Lecture notes

"sun-planet connections"

given at MPS

23 - 25 Feb. 2009

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Magnetic field in electrically conductive medium (fluid, gas)

Electric field

$$\vec{E} = \underbrace{-\vec{V} \times \vec{B}}_{\text{convective}} + \underbrace{\frac{1}{\sigma}\vec{j}}_{\text{Ohmic}} \quad \cdots (1)$$

$$= -\vec{V} \times \vec{B} + \frac{1}{\mu_0 \sigma} \nabla \times \vec{B} \quad \cdots (2)$$

(Ampère's law)

Induction eq.

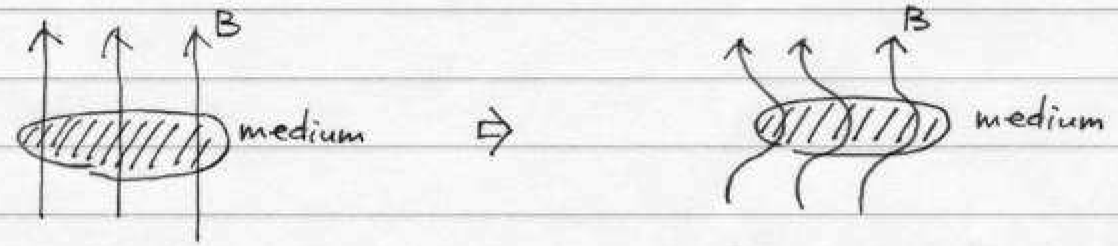
$$\partial_t \vec{B} = -\nabla \times \vec{E} \quad \cdots (3)$$

Combine (2) and (3) and $\nabla \cdot \vec{B} = 0$

↳

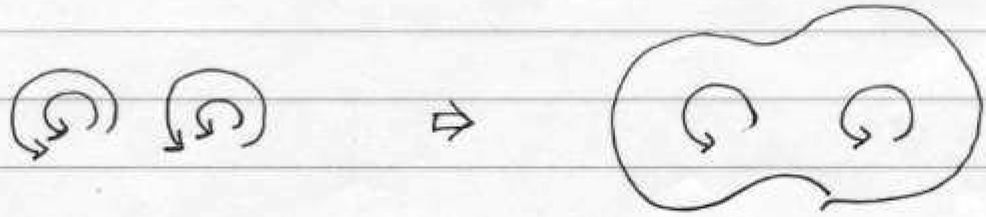
$$\underbrace{\partial_t \vec{B}}_{\substack{\text{Evolution of} \\ \text{mag. field}}} = \underbrace{\nabla \times (\vec{V} \times \vec{B})}_{\text{(A) frozen-in}} + \underbrace{\frac{1}{\mu_0 \sigma} \nabla^2 \vec{B}}_{\text{(B) diffusion}} \quad \cdots (4)$$

(A) Frozen-in magnetic field



Magnetic field moves with flow/medium.

(B) Diffusion



Magnetic field becomes weaker.

Space plasma ... collisionless, conductive medium.
Conductivity σ very large.

↘ Frozen-in magnetic field

Consequences

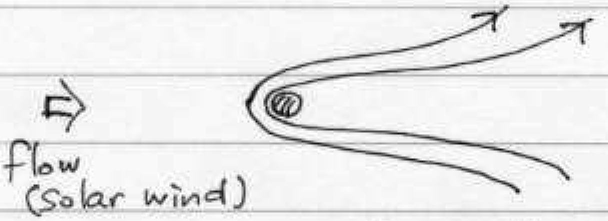
(1) Magnetic field moves with flow
(e.g. solar wind)

(2) Different media cannot be mixed.

↘ Formation of boundaries
(e.g. magnetopause)

