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The Solar-Wind-Magnetosphere-Ionosphere System: An Overview

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THE SOLAR WIND-MAGNETOSPHERE-IONOSPHERE SYSTEM: AN OVERVIEW

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The upper atmosphere at high geomagnetic latitudes is an active component of the solar-terrestrial system. This system, comprising a chain of several distinct plasma regions, features two important characteristics: (1) As one proceeds from the main particle, energy and momentum source on the sun through the solar wind, the magnetosheath, magnetosphere and ionosphere to the sinks in the neutral atmosphere, one observes an increasingly important feedback coupling between adjacent regions; (2) The time scales of response to perturbations originating on the sun are increasingly determined by the properties of the local medium in each region. Being the last link in the solar-terrestrial chain, the upper atmosphere exerts an important feedback effect on the preceding region, the magnetosphere; this in turn influences the form and rate of solar energy delivery to the upper atmosphere. The magnetosphere thus plays an important role as a non-linear transducer of solar energy. For a general review of the solar-terrestrial system see Parker et al. (1979).

Figure 1 depicts in schematic form three main channels of energy flow from the sun to the earth. The main power delivery to the atmosphere occurs via the practically constant solar blackbody radiation absorbed on the earth's surface and in the troposphere. Of the variable components of solar emissions, the solar wind exerts the principal control on the magnetosphere, the ionosphere and the upper atmosphere. This control depends on several solar wind parameters which regulate the efficiency of energy and momentum transfer to the magnetosphere. The quantitative under-

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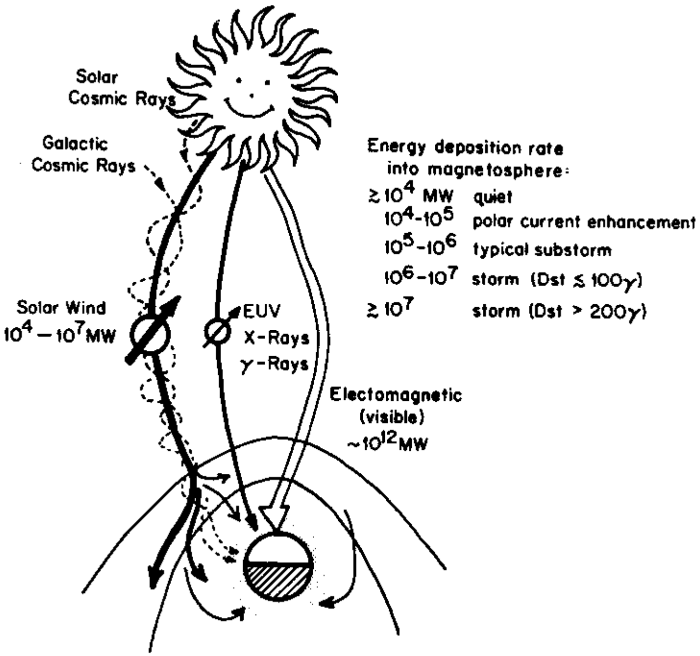

Figure 1. The three main channels of energy flow from the sun to the earth and the range of power transfer and corresponding magnetospheric response.

standing of the physical mechanisms responsible for this transfer is one of the most important current goals of solar-terrestrial physics. The table in Figure 1 indicates typical ranges of solar wind power transfer and related magnetospheric responses.

The interplanetary magnetic field (IMF) embedded in the solar wind modulates galactic cosmic rays and guides, traps and modulates energetic particles emitted by solar flares. Since these particles affect the ionization in the stratosphere and mesosphere, the solar wind thus exerts yet another, indirect kind of influence on the terrestrial upper atmosphere. The channel marked EUV and X-rays in Figure 1 represents sporadic electromagnetic emissions from active centers on the sun that also affect the ionization in the upper atmosphere.

In this chapter we are concerned with the key mechanisms operating in the terrestrial magnetosphere (for general and specific references, see for instance Parker et al. op. cit. Vols. 2 and 3.)

