Planetary Magnetospheres

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• Solar Wind / Solar Wind - Obstacle interaction
• Planetary Magnetic Fields
• Magnetospheric Boundaries
• Plasma Sources
• Plasma Circulation
• Role of Ionosphere
• Current Generators
• Aurorae (and satellite induced emissions)
• Exoplanetary Magnetospheres ?
• Foreword

High plasma conductivity
⇒ B frozen-in
⇒ \( E = -V \times B \) almost everywhere (0 in plasma frame)
⇒ quasi-neutrality
& \( E \cdot B = 0 \) (\( \Delta \phi \) conserved along B lines,
     = electric equipotentials)

• Acronyms

SW = solar wind
MS = magnetosphere
MP = magnetopause
B = magnetic field
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• Exoplanetary Magnetospheres ?
• Solar Wind

- dominated by bulk energy density: \( N mV^2/2 \)
- carries away solar B rooted in the Sun \( \Rightarrow \) ballerina skirt
- SW parameters at planetary orbits (r in AU):
  \[
  V \sim 400/r^{2/7} \text{ km/s} \quad T \sim 2 \times 10^5/r^{2/7} \text{ K}
  \]
  \[
  N = 5/r^2 \text{ cm}^{-3}
  \]
  \[
  B_r = 3/r^2 \text{ nT} \quad B_\phi = B_r \Omega r/V = 3/r \text{ nT}
  \]
  \[
  V_S \sim 60/r^{1/7} \text{ km/s} \quad V_A \sim 40x(1/2+r^{-2}/2)^{1/2} \text{ km/s}
  \]

- CIR, CME, more shocks away from the Sun (SW radial evolution)
- Solar Wind - Obstacle interaction

- depends on presence of obstacle’s:
  intrinsic large-scale B ionosphere conductivity

- 1\textsuperscript{st} case $\Rightarrow$ abrupt boundary in planetary $B = MP$

[Lepping, 1986]

[Cahill & Patel, 1967]
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- **Planetary Magnetic Fields**
  - dipole + high-order terms
  - known up to n~14 at Earth, n≤4 at other planets
  - measurements: MAG in-situ, teledetection (IR, radio)

<table>
<thead>
<tr>
<th>Planète</th>
<th>Terre</th>
<th>Jupiter</th>
<th>Jupiter</th>
<th>Saturne</th>
<th>Uranus</th>
<th>Neptune</th>
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<td>0.228</td>
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<td>-46.9°</td>
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<td>0.07</td>
<td>0.04</td>
<td>0.31</td>
<td>0.55</td>
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</tbody>
</table>

[adapted from Ness, 1992]
• Planetary Magnetic Fields [cont’d]

- weak dipolar field @ Mercury, ~10° tilt

[Acuña et al., 1983]

- ring current (magnetodisc) @ Jupiter & Saturn

[Ness et al., 1976, Connerney et al., 1988]
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• Magnetospheric Boundaries

- Pressure equilibrium : $P_{SW} = K N m V^2 \cos^2 \chi = P_{MS} = B_T^2 / 2 \mu_0$
  
  with $B_T = B_P + B_C = 2 B_P$ at MP nose

  $K = 1 - 2$

  $\Rightarrow$ MP shape

- MP sub-solar point (dipolar field : $B_P = B_{eq} (1 + 3 \cos^2 \theta)^{1/2} / R^3$):

  $R_{MP} = (2 B_{eq}^2 / \mu_0 K N m V^2)^{1/6}$
### Magnetospheric Boundaries [cont’d]

<table>
<thead>
<tr>
<th></th>
<th>Mercure</th>
<th>Terre</th>
<th>Jupiter</th>
<th>Saturne</th>
<th>Uranus</th>
<th>Neptune</th>
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</thead>
<tbody>
<tr>
<td>$R_p$ (km)</td>
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<td>6 378</td>
<td>71 492</td>
<td>60 268</td>
<td>25 559</td>
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<td>+11.7</td>
<td>-9.6</td>
<td>-0.</td>
<td>-58.6</td>
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<tr>
<td>Inclinaison $[B,\Omega]$(^\circ) et sens</td>
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<td>+11.7</td>
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<td>-46.9</td>
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<td>$R_{MP}$ ($R_p$) calculée [mesurée]</td>
<td>1.4</td>
<td>9</td>
<td>40</td>
<td>17</td>
<td>22</td>
<td>21</td>
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</table>

[Encrenaz et al., 2003]
Magnetospheric Boundaries [cont’d]