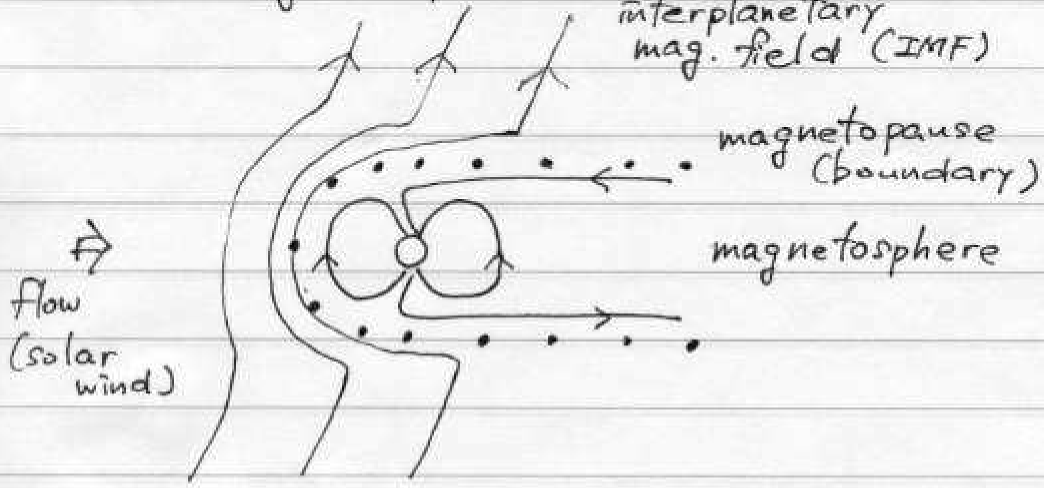
Applications

(1) Comet tail (Alfvén's idea, 1957)



curved magnetic field

(2) Magnetosphere



How large is magnetosphere?

Pressure balance

$$\frac{1}{2}\rho V^2 = \frac{B^2}{2\mu_0} \quad \ldots (5)$$

dynamic pressure (kinetic energy density)	magnetic pressure (mag. energy density)
solar wind	planet

Dipole magnetic field (for planet)

$$B \propto \frac{1}{r^3}$$

$$\leadsto \frac{B}{B_{surf}} = \left(\frac{R_{surf}}{R_{mp}} \right)^3 \quad \dots (6)$$

Combine (5) and (6)

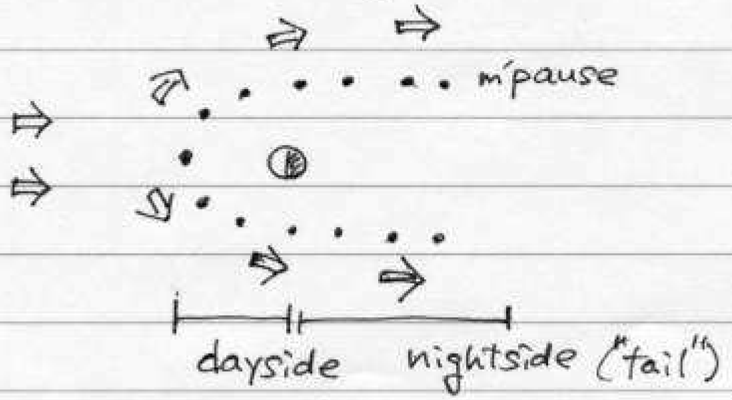
$$\leadsto \frac{R_{mp}}{R_{surf}} = \left(\frac{B_{surf}^2}{\mu_0 \rho V^2} \right)^{1/6} \quad \dots (7)$$

Classification of planets

	$R_{mp} > R_{surf}$	$R_{mp} < R_{surf}$
solid surface	Mercury	Earth Moon
gas surface (atmosphere)	Earth Jupiter, Saturn Uranus, Neptune	Venus, Mars

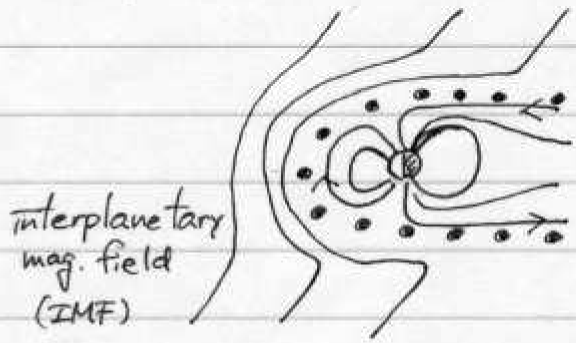
Chap. 2 Earth (static picture)

- Flow around magnetosphere



Surface mag. field 30 000 nT
Magnetopause distance ··· 10 ~ 11 R_E (dayside)

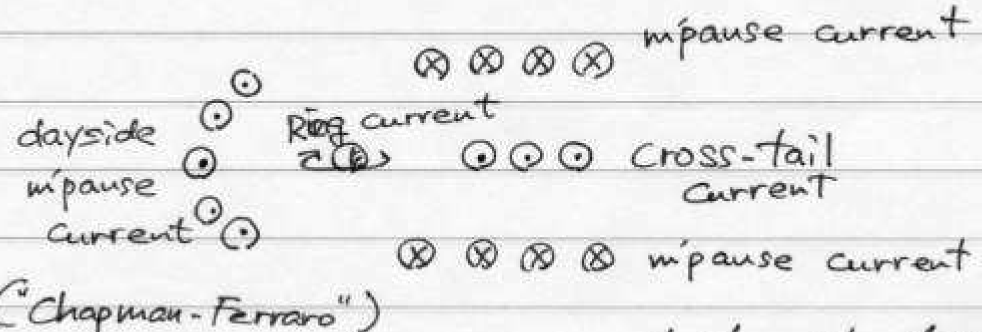
- Magnetic field



solar wind ··· curved mag. field
dayside magnetosphere
··· dipolar field
nightside ··· elongated / stretched field