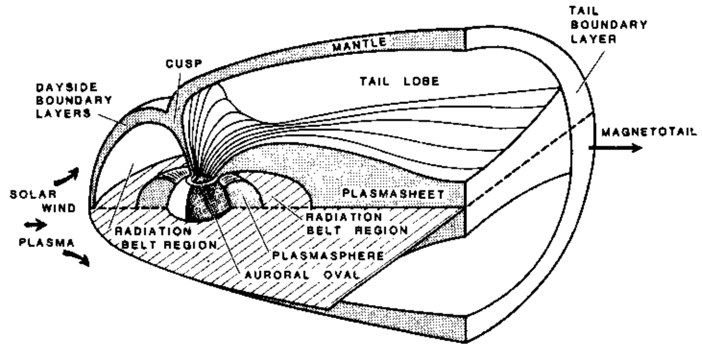

Figure 2. A sketch of fundamental plasma regions in the magnetosphere.

Figure 2 shows the principal magnetospheric plasma regions and how they are connected via magnetic field lines with the upper atmosphere. The same regions are displayed in Figure 3 in a matrix representation. Rows represent principal spatial domains; columns represent regions of specific magnetic field topology or morphology. This field configuration determines charged particle behavior (from left to right: field-aligned streaming, convection, transient trapping, stable trapping). It should be noted that cusp field lines probably are closed on the equatorward portion and open on the poleward side of the cusp. In the rows, resistivity is a distinctive parameter (zero in the plasma regions at the top; perhaps finite in the $E_{\parallel}$ region; finite in the bottom row).

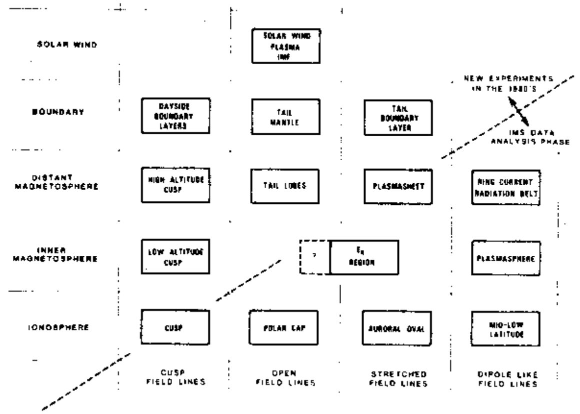

Figure 3. Plasma regions, spatial domains and magnetic field morphology, in matrix form.

A diagonal line from the lower left corner to the upper right side separates the matrix of Figure 3 into two parts: (1) the lower right portion will probably be understood fairly well when the IMS Data Analysis Phase is concluded (Roederer 1977): (2) the upper left portion will be in the focus of future experimental research. More specifically, the main goals of magnetospheric research in the eighties will be to achieve a quantitative understanding of how the regions in the upper left portion of Figure 3 interact and how particles and plasma waves are transferred from one to another (National Academy of Sciences 1980).

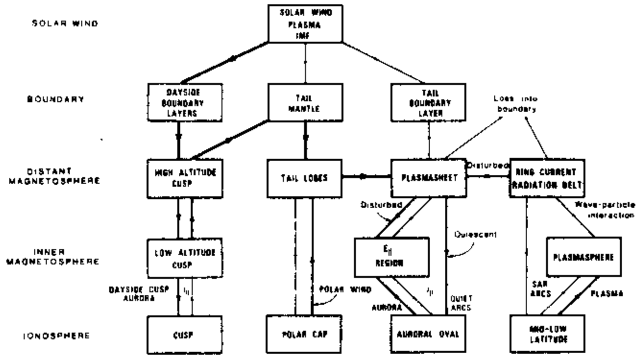

Figure 4. Magnetospheric particle transport routes.

