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AUTUMN COURSE ON GEOMAGNETISM, THE IONOSPHERE
AND MAGNETOSPHERE

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FUNDAMENTALS OF MAGNETOSPHERIC PHYSICS

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Fundamentals of Magnetospheric Physics
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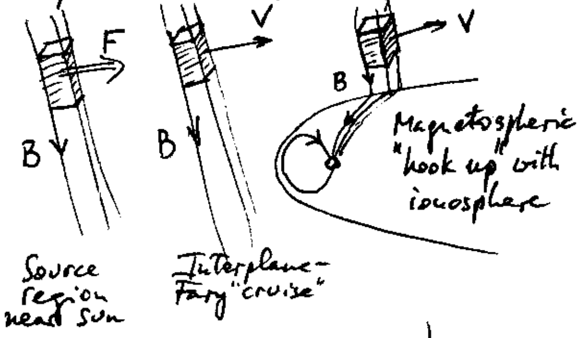
Summary Notes

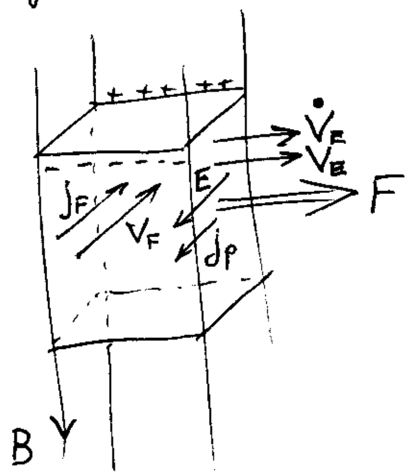
1. Introduction: please refer to hand-outs, particularly "The Solar Wind – Magnetosphere – Ionosphere System". See flow-charts describing particle transfer and electric coupling between principal magnetospheric regions.
   Refer to "Global Problems in Magnetospheric Plasma Physics" to see "idealized" magnetic field topology (Fig 2).

2. Solar wind – Magnetosphere – Ionosphere Dynamo

Consider a plasma element accelerated near the sun, travelling toward earth, then hooking up with magnetosphere.



In source region, suppose non-electromagnetic force F acts as shown. This causes force drift $V_F = \frac{\vec{F} \times \vec{B}}{qB^2}$ (opposite for opposite charges). This causes polarization as shown; E field as shown; $V_E = \frac{E \times B}{B^2}$ drift of all particles, as shown.



More detailed treatment:

On k-th class of particles $\vec{V}_{Fk} = \frac{\vec{f}_k \times \vec{B}}{q_k B^2}$ f_k: force on k-th class of particle

Leads to component of current $\vec{j}_{Fk} = n_k \vec{f}_k \times \vec{B}/B^2$ (n_k: particle density)

Total current: $\vec{j} = \frac{\Sigma n_k \vec{f}_k \times \vec{B}}{B^2} = \frac{\vec{f} \times \vec{B}}{B^2}$ (f = force density)

Leads to charges where $\vec{\nabla} \cdot \vec{j} \neq 0$ (sides of element)

$\vec{E}$ produced, changes with time: $\frac{\partial \vec{E}}{\partial t} \neq 0$ (increases)

So does electric field drift $V_E = \frac{\vec{E} \times \vec{B}}{B^2}$, which is also the plasma bulk velocity (because it is that velocity of a frame of reference in which $\vec{E} \equiv 0$ – true only for MHD plasmas, in which $E + V \times B \equiv 0$)

A changing V_{bulk} leads to an inertial drift V_p (because of the inertial force $-\rho\dot{V}$ in the plasma's frame of reference), and to a related current, called polarization current (ρ: mass density)

$$\vec{j}_P = -\rho \frac{\dot{V} \times B}{B^2} \quad \text{(see drawing for direction)}$$

One can show that $\vec{j}_F + \vec{j}_P \approx 0$ (only if $\frac{B^2}{\mu_0 \rho} \ll c^2$) (Alfvén vel^2) (always is, except near boundaries)

Then $\vec{f} - \rho\dot{V} = 0$ and the plasma blob behaves like Newton's equation prescribes

All this is an application of the equation

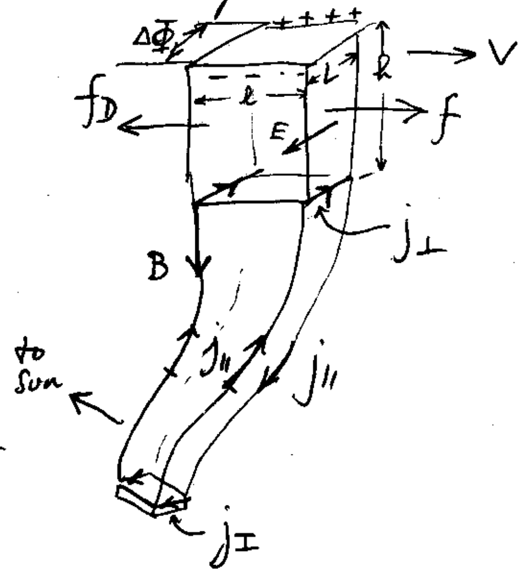
$$\rho\dot{\vec{V}} = \vec{j} \times \vec{B} + \vec{f} \quad (\text{for } j \approx 0\ !)$$

The important thing is to realize the correspondences
$f_\circ \to$ force drift $\to$ force drift current
$\dot{E} \to$ polarization drift $\to$ polariz. current
$E \to$ bulk drift

Plasmas follow $\rho\dot{V} = f$ only if $j \equiv 0$! In reality that would only be true "in the middle" of the element but not on the edges. These would "peel off", because of magnetic drag, in the real case ($j \neq 0$ there).

In the "cruise mode", f is essentially zero, $j \simeq 0$, and V = const. (Note that it remains polarized, to have an E field related ~~to~~ $V = E\times B/B^2$!)