- Jupiter’s MS larger and more compressible \( (R_{MP} \propto P_{SW}^{-1/4.5}) \)

\( \Rightarrow \) internal plasma pressure

[Huddleston et al., 1998]
• Magnetospheric Boundaries [cont’d]

- supersonic / super-Alfvénic flow ⇒ bow shock ahead of MP
- in magnetosheath: slowed flow ($V:4$ for $M_A >> 1$)
  ⇒ B draping / pile-up ($|V||B| = c^i$)

[Spreiter et al., 1966]
• Magnetospheric Boundaries [cont’d]

- if no intrinsic B field
  ⇒ induced MS, bow shock,
    B draping, tail
  No cusp
• Magnetospheric Boundaries [cont’d]

- Earth bow shock: $R = \frac{25 R_E}{1 + 0.8 \cos \theta}$  thickness ~40% of MP
- Jupiter: MP closer to BS (thickness ~15%)  
  \[ \Rightarrow \text{equatorial flattening due mass loading (Io)} \]

[Joy et al., 2002; Russell, 2004]  
[Courtesy R. Prangé]
- Magnetospheric Boundaries [cont’d]
  - on-going MS compression measured by Cassini + Galileo
  - Jovian magnetotail extent (≥5 AU) measured by Voyager

[Desch, 1983]

[Kurth et al., 2002]
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- **SW**: cusp + diffusion/reconnection across MP
  
  H & He, T~100 eV
  
  ~1% of SW flow
  
  $10^{26}$ ions/s @ Earth
  
  $10^{28}$ ions/s @ Jupiter

- **Ionosphere**: vertical diffusive equilibrium of cold plasma
  
  T~0.1-1. eV
  
  $N = N_0 \exp\left(-\frac{(z-z_0)}{2H}\right)$
  
  $10^{26}$ N & O ions/s @ Earth
  
  $10^{28}$ H ions/s @ Jupiter
- **Plasma Sources** [cont’d]

  - Satellites:

    - Io (volcanism)
      - \(3 \times 10^{28}\) S & O ions/s
      - \(\Rightarrow\) plasma torus [Bagenal, 1994]

    - Titan (atmospheric escape)
      - \(10^{26}\) H & N ions/s
      - (+C ?) [Sittler et al.; 2005]

    - Enceladus (exosphere, plumes)
      - source & sink?
      - [Dougherty et al., 2005; Jones et al., 2006]

  - Icy satellites (or Mercury’s) surface: sputtering
- **Plasma Sources** [cont’d]

- Rings (sputtering / photo-dissociation + ionisation)
  
  water ions, $O^+$, $O_2^+$ [Young et al., 2005; Bouhram et al., 2006]

  up to $10^{28}$ ions/s [Richardson & Jurac, 2005; Hansen et al., 2005]

- Plasma reservoirs: boundary layers, plasma/current sheet, radiation belts

- Total MS mass $\sim 10^{10}$ kg @ Jupiter, $\sim 10^7$ kg @ Earth
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- **Plasma Circulation**

  - **Closed MS**
    
    - $V_{SW} \parallel MP$
    - equipotential flow lines
    - no plasma penetration
    - MS electrically insulated from outside SW
    - Internal plasma entrained by friction (a few $\rho_{Li}$)
    
    $\Rightarrow$ 2 convection cells
**Plasma Circulation** [cont’d]

Ok / circulation observations at Earth **BUT**

- energetic plasma inside MS
- large scale E (dawn → dusk) inside MS
- quasi permanent circumpolar aurora (∅ = 10°-20°, UV + radio)
- SW control ($B_z$) of MS activity
- **Plasma Circulation** [cont’d]

  - **Open MS**

    B reconnection at MP (stationary ? patchy ? $\rightarrow B_N \neq 0$) when $B_z \parallel B_P$
    
    ( MS closed or high-latitude reconnection when $B_z$ anti// $B_P$ )

    Transport of B line to tail, reconnection, dipolarization (= Dungey cycle)

    Neutral (X) line at equator

    Penetration of plasma in MS $\Rightarrow$ no more equipotential

[Dungey, 1961]
cycle de circulation du plasma et du champ magnétique dans la magnétosphère terrestre
1ère reconnection (côté jour) = début du cycle
Transport au-dessus des pôles
2ème reconnection (côté nuit)
éjection d'une bulle de plasma (plasmoïde) vers la queue
et retour d'une boucle de champ magnétique vers le côté "jour"
= un sous-orage magnétosphérique
**Plasma Circulation**  [cont’d]

