Interaction between plasmas and magnetic fields

Motion of particles in magnetic fields - on larger ‘fluid’ scales?

Dominant type of plasma flow?

Compressibility?

Solar wind versus ‘internal’ effects (rotation)

Magnetosphere-ionosphere coupling
Sessions

- **Tue Feb 16, 2:00-~3:00 pm** – Lecture
- **Tue Feb 23, 1:00-~1:45 pm** – Lecture, assign example problems
- **Tue Mar 16, 1:00-~2:00 pm** – Lecture?, work through solutions to problems
- Material based on lectures given at Heliophysics Summer School, US (2015). Videos and notes for these and other material is at [http://www.ucl.ac.uk/~ucapnac](http://www.ucl.ac.uk/~ucapnac)
Prelude: Aurora

- Selfoss, Iceland, 2019
- Phone image of *auroral emission* in the sky.
- Dominant colour – green – from a transition of excited oxygen.
- What excites the oxygen?
Energetic electrons (~1-100 keV) ‘rain down’ onto the upper atmosphere and excite atomic oxygen at >~100 km altitude.

O relaxing from $S^1 \rightarrow D^1$ state radiates 5577 Å (green) photons.

Other colours / wavelengths from nitrogen and oxygen.

Proton precipitation can also produce aurorae.

The energetic particles come from the magnetosphere, and many are accelerated just before they enter the atmosphere.
What causes the aurora?

The “northern lights” are caused by collisions between fast-moving particles (electrons) from space and the oxygen and nitrogen gas in our atmosphere. These electrons originate in the magnetosphere, the region of space controlled by Earth’s magnetic field. As they rain into the atmosphere, the electrons impart energy to oxygen and nitrogen molecules, making them excited. When the molecules return to their normal state, they release photons, small bursts of energy in the form of light.

When billions of these collisions occur and enough photons are released, the oxygen and nitrogen in the atmosphere emit enough light for the eye to detect them. This ghostly glow can light up the night sky in a dance of colors. But since the aurora is much dimmer than sunlight, it cannot be seen from the ground in the daytime.

Why the different colors?

The color of the aurora depends on which gas is being excited by the electrons and on how much energy is being exchanged. Oxygen emits either a greenish-yellow light (the most familiar color of the aurora) or a red light; nitrogen generally gives off a blue light. The oxygen and nitrogen molecules also emit ultraviolet light, which can only be detected by special cameras on satellites.

Why does it take different shapes?

Scientists are still trying to answer this question. The shape of the aurora depends on where in the magnetosphere the electrons came from and on what caused them to precipitate into the atmosphere. Dramatically different auroral shapes can be seen in a single night.

Where can I see the aurora?

Auroras usually occur in ring-shaped areas centered around the magnetic poles of Earth. The complete rings, called the auroral ovals, can only be seen from space. False color picture of the auroral oval in ultraviolet light. The brighter the color, the more intense the aurora. The crescent of color on the left is from sunlight scattered over the upper atmosphere. The best places to see the aurora are in Alaska, Canada, and Scandinavia, during the late evening hours. Resident of the northernmost United States – near the Canadian border – typically see auroras several times a year. On rare occasions – perhaps once per decade – auroras are visible as far south as Florida or Japan.

Do auroras occur in the southern hemisphere?

An auroral oval also exists around the southern magnetic pole. This picture from space shows the simultaneous “crowns” of the auroral ovals.

Prelude: Aurora

- Precipitating particles which ‘power’ the auroral emissions are guided by the Earth’s magnetic field.
- The dipolar field ‘funnels’ source particles from wide regions in the magnetosphere down onto ‘oval-shaped’ regions which surround the magnetic poles.
Overview: Solar Wind–Magnetosphere Interaction

- Noon-midnight ‘slice’ of the system.
  - The magnetic field of the planet (Earth) deflects particles in the solar wind plasma.
  - Solar wind flows at hundreds of km / s – faster than plasma waves. A bow shock is formed.
  - Field is ‘frozen in’ to the flowing plasma (Alfven’s Theorem)
The fields of the Solar Wind (IMF=Interplanetary Magnetic Field) and the magnetosphere **merge across the dayside boundary** of the magnetosphere when these fields are oppositely directed.