The moment the plasma element flux tube is connected to the ionosphere, field aligned currents can drain charges into ionosphere (or pull out from ionosphere). Now $j_\perp \neq 0$ in plasma, and a drag force $f_D = j\times B$ will appear, slowing down the solar wind plasma. To keep plasma going with constant speed, I must ~~exert~~ external force f to equilibrate $j\times B$
($\rho\dot{V} = j\times B + f = 0$)



The work by this force f is equal to Joule heat $j_I \cdot E_I$ dissipated in ionosphere.

This is the elementary solar-wind ionosphere dynamo.

Note that if l, L, h are dimensions of plasma element, and $l^*\, L^*\, h^*$ those of intercepted ionosphere, we have $j_\perp = j_I \frac{l^* h^*}{l h}$

conductivity in iono (Pedersen)

Since $j_I = \sigma_I E_I = \frac{\Delta\Phi}{L^*}$ ← potential across plasma element – magnetic field lines are equipotentials, so it's the same across iono element)

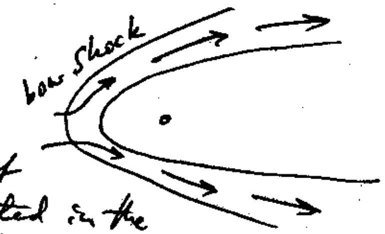
$= \sigma_I \frac{VBL}{L^*}$ E in solar wind plasma element

ionospheric resistance

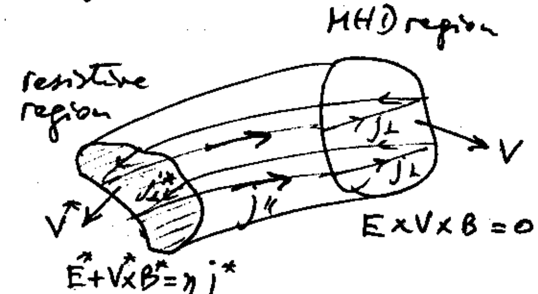
Total drag force $F = f_D l L h = R L^2 B^2 V$

Note that force is $\sim V$, therefore it has a "viscous friction" character.

In reality, plasma in the magnetosheath is accelerated by a hydrodynamic forces. Part of that force's work is dissipated in the ionosphere via the solar wind dynamo.



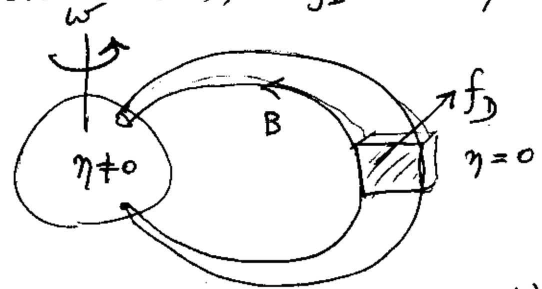
General remarks:



Whenever we couple an MHD region to a resistive medium, $j_\parallel$ will flow and a dynamo process will occur. Energy from the plasma is dissipated in the resistive region, as long as $j_\parallel$ flows. A drag force will act on MHD region.

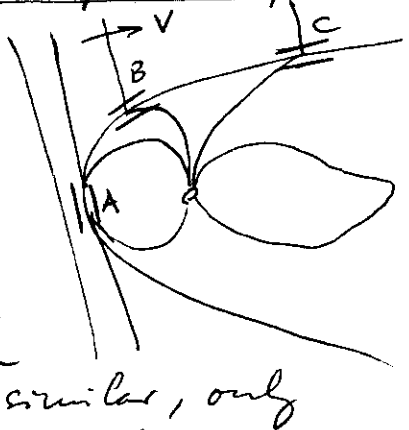
Condition for $j_\parallel \equiv 0$: both regions must "co-move", i.e., remain at all times connected through magnetic field lines (then $E \equiv 0$ also in the frame moving with the resistive medium (V^*), and $j_\perp^* = 0$ there).

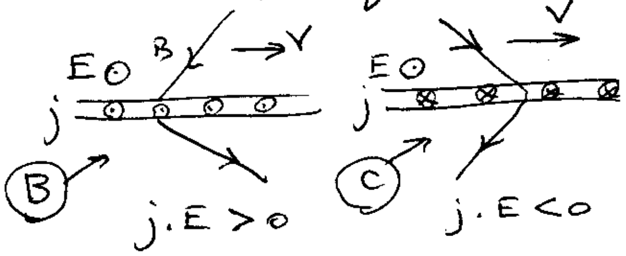
Example of corotation:
Take plasma initially at rest, connected to rotating ionosphere.
It is easy to figure out $j_\parallel$ using the previous example (just turn around frames of reference!)
The drag force density $j_\perp \times B$ will accelerate the blob until it ends up corotating!
Corotating plasma (the plasmasphere!) does not need field-aligned currents!



3. Energy and Particle Transfer through Boundary

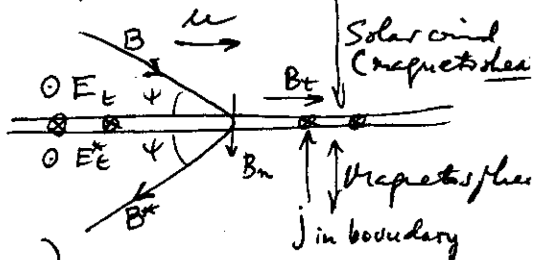
Consider plasma tubes connecting with magnetosphere in A, B, C.
At A we have a merging region. Special things may happen there — or nothing at all. There is no clear evidence for either. B and C are similar, only that at B, the boundary currents are ∥ to E ($j \cdot E > 0$) and in C anti parallel.
B is a mechanical ...





sink; C is a dynamo (conversion of mech. energy into elec. energy).

Consider case C (boundary along the tail).
One may assume a symmetric rotational discontinuity there (Landau + Lifshitz).