- **Solar Convection** in MS  [antisolar above the poles]
  \[ E = -V \times B \sim \varepsilon V_{SW} \times B_{SW} \]  
  \( \varepsilon = 0.1 - 0.2 \)  
  \( \Delta \phi \sim \varepsilon V_{SW} B_{SW} \times 3 R_{MP} \)  
  \( \sim 50 \text{ kV} @ \text{Earth} \)  
  \( \sim 1 \text{ MV} @ \text{Jupiter} \)

- **Corotation**
  \[ E = \Omega R \times B \]  
  \( \Delta \phi \sim \Omega B_{eq} R_p^2 \)  
  \( \sim 90 \text{ kV} @ \text{Earth} \)  
  \( \sim 400 \text{ MV} @ \text{Jupiter} \)
- **Plasma Circulation** [cont’d]

  - *Global circulation = Convection + Corotation*
    
    Equipotentials = flow lines
    
    Stagnation point at LT = 18 h
- **Plasma Circulation**  [cont’d]

- **Plasmasphere** = permanently closed field lines, corotation dominated
• **Plasma Circulation**  [cont’d]

- Auroral oval = limit open/closed field lines
  
  = projection of equatorial neutral line on ionosphere

- Tail = MS antisolar extension, plasma convected to neutral plasma sheet -- -- --, stores / releases energy and magnetic flux
• Plasma Circulation  [cont’d]
EARTH

SATURN

JUPITER

Corotation region
Plasmasphere

[Courtesy R. Prangé]
- **Plasma Circulation** [cont’d]

- Plasma sources vs Synchronous orbit (where $F_{\text{centrifugal}} = F_{\text{gravitation}}$)

<table>
<thead>
<tr>
<th>Planet</th>
<th>$R_p$ [km]</th>
<th>$\Omega$ [rads/s]</th>
<th>$G_{\text{surf}}$ [ms$^{-2}$]</th>
<th>$R_{\text{synch}}/R_{\text{planet}}$</th>
<th>Plasma sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
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<td>$1.24 \times 10^{-6}$</td>
<td>3.3</td>
<td>96</td>
<td>None</td>
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<tr>
<td>Earth</td>
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<td>9.8</td>
<td>6.6</td>
<td>Ionosphere</td>
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<td>Jupiter</td>
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<td>$1.77 \times 10^{-4}$</td>
<td>25.6</td>
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<td>60000</td>
<td>$1.71 \times 10^{-4}$</td>
<td>10.8</td>
<td>1.8</td>
<td>Rings, moons</td>
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<td>3.2</td>
<td>Moons</td>
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<td>Neptune</td>
<td>24830</td>
<td>$1.01 \times 10^{-4}$</td>
<td>10.1</td>
<td>3.4</td>
<td>Moons</td>
</tr>
</tbody>
</table>

[Russell, 2004]

- At Jupiter: extended current disk
• Plasma Circulation [cont’d]

- Jupiter: outward radial transport (centrifugal interchange instability)
  ⇒ Vasyliunas cycle ~ rotation driven Dungey cycle
  ⇒ origin of auroral oval?

[André, 2006]

[Russell, 2001]

[Vasyliunas, 1983]
- **Plasma Circulation** [cont’d]

- Saturn: «intermediate» circulation?

[Image: Diagram of plasma circulation with labels such as Dungey-cycle, Vasyliunas-cycle, and Magnetopause.]

[Cowley et al., 2005]
• **Plasma Circulation** [cont’d]

- **Earth** dominated by convection
  ⇒ little/no rotational signature in magnetospheric phenomena (e.g. AKR)

- Same (even more so) expected for **Mercury**

- **Jupiter** dominated by corotation
  ⇒ many magnetospheric phenomena
  (particle flux, radio emissions…)
  reveal a strong rotational signature
  ⇒ measurement of rotation period to $10^{-6}$ accuracy [Higgins et al., 1997]

- **Saturn** = intermediate situation:
  corotation and convection compete
  ⇒ corotational signatures, with fluctuations
  (e.g. variable radio period) [Cecconi & Zarka, 2005]

Independent of B tilt! (at 1st order, except Uranus & Neptune)
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- mapping of MS and SW \( \Delta \phi \) (via equipotential B lines)

\[ \Rightarrow \text{high-latitude convection cells: } E_i >> E_{MS}, V_i << V_{MS} \]

- currents closure (in sputtered/vaporized regolith @ Mercury? \([\text{Slavin, 2004}]\) )
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\[ \nabla \cdot J = 0 \]