- Plasma populations

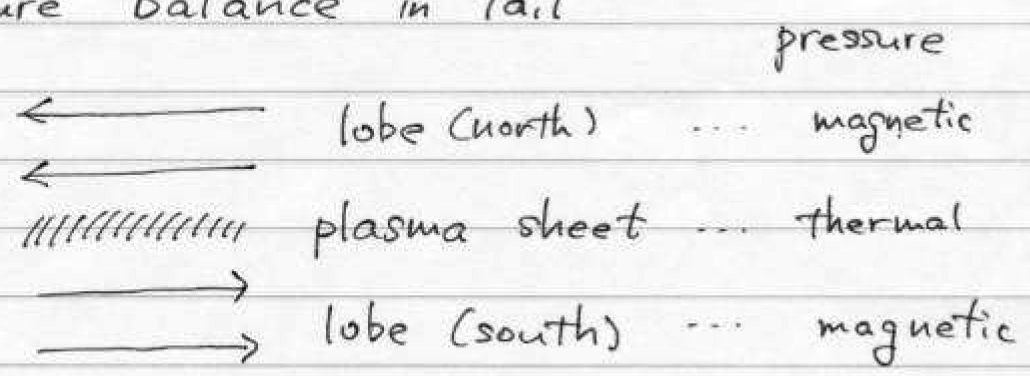
- Electric current



consistent with Ampère's law

$$\vec{j} = \frac{1}{\mu_0} \nabla \times \vec{B}$$

- Pressure balance in tail

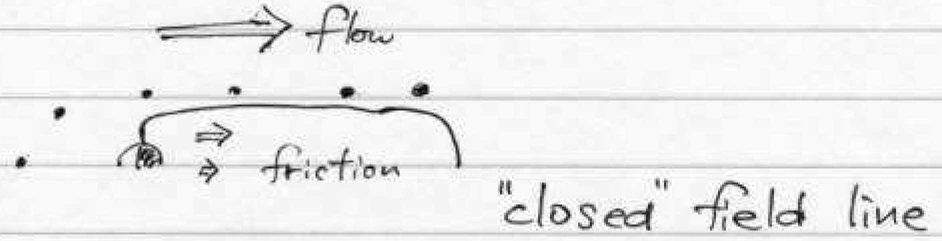


$$\underset{\text{plasma sheet}}{P_{th}} = \underset{\text{lobe}}{P_{mag}}$$

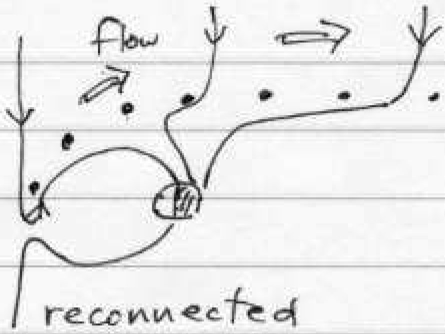
- Why is tail-field stretched?

possibility 1 ... viscosity / friction

(Axford and Hines, 1961)

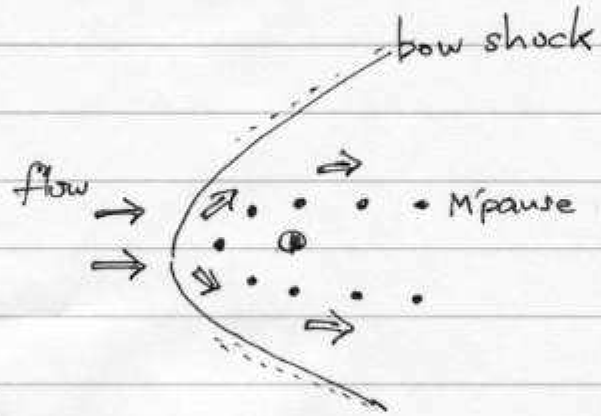


possibility 2 ... reconnection (Dungey 1961)



