Solar Wind Interaction with Planetary Bodies

Michele Dougherty, 1st November 2010

Recommended Reading:
   Chapter 7
Introduction to Space Physics, Ed. M. G. Kivelson & C. T. Russell.
   Chapters 8 and 15

Problem Sheet, solution at end of week
The solar wind and its interaction

- Flow of plasma from Sun - solar wind (SW), supersonic, hundreds kms/sec
- IMF is carried out into solar system by solar wind
- Planets & other solar system bodies act as obstacles to flow
- These bodies have varying characteristics, nature of interaction varies great deal
- 1st we knew about such interaction at Earth, Chapman and Ferraro, 1930 predicted Earth’s magnetic field act as obstacle to SW flow
The Solar Wind

- Ionised gas spirals out in steady stream
- What drives it?
- Base of SW is rotating; wind sweeps out in curve
- Cometary tails were a clue
Nature of interaction

- Depends on characteristics of body, such as:
  - Distance from Sun (SW density decreases as $1/r^2$)
  - Size of body
  - Does it have atmosphere/ionosphere?
  - Does it have intrinsic magnetic field & what is its strength (characterised via magnetic dipole moment)
Magnetic Field at Planets
Four types of interaction

1. Lunar/Moon type
   – Body with no atmosphere or magnetic field, e.g. our Moon
   – SW impacts directly on surface, plasma wake downstream
   – Other egs., asteroids, inactive cometary nuclei, certain moons at other planets

2. Earth type
   – Magnetised body
   – SW can’t penetrate magnetic field, diverts around it, forms cavity - magnetosphere (MS)
   – Other egs, Mercury, Jupiter, Saturn, Uranus, Neptune, Ganymede
   – Major differences in internal dynamics of various MS’s (solar wind driven versus rotation dominated)
   – Plasma flow at Mercury & Earth dominated by SW Electric field, whereas outer planets dominated rotational flow
   – Signature of this interaction is Bow Shock (BS) and Magnetopause (MP) boundaries upstream
3. **Venus type**
   - Unmagnetised body with significant atmosphere and ionosphere
   - Venus rotates very slowly (every 243 days) – lack of significant magnetic field
   - Has significant ionosphere & dense atmosphere
   - Ionospheric plasma very good electrical conductor, acts as obstacle to SW flow with its embedded IMF, shock wave results
   - Other egs. Mars, Titan (complicated eg can be in MS, magnetosheath, SW)

4. **Comet type**
   - Combination of:
     - Venus-like (close to Sun)
     - Lunar-like (far from Sun)
   - Cometary nuclei chunks ice & dust, radii few kms, negligible magnetic fields
   - Two states:
     - Inactive state, most of orbital period, when far from Sun
     - Active state, when nucleus approaches Sun, surface heated solar radiation, ice sublimates & produces water vapour & other volatiles
     - Produces extensive coma, millions kms extent, IS forms close to nucleus
     - ENCKE_042507.mpg
     - Stereo
Earth's Magnetosphere

Solar Wind

$\rho_{sw} u_{sw}^2$

B$^2$ / 2$\mu_0$

Current

Magnetopause

Bow Shock
Space Plasmas

- Plasma – gas of charged/ionised particles (ions & electrons)
- Most space plasmas are collisionless – assume magnetic field is frozen into the plasma
• Main pressure component in upstream SW is dynamic pressure
• Thermal pressure dominates dynamics downstream
• Inside MS magnetic pressure most important

• Why does intrinsic magnetic field act as obstacle to SW flow?

• Usually in space plasmas assume plasma & magnetic field are frozen together (MHD approx)
• External SW plasma flow with embedded IMF can’t easily penetrate another magnetised plasma region

• Examine in more detail............
• Mercury has small magnetic dipole

• Information from Mariner 10

• NASA – Messenger

• ESA – Bepi Colombo
**Solar wind interaction with Venus**

- Gases of atmosphere become ionised
- Also have B field in SW
- Formation of ionospheric (IS) planetary obstacle

![Diagram of solar wind interaction with Venus](image)
Lunar Interaction

- Body like our Moon, composed of insulating material & submerged in flowing plasma

- Simply absorbs SW particles incident on it

- No Bow Shock forms, SW plasma stopped at surface, IMF passes through body (so no field line pile-up)