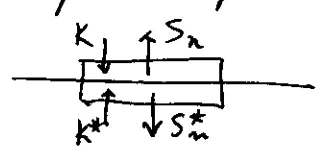


The following relations hold (* means magnetosphere)

$$B_t = B_t^*,\ B_n = B_n^*,\ B = B^*,\ \rho = \rho^*,\ p = p^* \text{ (assumed isotropic pressure)}$$
$$E_t = E_t^*,$$

and in frame of reference moving with $\vec{u} = \frac{\vec{E_t} \times \vec{B_n}}{B_n^2}$ to the right (gliding along with the solar wind plasma), the plasma flows into the magnetospheric "vacuum" with the Alfvén speed along $\vec{B}$: $v_\parallel = V_A = B/\sqrt{\mu_0 \rho} = v_\parallel^*$

With simple algebra, one can find expressions for kinetic energy flow $K = v_n(\rho v^2/2 + 5/2\, p)$ (Enthalpy flow) ($\vec{v}$: plasma velocity) and Pointing vector $S_n = \frac{1}{\mu_0} u B_n B_t$,



and ΔK (into box around boundary) $= \Delta S_n$ (out) $= -j_B \cdot E_t$

and flux into magnetosphere: $F = K^* + S_n^* =$

$$= \frac{1}{2}\rho V_A B_n/B\,(u^2 + V_A^2) + \frac{5}{2}\rho V_A \frac{B_n}{B}$$

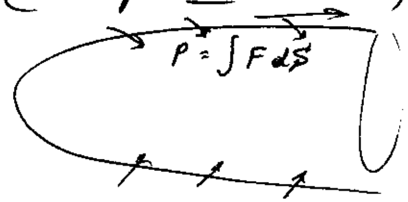
Orders of magnitude are $\sim 10^{-6}$ W/m^2

If ρ small, and $u \approx v_{\text{solar wind}} \approx V_A$ (as it is in the near-earth region of the boundary, behind the bow shock)

$$F \simeq S_n^* \gg K^*$$ (mainly electromagnetic energy flow)

Along tail $u \gg V_A$ and $F \simeq K \gg S_n$ (mainly kinetic energy flow). — (But ρ is not small!)

Integrating along the entire tail, one obtains for total power transfer:



$$P = \underset{\text{electrom}}{P_{elm}} + \underset{\text{kinetic}}{P_K},$$

with $P_{elm} = \frac{1}{\mu_0} V B \Psi$ | $\Psi = \int B_n\,dS$: interconnected magnetic flux ($\equiv$ open field polar cap flux)

and $P_K = (\frac{1}{2} M_A - 1) P_{elm}$

($M_A = \frac{V}{V_A}$, "Alfvén Mach number")

Since $M_A \gg 1$ along most of magnetopause, $P_{elm} \ll P_K$ and

$$P \simeq \frac{1}{2\mu_0} M_A V B \Psi$$

Note that interconnected flux regulates energy transfer. Depends on magnetic interconnection topology, which in turn depends on solar wind magnetic field – especially its direction.

Dimensional analysis for Ψ:

$$\Psi \sim B\, l^2\, G(\theta) \times M_A^{2\alpha}$$

2α ← coeff. to be determined.

B: interpl. field

l: scale size of magnetosphere

$G(\theta)$: geometric factor depending on angle of B → $= 1$ for B "downwards" (B_z …), $= 0$ for B "upwards" (B_z …)

M_A: Alfvén Mach number close to magnetopause in magnetosheath flow.

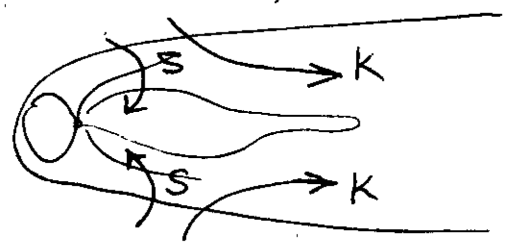
Take for l the Chapman–Ferraro stand-off distance to "nose" of magnetosphere ($l = (\mu_0 g_1^0/\rho V^2)^{1/6}$)

g_1^0: earth's dipole term coeff. (= 0.31 gauss)

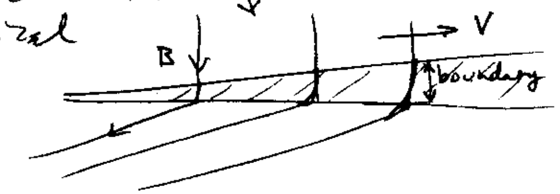
For a "reasonable" model of field interconnection one finds

$$P_{elm} \sim V^{5/6} B^{5/3} G(\theta)$$
$$P_K \sim V^{4/3} B^{2/3} G(\theta) \approx P_{\text{total}}.$$

We shall see that the main magnetospheric perturbations correlate with $V B^2$, so that it seems that electromagnetic energy transfer to the magnetosphere, though much smaller than the kinetic energy transfer, powers the near-earth region of the magnetosphere and its perturbations! The kinetic energy entering the magnetosphere would mainly flow down the tail (like in a comet):



In a real situation, rotational discontinuity is most likely not symmetric. →
In that case, only numerical simulation is possible.
One finds that: (1) no stationary solution exists; (2) thermal energy can be converted into electromagnetic energy at the boundary in the cooling process (flow into "vacuum"!), but the excess entropy must be convected away: the boundary itself expands down the tail.



Experimentally, rotational discontinuities have been seen in magnetic field signatures during boundary crossings. But at low latitude, they are not there all the time. (Few observations exist at high latitude tail).

Other observations seem to suggest "patchy" reconnection – a sort of spaghetti picture of interconnected flux tubes.

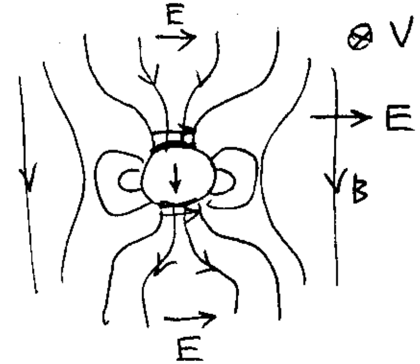
Yet indirect evidence of linked magnetic fields is overwhelming (see below and references).