Figure 4 shows the main particle transport routes in the magnetosphere, according to current (not necessarily universally accepted) thinking. The heavy lines represent what may be the principal entry route from the solar wind to the main magnetospheric plasma reservoir, the plasmasheet. Note the role of the entry layer and the high and low altitude cusp regions in these initial stages of particle transport. Figure 5 schematically illustrates this role. The entry layer consists of field-aligned streaming of plasma of density and temperature nearly the same as in the magnetosheath, but with reduced and irregular flow speed. Both the thickness of this layer and the plasma content increase gradually from zero at the subsolar point to the cusp latitude (about 78^{o}). The cusp or cleft is a longitudinally elongated region of intense low-energy charged particle fluxes, composed of entry layer plasma that is approaching the earth's ionosphere; of return streaming of these particles after they have mirrored or have been backscattered; and of upward streaming particles of ionospheric origin. The magnetopause exhibits a clear indentation in this area with interesting vortex signatures in the magnetoshea flow. It is now believed that localized "patchy" magnetic field reconnection events in the region of the indentation play an important role in particle access to the magnetosphere. The high-latitude large-scale electric field, generally directed from dawn-to-dusk in the vicinity of the noon meridian, imposes a tailward drift on the down-streaming entry layer particles. Although an independent particle description may seem rather unrealistic under cleft conditions, it does explain qualitatively many observed features: the softening of proton spectra when the cleft is traversed in poleward direction; the flow and temperature profile of incoming particles that mirror and then "expand" along the open field line into the mantle (Figure 5); and the observed correlation of mantle thickness with the southward component of the IMF.

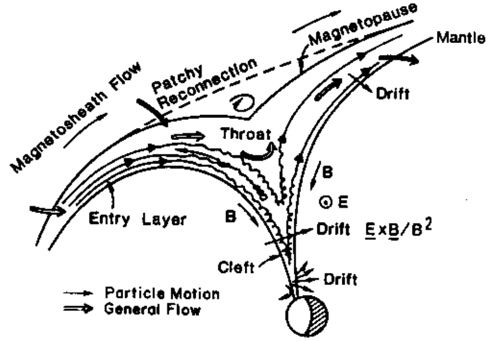

Figure 5. Sketch of particle motion and plasma flow into and out of the cleft region (not to scale).

Little is known about the specific transfer routes of solar wind plasma into the plasmasheet (Figure 4); the convection electric field is believed to be responsible for a general drift of streaming mantle plasma toward the center of the tail where particles are transiently captured to form the plasmasheet and, therein, the cross-tail current sheet.

During magnetospheric substorms, plasma is convected from the plasmasheet earthwards and betatron accelerated, feeding into the ring current, which is the most important energy reservoir of the magnetosphere. Further acceleration via radial diffusion feeds particles into the Van Allen radiation belts. During substorm events, a certain fraction of plasmasheet electrons is accelerated along the magnetic field by a transient parallel electric field; this process is responsible for the formation of substorm-associated auroral arcs.

Figure 4 also shows the main routes of particle transport from the ionosphere to the magnetosphere. The plasmasphere is a reservoir of ionospheric plasma corotating with the earth. The polar wind and upward acceleration of ionospheric ions by the $E_{\parallel}$

field during substorms represent the main particle routes linking the ionosphere with the plasmasheet.

Particle transport in the magnetosphere-ionosphere system is actually governed by electromagnetic coupling between the constituent plasma regions. This coupling is depicted schematically in Figure 6. We should point out five principal chains of electromagnetic linkage: (1) the "vertical" chain from the solar wind to the polar cap (and cusp); (2) the "horizontal" links between the ionospheric regions; (3) the "closed" chain involving the tail lobes, polar cap, auroral oval and plasmasheet; (4) the transient links between the plasmasheet and the ring current and $E_{\parallel}$ regions, respectively; (5) the link between the ionosphere and the plasmasphere. There are also indications of a link between the solar wind and the magnetosphere via the low-latitude boundary layer.

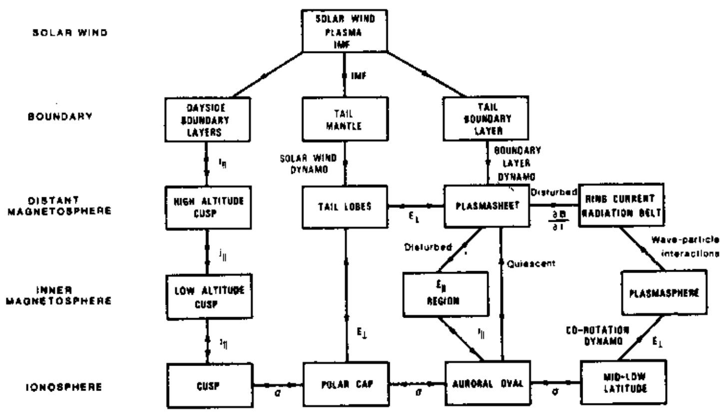

Figure 6. Principal electrical couplings.