"open" field line

- bow shock



- standing shock wave
- m'sphere as obstacle
- flow speed changes from super-magnetosonic to sub-magnetosonic

cf. magnetosonic speed

$$V \sim \sqrt{V_A^2 + C_s^2}$$

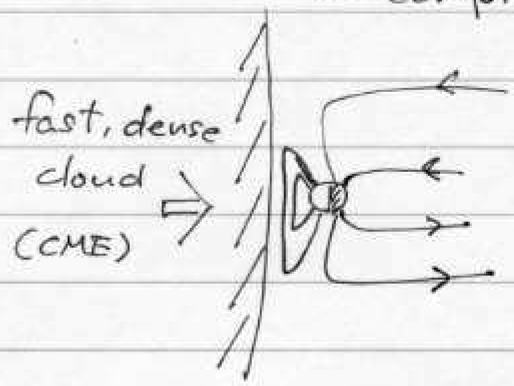
- plasma is (1) compressed, (2) heated

- magnetic field also compressed

Chap. 3 Earth (dynamic picture)

Geomagnetic storm

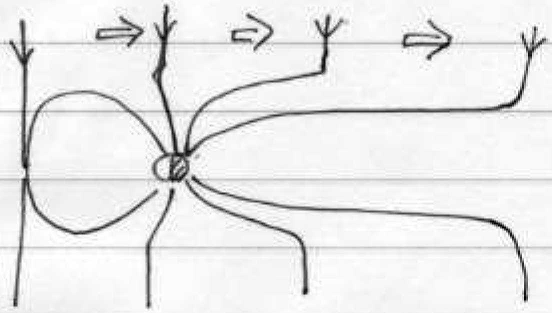
... compression of magnetosphere (Chapman, 1930)



1. dayside compression ~ minutes
2. nightside compression ~ hours
3. recovery phase (expansion) ~ days

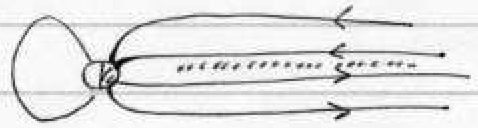
Substorm (reconnection model)

1. growth phase (T ~ 40 min.)



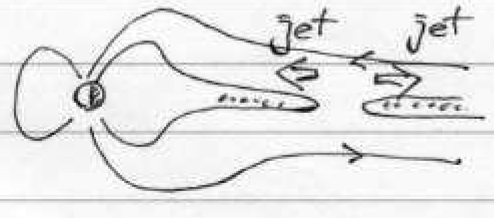
- magnetic field transport from dayside to tail (energy charge in tail)
- reconnection on dayside (southward IMF)

2. expansion phase ($T \sim 10$ min.)



thin current sheet
anti-parallel mag. field

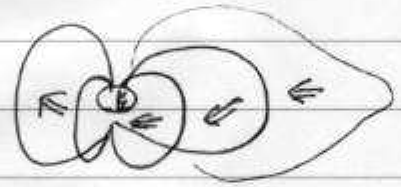
⇓ tail reconnection (energy discharge)



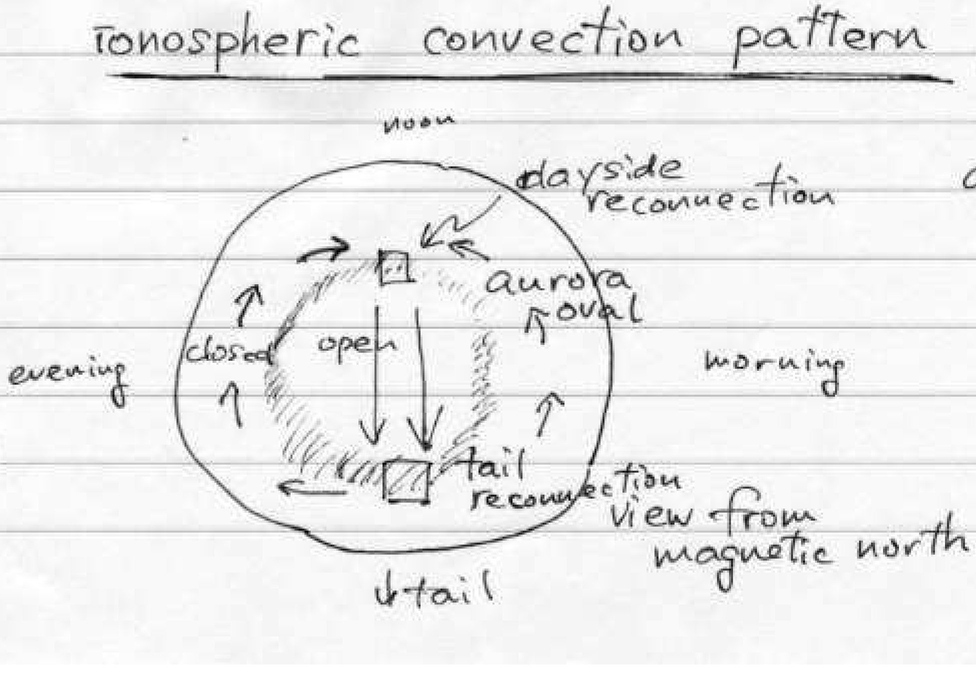
- "dipolarization"
- plasma jet ("plasmoid")
- field-aligned current into/out of ionosphere → bright aurora

3. recovery phase ($T \sim$ hours)

- magnetic field transport back to dayside



<u>ionospheric convection pattern</u> (southward IMF)



auroral oval
... open/close boundary

Chap. 4 Mercury

Magnetized, non-atmospheric body.