4. <u>Interconnection geometry and polar cap electric field</u>

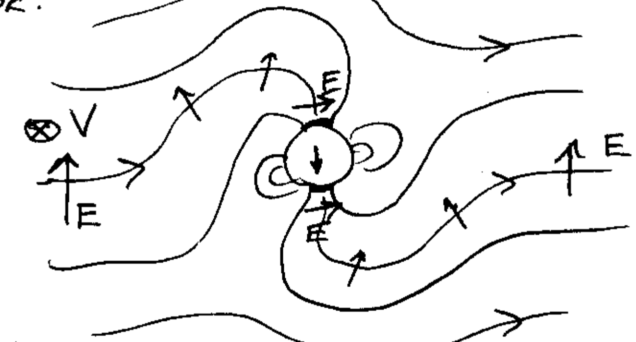
The electric field in the solar wind as seen by an observer fixed on earth

is always $\vec{E} = -\vec{V} \times \vec{B}$.

Take a pure dipole in a uniform field, with "solar wind" flowing into the paper.
See electric field and how it maps into the "polar cap" along equipotential field lines ($E_\parallel \equiv 0$ because of MHD relation $E + V \times B = 0$)
E is directed dawn-dusk.



But also for a $\vec{B}$ in the ecliptic, the electric field on the "polar cap" is dawn-dusk! →



As soon as there is connection, there will be a tendency of dawn-dusk electric field.

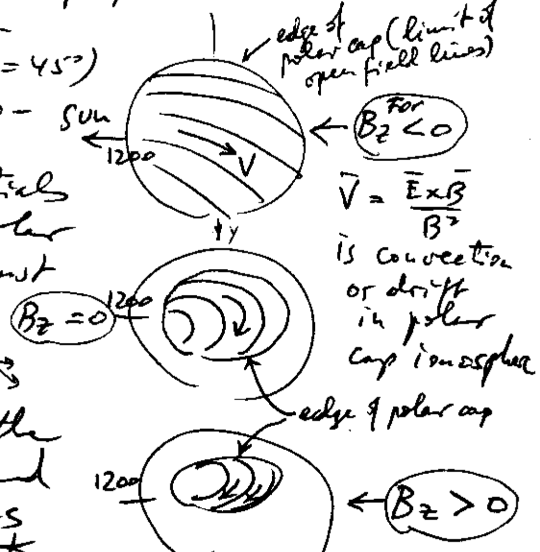
To find out reconnection geometry, one uses a magnetospheric B-field model and superposes a (uniform) solar wind magnetic field.

One generally finds:

1. Polar cap size (region of "open" field lines) is controlled by B_z (component of B ∥ magnetic moment of earth). Size is 0 for northward B, maximum for due southward field.

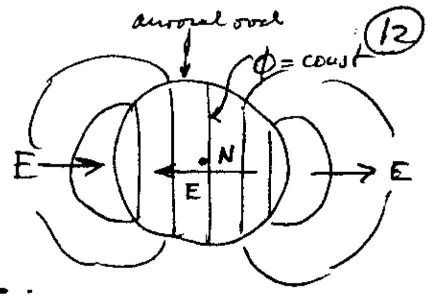
2. Dawn-dusk component of B (By component) shifts polar cap position.

3. For a field away from sun (garden hose angle = 45°) and different B_z components, one sees the behavior of equipotentials (mapped down from the solar wind potentials — Φ = const planes there) shown schematically in these figures. Note that as B turns "upwards", the polar cap shrinks and the main flow turns from antisunward to sunward.



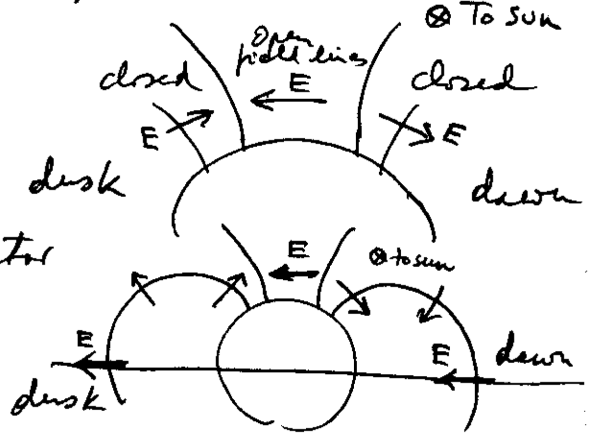
The interconnected flux $\Psi \sim B^{1/3}$, if no connection between tail field and interplanetary field is assumed. But this is not true. For an empirical relationship, one obtains $\Psi \sim B^{2/3}$. This is what led to the particular relationships for Pelm on p 8.

Qualitative agreement with experiment of many features given by the model is good. But magnitudes (of E) are too high. Reason is probably a "squeezing" of field lines in the tail and magnetosheath, that intercepts a smaller value of $\Delta\Phi$ in solar wind.



Assuming a constant E inside polar cap, how is rest of E determined? One can solve an electrostatic problem in the ionosphere: given Φ along auroral oval (boundary of polar cap), given conductivity, what is the potential outside polar cap? One finds the pattern as shown. Note that boundary of closed/open field lines is a source-sink of E ($\vec{\nabla}\cdot\vec{E} \neq 0$).

Projecting onto equator along equipotential field lines, one finds a general dawn-dusk E-field.



Currents in the ionosphere related to E are

$$\vec{j}_\perp = \sigma_P \vec{E} + \sigma_H \frac{\vec{B}}{B}\times\vec{E}$$

Pedersen conductivity dispersive ($j\cdot E \neq 0$) — Hall conductivity Non dispersive ($j\cdot E = 0$)

Pattern of $\vec{j}$ similar to E or Φ-lines, but <u>rotated</u> by $\tan\alpha = \sigma_H/\sigma_P$.