- B field perturbation forms downstream

- Propagates away at Alfven speed

- SW absorbed on ram side – flows back into plasma wake region
• Some additional effects if body has conducting core:
  – (a) insulating mantle is thin
  – (b) insulating mantle is thick
• Perturbation persists as long as external field varies on short time scales
Cometary Interaction

• Most extreme example of atmosphere interacting with flowing plasma

• When near Sun – have huge atmospheres & small solid body

• Need to introduce term – mass loading

• Where background flowing plasma becomes laden with heavy ions of atmospheric origin – slows down

• Our understanding greatly increased s/c missions
Comet MHD Model
Outer Planets

- Revisit Earth-type of interaction

- Knowledge of outer planets arisen from s/c flybys, orbiters

- Pioneer 10 & 11, Voyager 1 & 2, Ulysses, Galileo & Cassini

- All outer planets have large magnetic fields

- Use simple theory estimate MP locations at Saturn, Neptune & Uranus, reasonably consistent

- At Jupiter – MS plasma very important, interaction not entirely Earth-like
Outer planet s/c flybys
\[ \text{size of magnetic cavity } \propto \left( \frac{M_p^2}{\text{dyn. press}} \right)^{\frac{1}{6}} \]

\[ M_E = 8 \times 10^{15} \text{ Tm}^3 \]

<table>
<thead>
<tr>
<th>Planet</th>
<th>Heliocentric Distance (AU)</th>
<th>Magnetic Moment ($M_E$)</th>
<th>Tilt Angle</th>
<th>Expected Magnetopause Distance</th>
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<tbody>
<tr>
<td>Earth</td>
<td>1.0</td>
<td>1</td>
<td>10.8°</td>
<td>$0.7 \times 10^5$ $11R_E$</td>
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<tr>
<td>Jupiter</td>
<td>5.2</td>
<td>20,000</td>
<td>9.7°</td>
<td>$30 \times 10^5$ $45R_J$</td>
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<tr>
<td>Saturn</td>
<td>9.5</td>
<td>580</td>
<td>&lt;1°</td>
<td>$12 \times 10^5$ $21R_S$</td>
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<tr>
<td>Uranus</td>
<td>19.2</td>
<td>49</td>
<td>59°</td>
<td>$6.9 \times 10^5$ $27R_U$</td>
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<tr>
<td>Neptune</td>
<td>30.1</td>
<td>27</td>
<td>47°</td>
<td>$6.3 \times 10^5$ $26R_N$</td>
</tr>
</tbody>
</table>
Magnetosphere of Jupiter

Solar Wind

Magnetopause

Plasma Sheet

Bow Shock

Magnetosheath
- MP $45 - 113 R_J$
- Io produces sig. mass

Jupiter

noon - midnight meridian

Solar Wind

$Z(R_J)$

$X(R_J)$
Corotation

Convection

Earth — dominated

Jupiter — planetary

Saturn — combination

Figure 7
Saturn’s Magnetosphere
Enceladus

In inner magnetosphere

Source of Saturn’s E ring?

Relatively young surface

Three Cassini flybys (1265km, 500km, 173km)

Cracks on surface
• Rings are an enormous, complex structure
• E ring largest planetary ring in solar system (from orbit of Mimas to Titan)
• Particle’s in rings mainly water ice
Magnetic Field at Planets
Large increase in ion cyclotron wave activity

Water group ions
Field Line Draping

"Co-rotating" plasma

$v_M > v_T$
Draping geometry schematic, formation of an induced magnetosphere
Initial ideas after 2 flybys

• Diffuse atmosphere around Enceladus, strong source to maintain?

• Strong ion cyclotron wave activity – water group ions

• Seems to be additional signature around CA of March flyby – in addition to the atmospheric type signature

• Field is being pulled towards Enceladus – almost as if Enceladus is acting as an amplifier of the Saturn field

• Cassini Project moved 3\textsuperscript{rd} flyby much closer
Looking down on XY plane

YZ plane with Saturn to right
- Fractures/ Tiger Stripes near south pole
- Warm Spot near south pole
- Internal heat leaking out?
- Warmest temperature over one of fractures
- ISS & CIRS data (Porco et al., Spencer et al, 2006)
UVIS occultation data
(Hansen et al., 2006)
Polar Plume
VIMS data

- November 2005
- Enceladus is source of E ring
• Close flyby in 2008

• Numerous flybys in extended mission

• Discussions about future missions to Enceladus

• Marvellous example of inter-disciplinary science