- The ‘X line’ structure separates inflowing plasma and distinct B-field either side; from outflowing plasma which carries away *merged* or ‘reconnected’ field lines.
- The outflowing ‘open’ field lines **connect from the planet to the solar wind**.
Overview: Solar Wind–Magnetosphere Interaction

- Boundaries *and* points of ‘entry’ for plasma *(magnetic reconnection)*
- Dayside field merging produces **open field lines** (‘flux tubes’) which get ‘dragged’ by the ambient solar wind from dayside to nightside.
- Nightside field is very stretched *(‘magnetotail’)*.
- Open flux tubes pile up towards the mid-plane of the ‘tail’ – another X line (neutral point) is formed.
- **Open flux → closed flux** and ‘snaps back’ towards planet.
- **Plasmasheet**: hot (~keV), low-density (~0.3 cm\(^{-3}\))
- **Plasmasphere**: cool (~1 eV), high-density (~10\(^3\) cm\(^{-3}\)), flow is in sense of planetary *corotation*
Overview: Solar Wind–Magnetosphere Interaction

- This continual ‘cycling’ of magnetic flux and plasma is the Dungey Cycle (Dungey 1951)
- It is a result of the magnetosphere-solar wind interaction, and is fundamental to the formation of the aurora.
Overview: Solar Wind–Magnetosphere Interaction

- Noon-midnight ‘slice’.
  - Boundaries and points of ‘entry’ for plasma (magnetic reconnection)
  - Strong asymmetry in field structure.
  - Plasmasheet: hot (~keV), low-density (~0.3 cm\(^3\))
  - Plasmasphere: cool (~1 eV), high-density (~10\(^3\) cm\(^3\)), flow is in sense of planetary corotation

‘Close-up’. ➔

- Ring current region.
- Auroral oval associated with particles which impact neutral molecules in atmosphere.
Substorm

Fig. 00 [The development of a magnetospheric substorm in the magnetotail according to the near-Earth neutral line hypothesis “after Hones (1984).]

Fig. 01 [Magnetic field variations associated with a structure defined as a plasmoid which was detected behind the Earth by the ISEE 2 satellite “after Slavin et al. (1978).] The variation in the u angle between 9719 and 9899 UT indicates a positive Bz perturbation followed by a negative perturbation. The plasma flows tailward at 399 km/s during this transient disturbance. It is important to note that the magnetic field is strongest in the center of the structure contrary to what one would expect for a plasmoid as originally conceived but consistent with that expected for a flux rope.

(Hones, 1984)
the pressure peaks in the interval 18:00 – 21:00 MLT. There is a second peak at 02:00 – 05:00 MLT. However, after the substorm onset, the pressure increases mostly in the sector 21:00 – 05:00 MLT, the same local time sector where ion \( \text{flux} \) Figure 3. Monoenergetic aurora electron energy \( \text{flux} \) from 1 h before to 1 h and 45 min after the substorm onset in the same format as in Figure 2. The substorm onset occurs at \( \Delta t = 0 \) min. (Wing, 2013)

‘Epoch-superposed’ maps of electron precipitation added over both nightside hemispheres. Time zero is ‘substorm onset’. This is for one type of aurora – ‘monoenergetic’ / discrete.
To make progress in understanding observations of aurorae and magnetospheres, we need to understand the different ways in which charged particles can move in a planetary magnetic field.

The plasma in the magnetosphere – most of the time – can be thought of as a magnetized fluid whose motion we can think of as the ‘average’ of the many particles which are in that fluid.

This ‘collective action’ of individual particles to form ‘average’ properties is the basis of magnetohydrodynamics (MHD).
Amendments

- **Tue Feb 23, 1:00-~1:45 pm** – Lecture material / Q&A

- **Tue Mar 16, 1:00-~2:00 pm** – Lecture material, assign ‘homework’ problems.