A simple-minded first order description of chain (1) invokes the mapping of the $-\underline{V}\times\underline{B}$ electric field in the solar wind along the (equipotential) open field lines onto the polar cap ionosphere. This yields a convection electric field whose geometry is strongly dependent on the interplanetary magnetic field and the topology of its interconnection with the terrestrial field, but which bears some invariant features such as general direction from dawn to dusk for a wide range of interplanetary field configurations (except due northward IMF). Once the electric field is impressed on the open field lines of the polar cap, the distribution of ionospheric conductivity determines the electrostatic field in the remaining portion of the ionosphere (chain 2). Although this simple-minded picture of the solar wind acting as a "voltage source" of magnetospheric behavior yields some quantitative

predictions in fairly good agreement with observations, a full quantitative understanding of the electrodynamic coupling between the solar wind, the magnetosphere and the ionosphere, requires a self-consistent solution of the closed system of interacting plasmas represented by the above mentioned chain (3), shown in Figure 6.

An important feature of electrodynamic coupling in the magnetosphere is the system of field-aligned currents (Birkeland currents) that appears in connection with the relevant dynamo processes. Consider a blob of plasma (Figure 7) under the action of an external force $\underline{F}$ (assumed applied with uniform force density). This force causes electrons and ions to drift in mutually opposite directions; the plasma is polarized in such a way as to generate an electric field that imparts a bulk drift $\underline{V}$ whose acceleration satisfies exactly $\dot{\underline{V}} = \underline{F}/m$ (i.e., the plasma follows the dictates of the external force). If this plasma is now coupled to a resistive region via magnetic field lines that join both regions (Figure 7), the polarization charges will be drained into (or draw neutralizing charges from) the resistive medium in the form of field-aligned currents $j_{\parallel}$: the polarization of the plasma will be altered, and so will the electric field configuration and associated plasma drift (bulk motion). The currents $j_{\parallel}$ will be closed by perpendicular currents $j_{\perp}$; the corresponding Lorentz forces $\underline{j} \times \underline{B}$ play the role of "viscous" forces. Energy is dissipated in the "load" of the resistive medium, and the plasma blob will be forced into co-motion with the former. If that state is achieved, all field-aligned currents disappear, and the field lines will appear as "frozen" into both co-moving media.

The most important magnetospheric dynamos are pointed out in Figure 6. In the solar wind dynamo, the plasma "blob" of Figure 7 is the solar wind, driven by coronal expansion, connected to the resistive polar cap ionosphere by the open magnetic field lines. The associated system of Birkeland currents will flow along the boundary of closed field lines and be directed into the ionosphere on the postmidnight side, and out of it at premidnight. This is

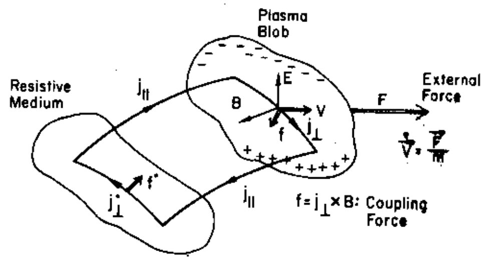

Figure 7. Schematic diagram of the solar wind dynamo.

indeed observed. Although the geometry and intensity of this system of field-aligned currents will depend on the actual configuration of the field interconnection, the direction of the currents and some other general features will remain the same as long as there are open field lines. The cusp regions feature a specific field-aligned current system (Figure 6) that is also controlled by the solar wind dynamo; the dominating solar wind parameter here is the B_y component of the IMF.