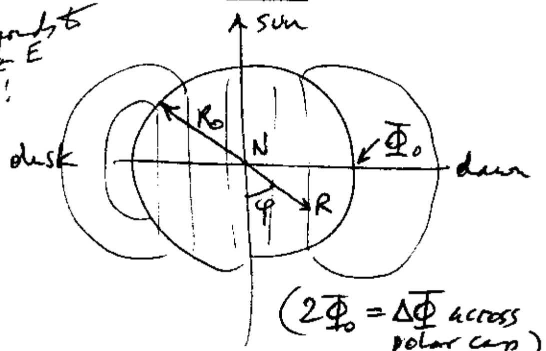
Drift of ionospheric plasma due to E imposed by solar wind: $V = E\times B/B^2$, which is tailward on the polar cap and sunward outside (equatorward of polar cap). Flow lines of V are the equipotentials $\Phi = \text{const}$!

5. General electric field and general magnetospheric convection

For a potential

$$\Phi = \Phi_0 \, R/R_0 \, \sin\varphi$$

← corresponds to uniform E field!



$(2\Phi_0 = \Delta\Phi$ across polar cap$)$

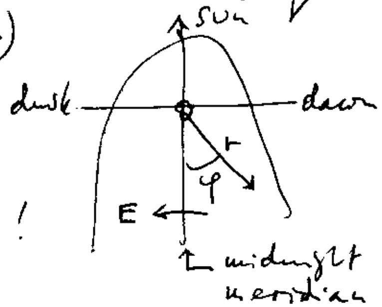
inside the polar cap, the field outside is

$$\Phi = \Phi_0 \left(\frac{R_0}{R}\right)^k \sin\varphi$$

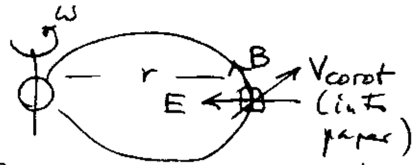
(k "arbitrary" constant – depends on ionosph. conductivity assumptions).

Projecting along field lines to the equator, one obtains (see coordinates) for a dipole field:

$$\Phi = \Phi_0 \left(\frac{r}{r_0}\right)^{k/2} \sin\varphi$$



For $k = 2$, it's a uniform dawn-dusk field! But one must add a corotational field also (such that a plasma at r in absence of externally imposed E, corotates with $V = \vec{\omega} \times \vec{r}$):



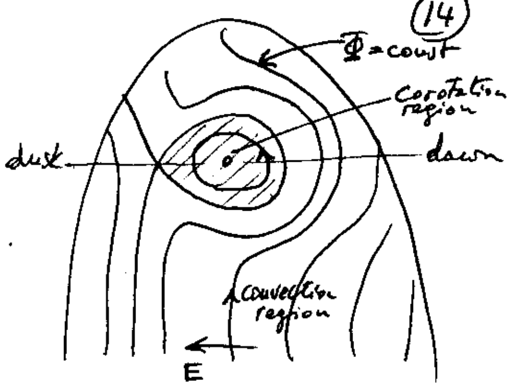
$$\Phi_{corot} = -\omega g_i^0 a^2 \frac{a}{r} \quad a: \text{radius of earth}$$

Thus on the equator,

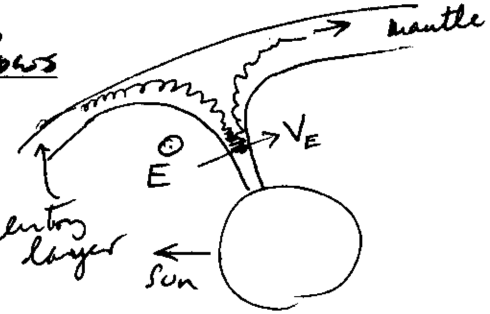
$$\Phi = C_2 r \sin\varphi - C_1/r$$

is the equation of an equipotential (for $k=2$).

See figure sketched →



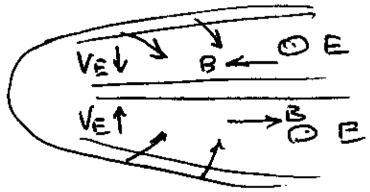
Effects on particle flows



(A) A general dawn-dusk field has important effects on flow from dayside entry layer through the cusp into the mantle (refer to hand-out, for flow charts). (1) A particle that mirrors in the cusp will be subject to drift V_E. The greater E (greater interconnection!) the more it will drift, hence the thicker will be the mantle. (2) The lower the energy of a particle, the more time it will have to drift under V_E; hence, the spectrum of particles in the mantle will soften at its inner edge. These are observed facts.

In summary, the externally controlled electric field is an important modulating and organizing agent in the otherwise very "messy" region of the cusp.

(B) In the tail lobes the electric field causes a general drift from the mantle to the plasma sheet – tail current sheet. This drift probably is the main source for the plasma sheet. There is a simple relationship between B (thus, the current density in the sheet) and potential difference $\Delta\Phi$ across tail:

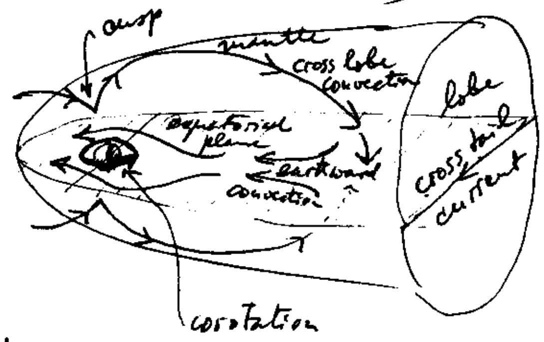


$$B^2/\mu_0 = \overset{\text{number density}}{n}\, e\, \Delta\Phi$$

Again, see how $\Delta\Phi$ would control tail!

(C) Inside the plasma sheet, a dawn-dusk E causes a general earthward drift.

A general steady state convection picture is sketched in the figure. →



Everything is ultimately controlled by the solar wind electric field projected along interconnected field lines into the magnetosphere.