Surface magnetic field ~ 200 nT
(Mariner 10, Messenger)
cf. 30000 nT at Earth surface

Magnetopause distance

$$\frac{1}{2}\rho v^2 = \frac{B^2}{2\mu_0} \quad \text{(pressure balance)}$$

$$B \propto \frac{1}{r^3} \quad \text{(dipole field)}$$

$$B_0 = 200\,(\text{nT}) \quad \text{(surface)}$$

$$\rho = m_p \times 20\,(\text{cm}^{-3}) \quad \text{(solar wind mass density)}$$

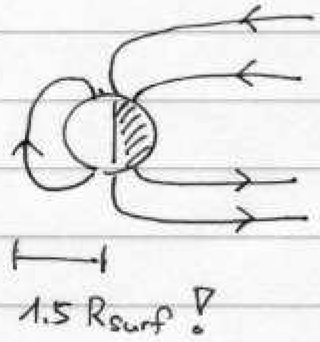
$$v = 300\,(\text{km/s}) \quad \text{(solar wind speed)}$$

$\Rightarrow$ $R_{mp} \simeq 1.5\ R_{surf}$ (from planet center) !

surface - magnetopause distance

$$0.5\ R_{surf} = 1200\ \text{km}$$

Magnetosphere



weak magnetic field

↓

small magnetosphere

- No radiation belt (or ring current)
  ... planet ~~occupying~~ occupies a lot of volume

- Sodium (Na) sputtering
  → sodium-rich plasma

- "Hybrid" scale ... magnetosphere size of the order of ion gyro-radius

- → currents are carried by electrons? (m'pause, plasma sheet)

- Fast reaction, rapid reconfiguration

  length dayside-tail $\ell \sim 10\ R_{surf}$ (24000 km)
  solar wind speed $V \sim 300$ km/s

  ↘

  reaction time $\tau = \ell / V \sim 80$ s
  (cf. 40 min. at Earth)

- reconnection ? substorm ?

Dynamo problem

Theoretical estimate of surface magnetic field

$$\underset{\Lambda}{\text{Elsässer number}} = \frac{|\text{Lorentz force}|}{|\text{Coriolis force}|}$$

$$= \frac{|\sigma(\vec{v}\times\vec{B}) \times \vec{B}|}{|2\rho\vec{\Omega}\times\vec{v}|}$$

$$\sim \frac{\sigma B^2}{2\rho\Omega}$$

Assume $\Lambda \sim 1 \;\Rightarrow\; B \propto \sqrt{\Omega}$.

Scale Earth magnetic field into Mercury,

$$B(\text{earth}) = 30000 \text{ nT}$$
$$\Omega(\text{earth}) = 2\pi/1 \text{ (rad/day)}$$
$$\Omega(\text{merc}) = 2\pi/58 \text{ (rad/day)}$$

$$\Rightarrow \quad B(\text{merc}) = 4000 \text{ nT}.$$

Mercury field is weaker than Earth-scaled field.

Chap. 5 Venus and Mars

Lost dynamo

Venus and Mars have atmosphere
but no global magnetic field.
(dipole)

Estimate of dipole moment (upper limit !?)

Venus $10^{-5} \times$ (Earth dipole)
↘ 0.1 nT at surface PVO

Mars $10^{-5} \times$ (Earth dipole)
↘ 0.5 nT at surface MGS

Mars have magnetized crust
e.g. 200 nT at 400 km altitude

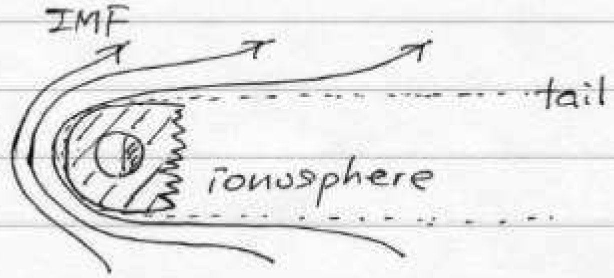
→ Dynamo operating in early time?

Why is dynamo missing?

Venus ... slow rotation (243 days)?