- SW / MS interaction : « region 1 » currents @ Earth
driven by \( \Delta \phi \) (dawn \( \rightarrow \) dusk) \( \propto V_{SW} \times B_{SW} \)
- **Current Generators** [cont’d]

- radial diffusion from Io ⇒ \( J_r \)
- plasma acceleration (corotation) by \( J_r \times B_{MS} \)
  (+ slowing down MS plasma due to mass loading)
  at expense or ionospheric plasma momentum via \( J_i \times B_i \)
  \( \nabla \cdot J = 0 \Rightarrow J_i = J_r B_i / B_{MS} \sim 2R^3 J_r \leq \sigma_i E_i \sim \sigma_i \Omega B_e / R^{1/2} \)
  ⇒ Ok as long as \( J_r \leq \sigma_i \Omega B_e / 2R^{7/2} \)
- Corotation breakdown at 20-50 \( R_j \)
  ⇒ \( J_{//} \) max ⇒ main auroral oval at Jupiter
- **Current Generators** [cont’d]

Unmagnetized satellite / MS interaction \([\text{Saur et al., 2004}]\) :

\[
E = -V \times B_J \quad \text{with} \quad V = V_{\text{corot}} - V_K \quad (=57 \text{ km/s @ Io})
\]

\[
\Delta \phi \sim 2 R_{\text{sat}} E \quad (=4 \times 10^5 \text{ V @ Io})
\]

Flow dominated by magnetic energy \(B_J^2/2\mu_0\)

\(M_A < 1\) (no bow shock)

[1 case of TransAlfvénic shock @ Europa with Galileo? \(\text{Kivelson, 2005}\)]

[Piddington & Drake, 1968; Goldreich & Lynden-Bell, 1969]
- **Current Generators** [cont’d]

Current induced by $E$ (a few $10^6$ A) closes
in Jupiter’s ionosphere (if $M_A << 1$, no $j_\perp$ in MS, $2\int_{B\text{-line}} ds/V_A << \int_{\text{flow}} ds/V$ (unipolar inductor))
in Jupiter’s magnetosphere (if $M_A < 1$, $j_\perp$ in MS, $2\int_{B\text{-line}} ds/V_A \geq \int_{\text{flow}} ds/V$ (Alfvén wings))

[Kivelson et al., 2004]
• **Current Generators** [cont’d]

- Dione interaction with Saturn MS?
- Enceladus? (exosphere, B draping [Dougherty et al., 2005])
- Titan, Rhea? (alternatively super/sub-Alfvénic interaction [Ledvina et al., 2004], induced radio emissions? [Menietti et al., 2007])

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[Desch & Kaiser, 1981; Kurth et al., 1981]

SKR @ 174 kHz, 28 Oct. - 18 Dec. 1980

SKR @ 59 kHz, 10-18 Nov. 1980
• **Current Generators** [cont’d]

- **Magnetized satellite / MS interaction** [Kivelson et al., 2004]: B reconnection

\[ P_{\text{dissipated}} \sim B_J^2/2\mu_0 V k\pi R_{\text{obstacle}}^2 \]

[McGrath et al., 2002; Feldman et al., 2000]

[Zarka et al., 2001, 2006]
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• Aurorae (and satellite-induced emissions)
  - Source = 1-10 keV electrons $\Rightarrow$ acceleration required
    - Strong currents + low plasma density [Knight, 1972]
    - Reconnection + dipolarization (adiabatic)
    - Compressions, $E_{\parallel}$, waves …
    - $\Rightarrow$ UV, IR, radio emissions
  - $\not=\,$ direct precipitation of SW in polar cusps

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[Birkeland, 1910]
• Aurorae (and satellite-induced emissions) [cont’d]

[Clarke, Prangé…]
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- High SW pressure $\Rightarrow$ compressed MS
- High SW power input $\Rightarrow$ very energetic MS $\Rightarrow$ intense e.m. emissions

[Zarka et al., 2001, 2006]
• Exoplanetary Magnetospheres? [cont’d]

- reconnection with stellar B
  (~ magnetic binaries, Ganymede-Jupiter) [Ip et al., 2004]
  or giant Io-Jupiter like interaction ($M_A < 1$ for hot Jupiters) [Zarka, 2006]

⇒ cf. observations by [Shkolnik et al., 2003, 2005]
Conclusions

• Variety of magnetospheric structures
  (function of SW strength, mass-loading…)
• Comparative approach of magnetospheres essential
• Saturn especially interesting because « intermediate »
• Prospects for exoplanets
• How can one do so much with so little mass?