6. Particle motion and ring current injection (no p. 16)

Consider electrons and protons spiralling in the equatorial plane (no field-aligned motion). They will be subject to two drifts

$$\vec{V} = \frac{\vec{E}\times\vec{B}}{B^2} + \frac{T_\perp}{qB^3}\,\vec{B}\times\vec{\nabla}|B|$$

$T_\perp$: kinetic energy

electric drift (independent of q, T)   gradient-B drift.

Note that if $T_\perp \to 0$, only electric drift (particles follow plasma bulk motion along equipotentials)

If T large, only gradient-B drift.

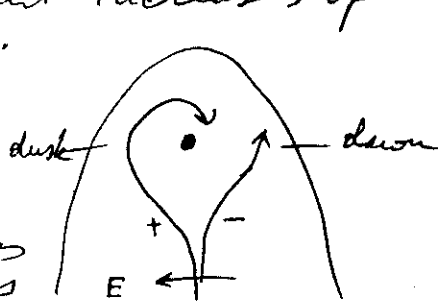
To solve trajectories for our Φ model, use $W = T + q\Phi = \text{const.}$ and $M = T/B = \text{const}$ (first adiabatic invariant). Thus

$$M\,B(r,\varphi) + q\,\Phi(r,\varphi) = \text{const}$$

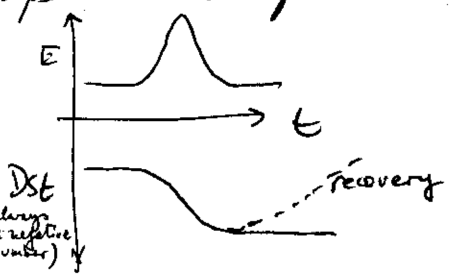
is equation of trajectory. Again, if $M \to 0$ (low energy) $\Phi = \text{const}$ is trajectory. If M large, $B = \text{const}$ is trajectory (e.g., of ring current and radiation belt particles mirroring on the equator).

Trajectories in general depend on energy (M). For protons, there are some "funny" trajectories around the dusk meridian (competing electric field and gradient-B drifts!)

It is important now to see what happens during transient increases of E in the magnetosphere. The earthward convection will increase, but as particles get energized in higher B regions, their gradient-B drift becomes more important: protons will drift toward dusk, electrons toward dawn. This necessitates field-aligned currents to preserve charge neutrality of the plasma.



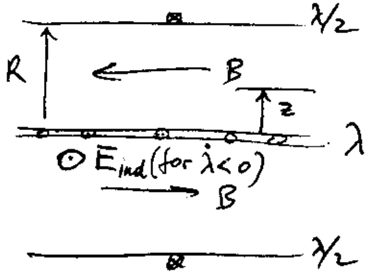
If the E-increase stops at the right time, the protons will have a chance to be left in closed orbits around the earth: they become part of the ring current, and the Dst index will have increased! (It recovers afterward due to removal of protons through collisions and charge exchange with neutrals).



It is clear that large temporary increases of E lead to ring current injections.

At the same time, such increases lead to an "erosion" or "peeling-off" of the plasma in corotating region — the plasmasphere.

What causes such large increases in the dawn-dusk electric field in the tail that are necessary to explain the observed ring-current injections? It is not directly the solar wind E field (such increases are not seen in the polar cap). A local collapse of the cross-tail current can lead to large induced electric fields (see Lenz' law!):



If we take a primitive model of the tail (sheet currents!), with λ the linear current density in the center (and return currents $\lambda/2$ at distance R), we have $|B| = \frac{1}{2}\mu_0 \lambda$ and

$$E_{induced} = -\frac{1}{2}\mu_0 \dot{\lambda}(R - |z|) \quad \text{(out of paper)}$$

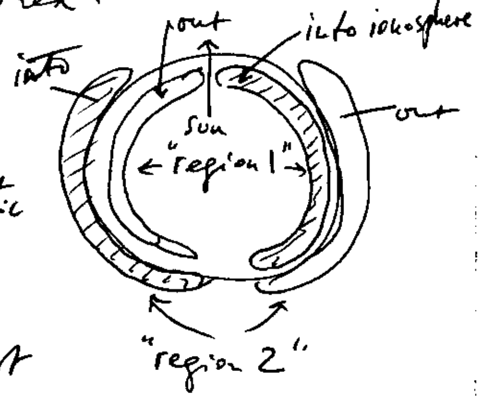
If $\dot{\lambda} < 0$, $E_{ind} > 0$ is out of paper, i.e., dawn-dusk.

Shunting λ into the ionosphere along field lines, for instance, could lead to a large E_{ind}, if it is done quickly enough.

The magnetic merging process has been invoked also as a possible cause for large earthward injection. But evidence that it occurs as a cause of plasma behavior is elusive.

7. Field-aligned currents and $E_{\parallel}$

Field-aligned currents in or near auroral oval are well-established.

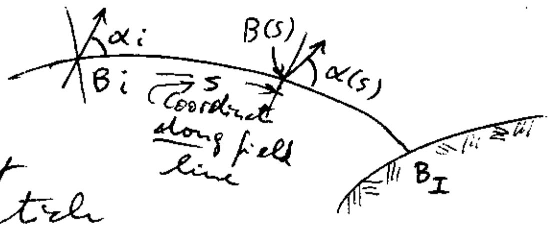


Poleward are the "region 1" currents, present at all times (even very low geomagnetic activity). Typical fluxes are $1.6\,\mu A/m^2$, up to 2-$3\,\mu A/m^2$ during storms. This current system most probably represents the solar wind dynamo (see drawing on p. 3)

Region 2 is on the equatorward edge of the auroral oval. Highly variable. Inside auroras, the $j_{\parallel}$ increases to about $10\,\mu A/m^2$. This system corresponds to flows (is closed by currents) in the plasmasheet. They are related to the formation of auroral arcs and to the process of auroral breakup.

