and the tail magnetic energy increases. Eventually tail reconnection must increase to balance the dayside merging rate. Recent observations indicate that tail reconnection onsets explosively with the formation of a new neutral line 10 - 20 $R_E$ behind the earth. Reconnection probably begins when the plasma sheet has thinned (due to plasma losses) to the critical thickness for the excitation of some mode of plasma turbulence which increases the tail dissipation rate. During reconnection a small fraction of the plasma sheet electrons and ions are accelerated to energies of 0.1 - 1.0 MeV.

On the ground tail reconnection onset corresponds to the breakup or expansion phase of the auroral substorm. The aurorae, which are recombination radiation caused by the precipitation of 1 - 10 keV electrons, brighten and then expand poleward and westward. In the nightside ionosphere an electrojet current of about $10^6$ Amps flows between 100 and 120 km altitude causing a negative depression or bay in the geomagnetic field. The expansion phase lasts 0.5 - 1.0 hours and may have a total energy dissipation rate exceeding $10^{11} - 10^{12}$ Watts.

During recovery phase, the aurorae move equatorward and become faint as the electron precipitation fluxes decrease. In the tail the neutral line either disappears or moves rapidly tailward to very large distances. Athough substorms occur at irregular intervals, a typical moderately disturbed period has 4 to 8 substorms per day.

Of all substorm phenomena, the aurorae remain the least understood. The precipitation of the inward convecting plasma sheet electrons produces a diffuse and relatively unstructured auroral luminosity between 60° - 70° geomagnetic latitudes. The precipitation is caused by a complex spectrum of electromagnetic and electrostatic plasma wave turbulence which is excited by convection-induced anisotropies in the electron distribution.

The discrete auroral arcs occur near the poleward boundary of auroral activity. The arcs are typically 1 - 20 km in north-south extent and $3 - 5 \times 10^3$ km in east-west extent. Strong magnetic field-aligned currents flow within the arc in a co-axial configuration with about 10 - 50% of the upward current carried by the precipitating electrons. These electrons have a highly nonthermal distribution often in the form of a 1 - 10 keV field-aligned beam with an energy flux of $10^{-1} - 10^{-2}$ Watts/m$^2$. The beam probably results from acceleration in a field-aligned electric field, but the spatial location and dynamics of the acceleration region are unknown. By an undetermined plasma instability process, the auroral beams radiate electromagnetic waves with frequencies of $10^2 - 10^3$ kHz. The total radiated power is $10^8 - 10^9$ Watts or roughly 0.1 - 1.0% of the total substorm power. As a radio source the earth puts out a power which is comparable to the Jovian Io-modulated decametric radiation.

## IV. Magnetic Storms

A large solar flare produces a major perturbation in the solar wind which may double the wind velocity and raise $\underline{B}_{sw}$ and the density by a factor of 5. During the disturbance $\underline{B}_{sw}$ often remains southward for 8 - 12 hours; the enhanced internal convection and energy input results in a magnetic storm. The increased solar wind dynamic pressure moves the magnetopause inward to 5 - 6 $R_E$. During the storm main phase large fluxes of 20 - 50 keV protons, singly ionized oxygen, and possibly helium ions are injected deep within the radiation belts and form a westward ring current which produces a world-wide depression in the geomagnetic field. Convection is so strong that the plasmapause may move to within 2 $R_E$. The storm recovery phase begins when $\underline{B}_{sw}$ shifts northward and convection slows. The ring current ions decay by charge exchange with the neutral hydrogen geocorona over a period of 1 - 2 days. The storm dissipates a total energy of $10^{16}$ Joules.

## V. Comparative Magnetospheres

The earth's magnetosphere serves as the prototype for investigating the hydromagnetic and plasma turbulent interaction of a compact, magnetized object in an external plasma wind. Within the solar system, magnetospheres of various types exist at Mercury, Venus, Mars, and Jupiter. The recent discovery of nonthermal radio emissions from Saturn and Uranus also indicates magnetospheres around these planets. In astrophysics, magnetospheric concepts have been applied to pulsars, compact x-ray sources, black holes, and radio galaxies. Magnetospheric physics is thus entering a new phase--the study of comparative magnetospheres.