Mars ... core in solid state?
(Liquid core became solid.)
Small planet size

Magnetosphere



Pressure balance

(1) magnetic boundary

$$\frac{1}{2} \rho v^2 = \frac{B^2}{2\mu_0}$$

solar wind dynamic pressure — solar wind magnetic pressure

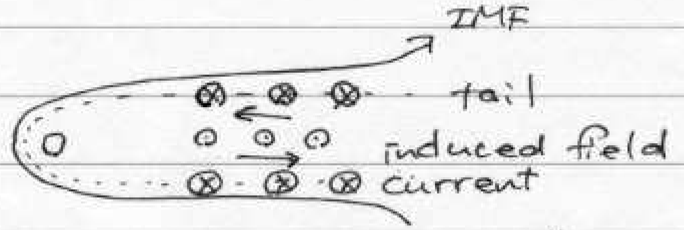
↑ field compression on dayside

(2) ionopause

$$\frac{1}{2} \rho v^2 = nkT$$

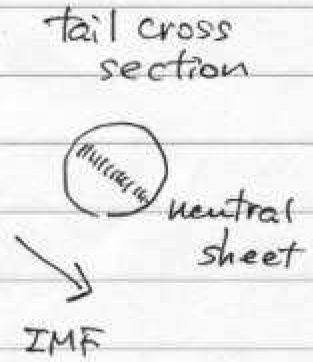
ionosphere gas pressure

Induced magnetic field



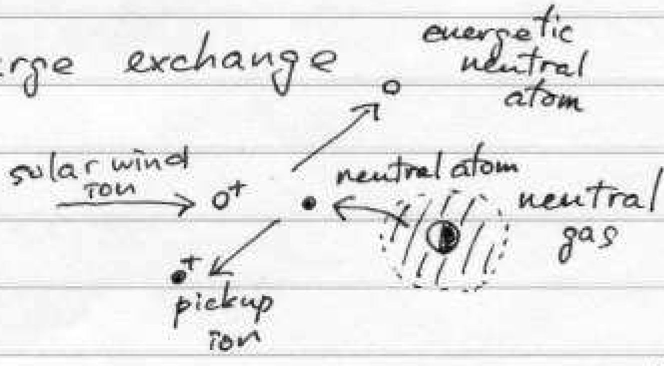
→ "induced magnetosphere"

sensitive to IMF direction



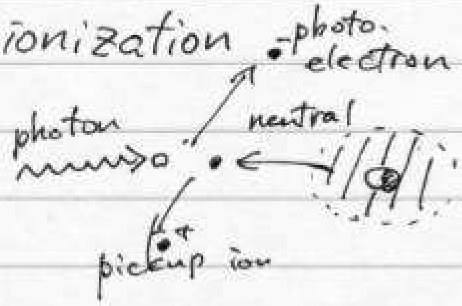
Pickup process

(1) charge exchange



plasma gains
additional mass

(2) photoionization



Chap. 6 Jupiter and Saturn

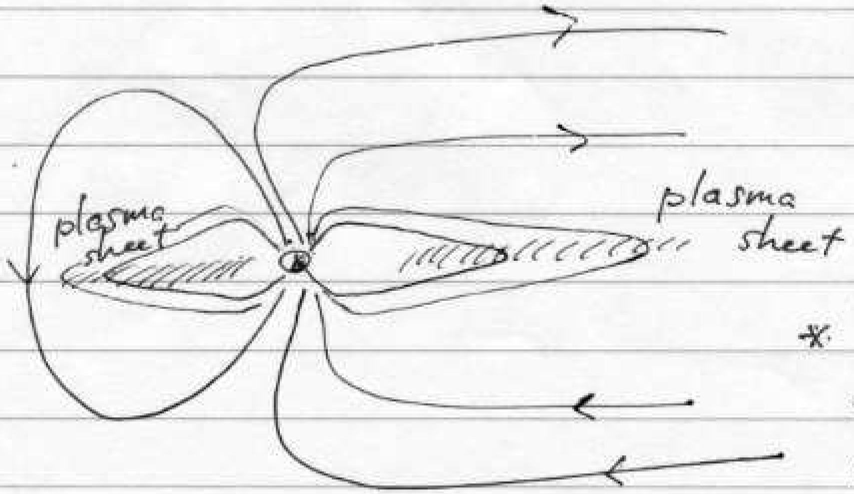
Giant magnetosphere

surface magnetic field
400 000 nT (Jupiter)
20 000 nT (Saturn)
metalic hydrogen core ?

magnetopause distance
50 - 100 R_{surf} (Jupite) ca. 5 R_{sun}!
20 R_{surf} (Saturn) ca. 2 R_{sun}