A field-aligned current (out of the ionosphere) of $10\,\mu A/m^2$ could not be furnished by plasmasheet electrons. The reason is that the loss-cone out there is too small to contain enough particles. A field-aligned electric field $E_{\parallel}$ (directed upwards) is the only way to "draw" enough electrons from the plasmasheet. An equivalent way to say this is to state that such a field (or a potential Φ along the field lines) will "open up" the loss cone at the equator.

Consider the field line of the picture. From conservation of magnetic moment we have, for a particle spiralling along s:



$$M = \frac{T_i \sin^2\alpha_i}{B_i} = \frac{T(s)\sin^2\alpha(s)}{B(s)} = \text{const}$$

generic point s

i: initial point

but $T(s) = W - q\Phi(s)$ electric potential along field line

and $W = T_i + q\Phi_i$ (total energy)

$$\text{Thus}\quad \sin^2\alpha(s) = \underbrace{\sin^2\alpha_i \frac{B(s)}{B_i}}_{\text{"usual relation"}} \overbrace{\frac{1}{1+\frac{q(\Phi_i-\Phi(s))}{T_i}}}^{\text{field-aligned } E_\parallel \text{ factor}}$$

Note that for $\Phi = \text{const}$ along field line, the "usual" pitch angle relationship is obtained.

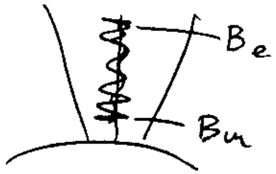
The loss cone for precipitation into the ionosphere (where $B = B_I$) would be

$$\sin^2\alpha_{loss} = \underbrace{\frac{B_i}{B_I}}_{\text{very small number!}}\left[1 + q\frac{(\Phi_i - \Phi_I)}{T_i}\right]$$

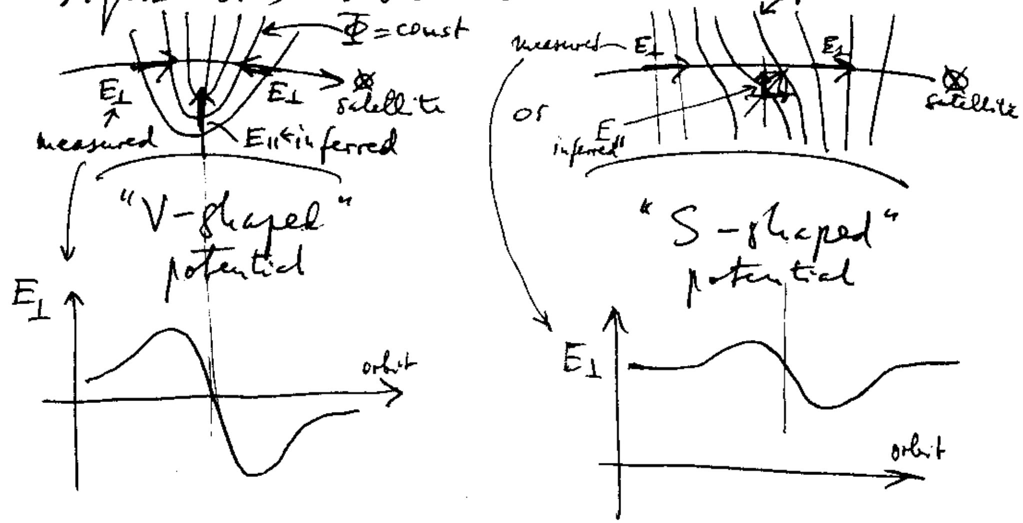
For electrons $(q<0)$, a Φ that increases downward gives an increase in $\sin^2\alpha_{loss}$!

There are other, more experimental reasons to believe that $E_\parallel$ exists in auroral structures [$\Delta\Phi$ along field lines is ~ several KV between ~500km and 2-3 earth radii).

1. Barium ion jets injected are seen to be accelerated upwards in auroral arcs.
2. O^+ from the ionosphere are seen being accelerated upwards.
3. The particle populations seen in or above auroral arcs testify to $E_\parallel$ (for instance, electrons trapped between a magnetic mirror point B_m at low altitude and an electric potential mirror point B_e at higher altitude).

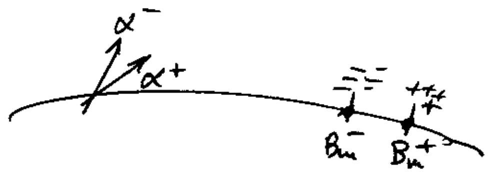


4. Satellite transverse electric field signatures as shown:



Mechanisms to sustain $E_\parallel$:

A. Pitch angle distribution difference between electrons and protons.
Would cause polarization if no electric field (see sketch) →



different mirror points → charge separation!

But with suitable $E_\parallel$, one can make mirror points coincide (assume equal T for both):

$$\frac{\sin^2\alpha^+_{\text{protons}}}{1+\frac{|q|\Delta\Phi}{T}} = \frac{\sin^2\alpha^-_{\text{electrons}}}{1-\frac{|q|\Delta\Phi}{T}} \rightarrow e\Delta\Phi = T\,\frac{\sin^2\alpha^- - \sin^2\alpha^+}{\sin^2\alpha^- + \sin^2\alpha^+}$$

Note that potential drop only of order of T of particles.

B. Double layer formation.

A long-known discharge phenomenon, driven by an external e.m.f. that supplies energy. Involves counter-streaming of electrons (down) and protons (up). e.m.f. related to ionosphere – plasmasheet interaction (dynamo)! Both particle classes are accelerated (down, up, respectively). Strong current involved. But problem is very limited vertical (field-aligned) range.

C. Electrostatic shocks

Involve parallel streaming of electrons and ions, in which ions give up energy to electrons. No external e.m.f. involved. Electrons are accelerated at the expense of protons (both from plasmasheet). There is no current involved.