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# TABLE I

Location of Boundaries and Scale Size of Regions [in earth radii $1.0\ R_E = 6.378 \times 10^6$ m]

| | | Location | Spatial Extent |
|---|---|---|---|
| 1. | Bow Shock | 13 - 17 | |
| 2. | Magnetosheath | | 3 - 5 thick |
| 3. | Magnetopause | 10 - 12 (dayside) | |
| 4. | Magnetotail Boundary Layer | | 1 - 3 thick |
| 5. | Magnetotail | | ∿30 - 40 wide, ∿1000 long |
| 6. | Plasma sheet | | 2 - 4 thick |
| 7. | Plasmasphere | 4 - 6 (dusk),<br>2 - 3.5 (dawn) | |

TABLE II

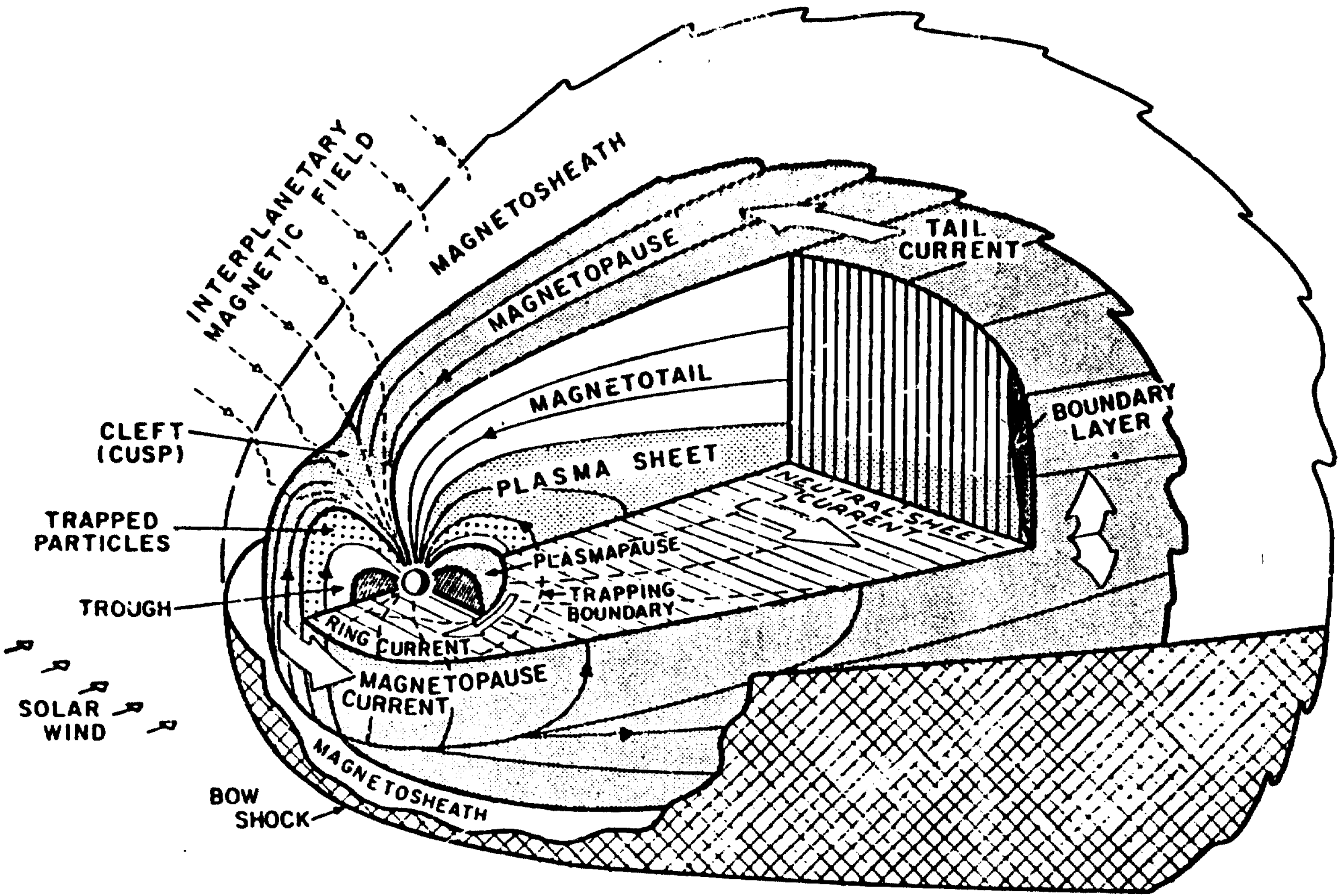
Thermal Plasma Properties

| Region | Density $[cm^{-3}]$ | Electron Temperature [ev] | Ion Temperature [ev] | Magnetic Field $[10^{-5}$ Gauss] | Flow Speed [km/sec] |
|---|---|---|---|---|---|
| 1. Solar Wind | 5 - 20 | 20 - 40 | 10 - 20 | 5 - 15 | 350 - 1000 |
| 2. Magnetosheath | 20 - 40 | 100 - 200 | ~1000 | 20 - 40 | 100 - 200 |
| 3. Magnetotail Boundary Layer | 0.01 - 0.1 | 10 - 50 | | 10 - 30 | 200 |
| 4. Plasma Sheet | 0.1 - 1.0 | 200 - 2000 | 500 - 5000 | 10 - 20 | 0 - 1000 |
| 5. Ring Current | 5 - 20 | ~1000 | $(10 - 50) \times 10^3$ | 100 - 500 | 10 |
| 6. Plasmasphere | 100 - 1000 | ~1.0 | ~1.0 | >100 | <1.0 |
| 7. Ionosphere | $10^4 - 10^6$ | 0.1 - 0.2 | 0.1 - 0.2 | 0.3 - 0.6 | <1.0 |