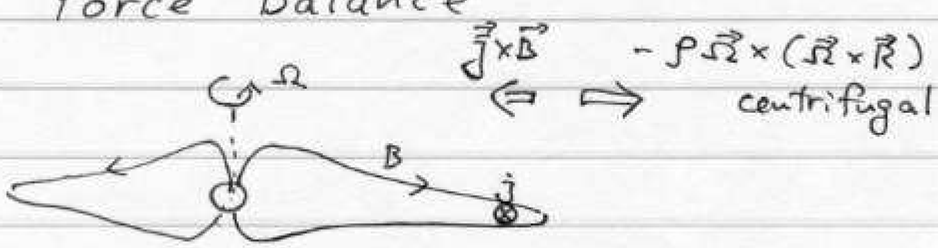
rotation - dominant
10 hours (Jup.), 10.5 hours (Sat.)
→ large centrifugal force

aurora ... magnetosphere - ionosphere coupling.
radio emission source

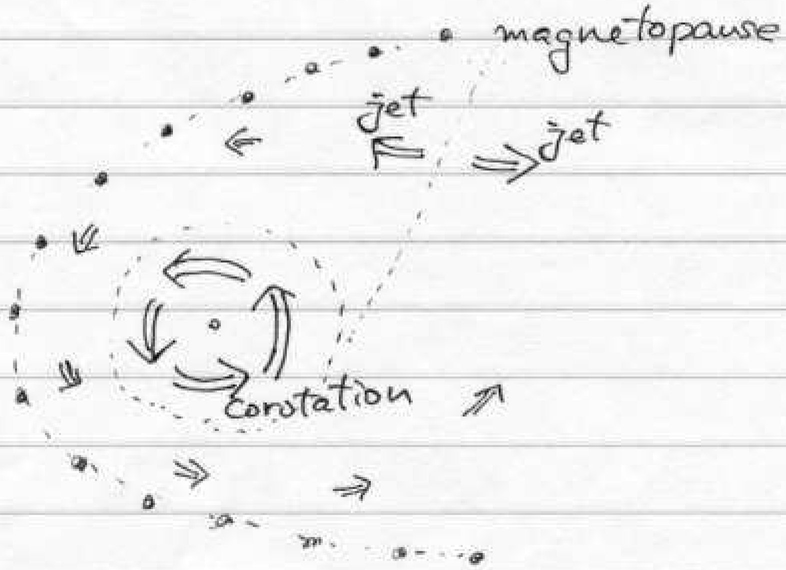


* Saturn dipole axis aligned with rotation axis

Force balance



View from rotation axis (Jupiter)



periodic jet → substorm? reconnection?
on morningside
internally driven substorm?

Plasma source from satellites

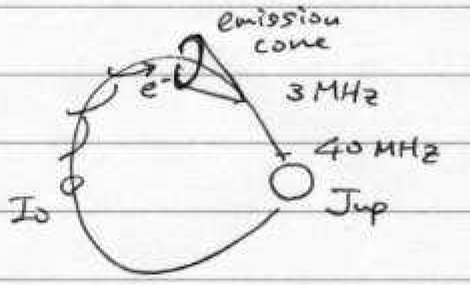
Io (Jup.) ... volcanism, sulfur-rich plasma torus

Enceladus (Sat.) ... water ice, water-ion products

Radio emission

- auroral emission (cyclotron maser)
- radiation belt (synchrotron)

Jupiter aurora emission



← detectable at Earth surface

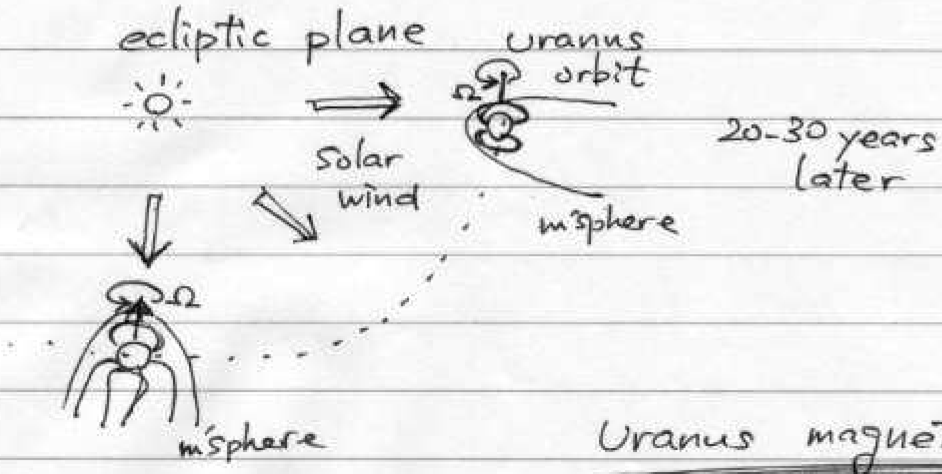
Uranus and Neptune

Magnetized, gas planets
- surface mag. field 23 000 nT (U), 14 000 nT (N)
- magnetopause distance 25 R_{surf} (U) 26 R_{surf} (N)