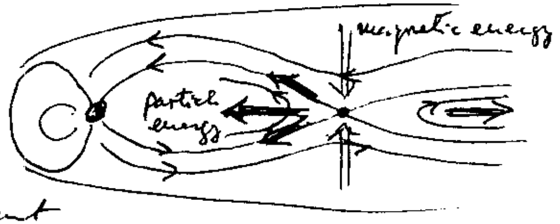
There are other possible mechanisms; probably not very important, though.

The appearance of field-aligned electric fields plays a crucial role in the auroral process as a whole; particularly in auroral acceleration and ionosphere – plasmasheet coupling.

Current research (using simulation studies) tries to explain why auroral arcs are so thin (100 m – 10 km!), why there are multiple arcs, and exactly how the instability leading to $E_\parallel$ is triggered (what is chicken, what is the egg: increased $j_\parallel$, $E_\parallel$, thinning of precipitation region?). Clearly, there is an interplay between all three, plus the enhanced ionospheric conductivity in the precipitation region).

8. Geomagnetic storms and substorms

For many years, it was believed that a storm or substorm is triggered by an instability developing in the tail and running out its own course, converting previously accumulated magnetic energy ("growth phase") – that was a result of increased magnetic flux transfer from the solar wind (during negative B_z periods) – into particle energy. The process invoked was magnetic merging along a neutral line in the tail. Earthward convection, ring current acceleration, auroral precipitation were thus explained.



Several questions remained, or started emerging.

Such an explosive event should "run its own course", once started. Why are there so different types of storms? Why are there storms (big ring-current build up (Dst)) and why are there substorms (auroral events, but no big Dst increases)? Why does a substorm suddenly stop when B_z turns northwards? Where is the evidence for explosive events in the tail? And what is the role of the "newly discovered" $E_\parallel$?

Finally, it was found that energy consumption in the inner magnetosphere

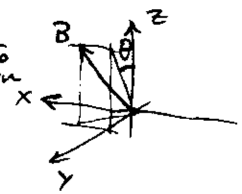
$$U = U_{Aurora} + U_{Ring\ current}$$

$\hookrightarrow \sim$ AE index $\quad \searrow \sim \dfrac{d\,Dst}{dt}$ and $\dfrac{Dst}{\tau_{decay}}$

Ring current build-up — Maintenance of ring current against decay.

seemed to be controlled in real time by solar wind parameters. Of these, <u>best correlation</u> with U is given by

$$\epsilon = k_0 V B^2 \sin^4\left(\frac{\theta}{2}\right)$$



the <u>solar wind coupling function</u>.

V: velocity of solar wind
B: solar wind magnetic field
θ: projection polar angle on yz plane (in solar-magnetospheric coordinates) of $\vec{B}$.
$k_0 = 2 \times 10^4$ (to give ϵ in kW for B in gamma and V in km/sec.)

Specifically,
$$U = k_1\left(\frac{d\,|Dst|}{dt} + \frac{Dst}{\tau}\right) + k_2\,AE$$

with $k_1 = 1.1 \times 10^7$, $k_2 = 3 \times 10^5$ and $\tau \lessapprox$ 1 hr, strong storms; $\gtrapprox$ 1 day, weak storms

for Dst and AE in gamma, and U in kW.

ϵ and U are not only well correlated on a short time scale (minutes), but the following is found:

ϵ	Magnetospheric response
$\leq 10^7$ KW	Quiet condition
$10^7 - 10^8$	Polar activity enhancement
$10^8 - 10^9$	Typical substorm
$10^9 - 10^{10}$	Magnetic storm (Dst ~ 100γ)
$\gtrsim 10^{10}$	Large storm (Dst ≳ 200γ)

What is the physics behind all this? The magnetospheric storm seems to be more of a "driven" system than an "unloading" process.

The chain of events may be as follows:

1. Enhancement of interconnected flux Ψ (see pp 7, 11)
2. Increase of tail current intensity and earthward convection. Slight increase of ring current (Dst)
3. Increase of $j_\parallel$, increase of precipitation (brightening of quiet auroral arc).
4. Trigger of $E_\parallel$ on auroral field lines (caused by interplay of increase $j_\parallel$, increased precipitation, increase of σ ionosphere at precipitation region)
5. Formation of auroral arcs.

↳ Up to here: substorm.

If enhancement of Ψ (ϵ) is beyond

another threshold (see table), the following goes on:

6. Great intensification of $E_\parallel$, intensification of $j_\parallel$, diversion of tail current (decrease of λ, see p. 19)
7. Strong enhancement of cross tail electric field (E induced? - p. 19) Strong ring current injection (p. 18).

↳ Magnetic storm.

Note that in the above picture, the explosive character is not controlled by the tail, but near the earth by the formation of $E_\parallel$, the increase of $j_\parallel$ and only then, decrease of $j_\perp$ in tail!!

It is of course possible that in part an "unloading" process also goes on at the same time. Only future measurements (with still non-existing satellites) will resolve this question.

9. References

It was assumed that participants in this course had general knowledge of magnetic field morphology, magnetic storm morphology and adiabatic theory elements.

For Section 1: See other handouts and references therein.
For Section 2: See hand-out review articles and Longmire, Elementary Plasma Physics, Wiley, 1963

For Section 3:

Sonnerup, p. 77, in Dynamics of Magnetosphere, ed. Akasofu, Reidel 1979.
Lee + Roederer, JGR, 87, 1439, 1982
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Also hand-out: "Global Problems ...." and references therein.

For Sections 4, 5, 6:

Stern, Rev. Geoph. + Space Phys., 15, 156, 1977
Fälthammar, " " 15, 457, 1977
Longenecker + Roederer, Geoph. Res. Lettr., 8, 1261, 1981
Roederer: Dynamics of Geomagnetically Trapped Radiation, Springer Verlag, New York, 1970.
Roederer + Hones, JGR 79, 1432, 1974

For Sections 7, 8

Potemra, Rev. Geoph + Space Phys., 17, 640, 1979
Kan + Lee, p 206 in Formation of Auroral Arcs, Kan + Akasofu eds., AGU publication, 1981.
Akasofu et al., Planet. + Space Sci, 30, 537, 1982

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