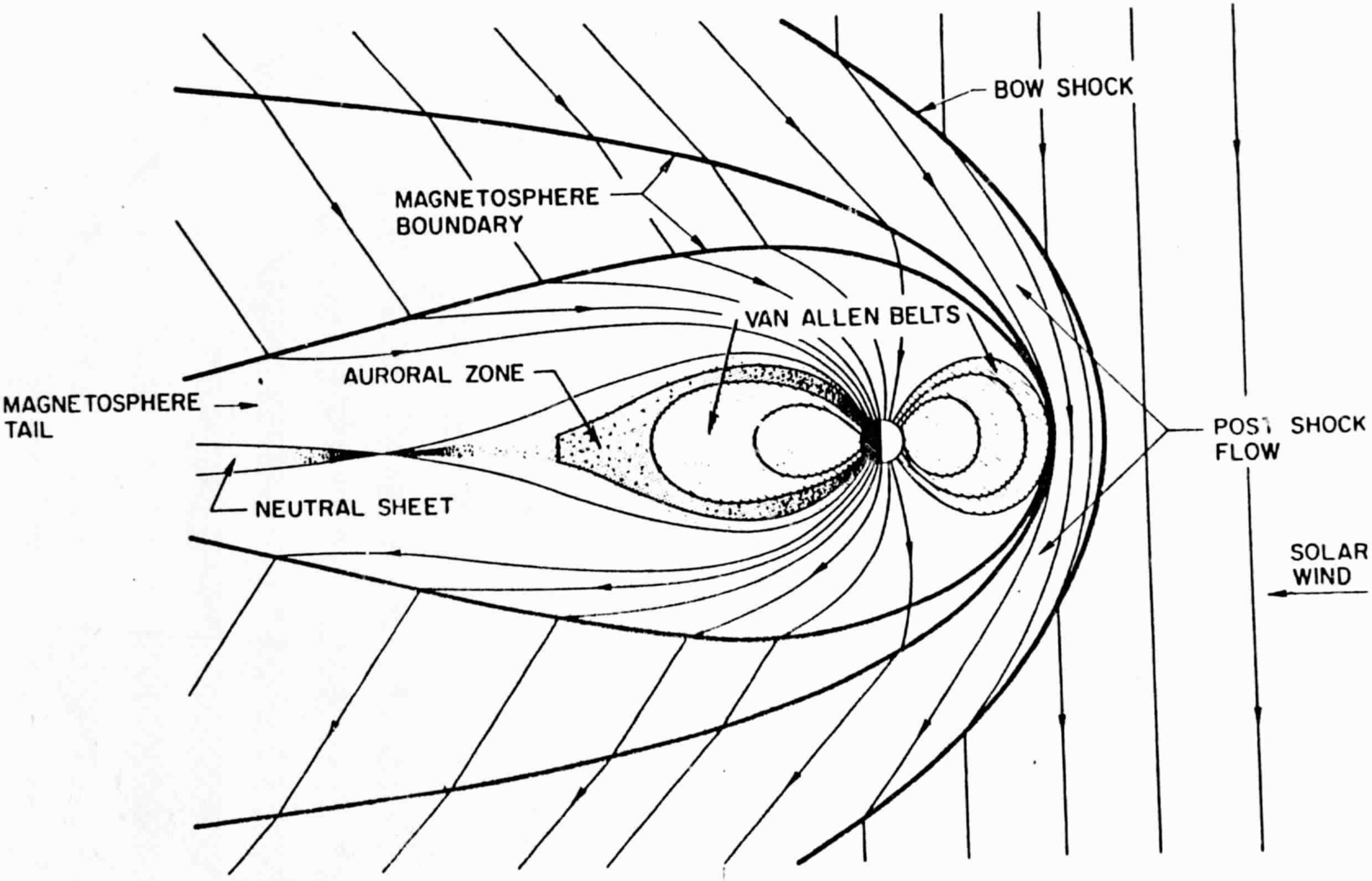
# Figure Captions

**Figure I.** A three-dimensional view of the magnetosphere drawn by W.J. Heikkila, University of Texas. The magnetopause current provides the $\underline{J} \times \underline{B}_M$ force which holds off the solar wind dynamic pressure. The polar cleft is an opening in the geomagnetic field which permits the direct penetration of magnetosheath plasma onto the ionosphere; this plasma precipitation produces the dayside aurorae. The tail boundary layer, which is now known to encircle the tail, is a region of anti-sunward plasma flow on recently merged field lines. The tail magnetopause current closes through the plasma sheet and produces the extended tail magnetic field. The trapping boundary denotes the outermost extension of the Van Allen radiation belt of trapped particles, i.e., particles which execute complete drift orbits around the earth. The trough is a region of very low plasma density.

**Figure II.** The topology of the interconnected solar wind and magnetospheric magnetic fields drawn for the optimum merging configuration of a southward solar wind field. After dayside merging the solar wind flow drags the field lines into the tail while the foot of the field in the ionosphere flows anti-sunward across the polar cap. In the tail field lines flow toward the neutral sheet and reconnect. Reconnected or plasma sheet field lines flow toward the earth and connect to the nightside auroral zone ionosphere. The field lines flow around the earth and back to the dayside magnetopause.


INTERPLANETARY MAGNETIC FIELD
MAGNETOSHEATH
MAGNETOPAUSE
TAIL CURRENT
MAGNETOTAIL
BOUNDARY LAYER
CLEFT (CUSP)
PLASMA SHEET
NEUTRAL SHEET CURRENT
TRAPPED PARTICLES
PLASMAPAUSE
TRAPPING BOUNDARY
TROUGH
RING CURRENT
MAGNETOPAUSE CURRENT
SOLAR WIND
MAGNETOSHEATH
BOW SHOCK

MAGNETOSPHERE



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