Large tilt angle (rotation axis – dipole axis)
59° (U), 47° (N)

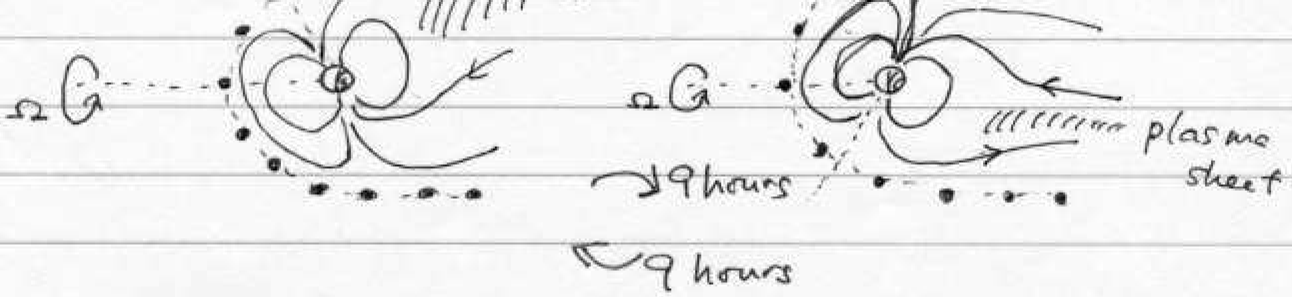
Uranus

Rotation axis almost in the orbital plane



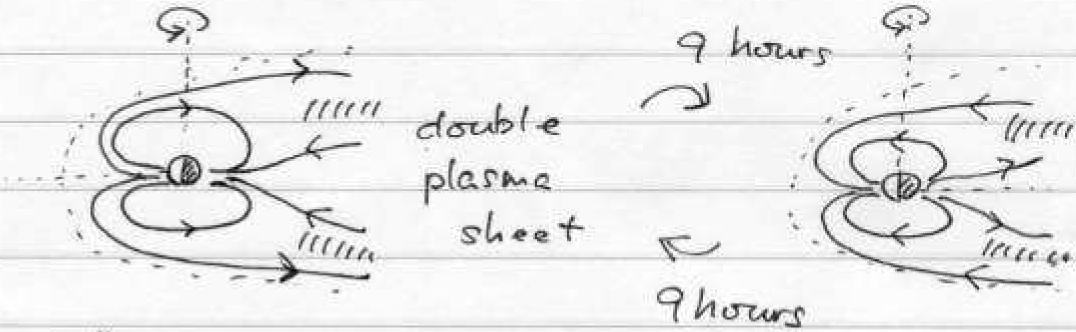
Voyager encounter 1986

Uranus magnetosphere (1)
(Voyager encounter 1986)



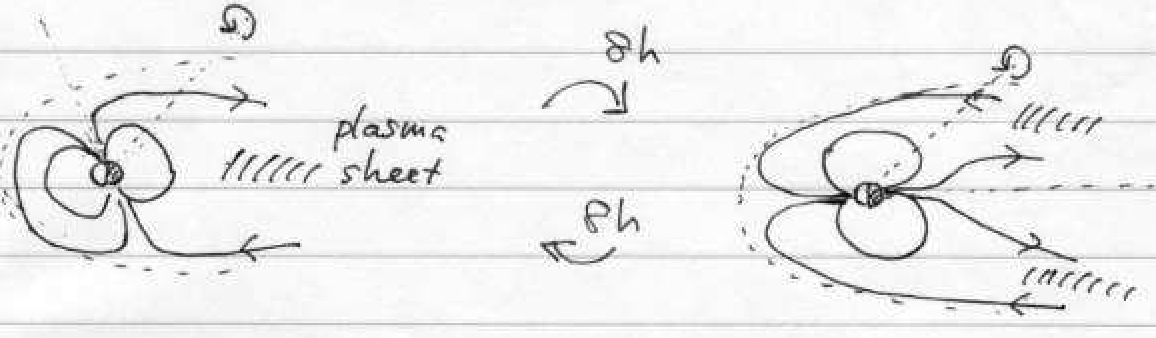
Uranus magnetosphere (2)

20 - 30 years later



"pole-on magnetosphere"

Neptune



pole-off

pole-on