The corotation dynamo indicated in Figure 6 causes the plasmasphere to co-move with the low-latitude ionosphere, driven by the interaction with the neutral atmosphere. Since co-motion exists in this case, there is no field-aligned current system associated with the plasmasphere-ionosphere interaction in a steady-state situation.

The boundary layer dynamo marked in Figure 6 is assumed to be yet another form of solar wind dynamo, driven by plasma of solar wind origin flowing in the low latitude boundary layer on closed field lines in the antisunward direction, along the flanks of the magnetopause. This latter dynamo should be independent of whether or not there is magnetic interconnection between the solar wind and the magnetosphere. The associated field-aligned current system should lie along the auroral oval sunward of the Birkeland currents associated to the first solar wind dynamo. Its configuration should depend on the particular plasma flow in the low-latitude boundary layer.

A complex and highly variable field-aligned current system is driven by the bulk motions in the plasmasheet. This system is part of the closed chain of electrodynamic coupling shown in Figure 6. A complicating factor is that plasmasheet-ionosphere coupling depends on ionospheric conductivity, which in turn depends on auroral precipitation from the plasmasheet, which in turn depends on plasmasheet-ionosphere coupling!

Auroral precipitation during substorms is controlled by the field-aligned electric field in the $E_{\parallel}$ region (Figures 4 and 6). The generation of this electric field is currently a subject of intensive study. Several mechanisms have been proposed: (1) field-aligned currents with finite resistivity caused by electrostatic or electromagnetic plasma- wave turbulence; (2) trapped electrons and ions with mutually different distribution functions causing a charge density buildup (double layers); (3) current-driven electrostatic shocks.

Another topic under intensive study is the cause of substorms. It has been known for over a decade that the behavior of the interplanetary magnetic field plays a crucial role in causing, or creating conditions favorable for, substorm events. A commonly

cited sequence of events is the following: (i) A southward turning of the IMF increases the rate at which plasma flux tubes are transferred from the solar wind to the tail; (ii) as a result, the cross-tail current intensity increases, tail field lines are increasingly stretched, and the intensity of the mutually opposing fields in the tail lobes increases; (iii) if the southward-directed IMF persists, the thickness of the plasmasheet decreases, an X-type neutral line (or several of them) is formed in the cross-tail current sheet, and a magnetic merging process is eventually triggered along the neutral line leading to an enhanced plasma flow away from the neutral line; (iv) the plasma stream flowing toward the Earth is being betatron accelerated, feeding ring current and particle precipitation; (v) as this process continues, the neutral line migrates down the tail until the magnetic field relaxes back to a less stretched, more dipole-like configuration.

This picture is presently being challenged on several fronts. (1) The existence of, and need for, a large-scale neutral line and associated magnetic merging process in the tail has been questioned (e.g., Heikkila and Pellinen 1977; Perrault and Akasofu 1978). The observed earthward convection and acceleration of plasma could be accomplished by an electric field induced by a time-dependent magnetic field in the tail caused by a sudden decrease of the cross-tail current density. (2) The picture of gradual energy storage and subsequent triggered release as a basic, perhaps even cyclic, feature of substorm dynamics has been questioned and replaced by a model of "real time" control of substorm activity by solar energy transfer to the magnetosphere. This transfer would be governed by a quantity ε that is a function of solar wind parameters: $\varepsilon \sim V B^2 \sin^4(\theta/2)$ (V: solar wind velocity; B: IMF magnitude; θ projection of the polar angle of the IMF on the y-z plane in magnetospheric coordinates).

Many of these questions will hopefully be clarified during the next few years; the answers may well be contained in the impressive data base acquired during the IMS. What will not be solved are problems pertaining to the early stages of entry of solar wind plasma into the magnetosphere and its transfer to the plasmasheet reservoir. The proposed OPEN mission and other high latitude, high altitude satellite programs such as PROGNOZ will be necessary to provide the needed information.

Since all solar wind plasma entry and early-stage transfer processes occur on magnetic field lines connected to the polar regions of the earth, many of their manifestations have effects on the upper atmosphere in the cusp, the polar cap and the auroral oval. This is why I like to tell the "man in the street" that the high latitude upper atmosphere is "where outer space meets planet earth"!

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