- **Homework solutions posted at a later date. Email:** nicholas.achilleos@ucl.ac.uk

- **Material based on lectures given at Heliophysics Summer School, US (2015). Videos and notes for these and other material is at** [http://www.ucl.ac.uk/~ucapnac](http://www.ucl.ac.uk/~ucapnac)
Starting Point: Particle Motion in a Magnetic Field

- **Lorentz Force:** For a particle of charge \( q \), mass \( m \) and velocity \( \mathbf{v} \) moving in electric field \( \mathbf{E} \) and magnetic ‘field’ \( \mathbf{B} \) (N.B. SI units):
  \[
  \mathbf{F}_L = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = m \frac{d\mathbf{v}}{dt}
  \]

- **Motion:** If \( \mathbf{E} = 0 \) and \( \mathbf{B} = B \mathbf{e}_z \) in Cartesian frame (uniform field along \( z \)), xy motion is *circular* (right-handed for electrons) with angular frequency \( \Omega_C = |qB/m| \) (cyclotron or gyrofrequency)
  the radius of the circle is \( r_C = |mv_\perp/(qB)| \) (also called Larmor radius)
  where \( v_\perp \) = speed perpendicular to \( \mathbf{B} \)

![Diagram](image)

- **Kinetic Energy:** Does not change, since force always acts perp. to \( \mathbf{v} \)
Now add $E$ perpendicular to $B$:

- **Motion**: $E$ field accelerates particle for ‘one half’ orbit – increased $r_c$.
- Over ‘other half’ have decreased $r_c$ - the two combined causes a ‘drift’ of the guiding centre.
- One can show that the drift velocity is: $u_E = \frac{E \times B}{B^2}$
- Forces which depend on sign of charge do *not* generate drift currents.
Other Types of Drift

- **Guiding principle:** Drift occurs when particle ‘sees’ significant changes in force during a single gyration.

- **Gradient Drift:** $B$ changes with spatial position.
  \[ u_g = \left( \frac{W_{\perp}}{qB^3} \right) B \times \nabla B \]

- **Curvature Drift:** Particle whose g.c. moves along curved field line feels a centrifugal force.
  \[ u_c = \left( \frac{2W_{||}}{R_c qB^2} \right) \hat{n} \times B \]

- **‘W’ terms:** Kinetic energy

- **$\hat{n}$** Unit vector pointing out from C to particle
Question

• Gradient Drift:

\[ u_g = \left( \frac{W_\perp}{q B^3} \right) B \times \nabla B \]

• Curvature Drift:

\[ u_c = \left( \frac{2W_\parallel}{R_c q B^2} \right) \hat{n} \times B \]

Q: Explain why these drifts contribute to a **westward** directed ring current (consider particle at the magnetic equator of the planet’s dipole field)?
Answer

- **Gradient Drift:**
  \[ u_g = \left( W_\perp / (qB^3) \right) B \times \nabla B \]

- **Curvature Drift:**
  \[ u_c = \left( 2W_\parallel / (R_c qB^2) \right) \hat{n} \times B \]

**Q:** Explain why these drifts contribute to a **westward** directed ring current (consider particle at the magnetic equator of the planet’s dipole field) ?

**A:** Check the relevant directions in the diagram – an ion would drift east-west while an electron would drift in the opposite direction. Do you know of any other types of current which may contribute to the *ring current* ?

*adapted from Tsyganenko and Usmanov 1982*
Q: Explain why these drifts contribute to a westward directed ring current (consider particle at the magnetic equator of the planet’s dipole field)?

A: Drift currents come from long-range drift of the particle’s guiding centre. Another type of motion which can create current is collective motion of many gyrating particles – magnetization current.
Where plasma density / pressure shows strong spatial gradient – within an ‘averaging box’ for calculating current, more particles, on average, moving in one direction than the opposite direction.

This example is often referred to as diamagnetic current.

The guiding centres can be *stationary*, but the collective superposition of many gyrations constitutes current flow.

Here it is microscopic motions rather than g.c. drift.

In a system at equilibrium, \( \mathbf{J} \times \mathbf{B} \) arising from all sources of current will balance the other forces on the plasma.
Constants of the motion: ‘Invariants’

- **Guiding principle**: In collisionless plasmas, we may identify an ‘invariant’ if $\Delta B \ll B$ over one gyration.

- **First adiabatic invariant** - ‘magnetic moment’
  \[ \mu = \frac{W_\perp}{B} \]

- **An effective force $\parallel B$:**
  \[ F = -\mu \frac{dB}{ds} \]

- **Particle moves to higher $B$, $v_\parallel \downarrow$, $v_\perp \uparrow$, $v$ const.**

- **Invariant**
  \[ \frac{\sin^2 \alpha}{B} \]

- **‘Mirror point’**
  \[ \alpha_M = \pi/2 \quad B_M = B / \sin^2 \alpha \]

- **Consider the situation** $B_M > B_{\text{SURF}} \rightarrow \sin^2 \alpha < B/B_{\text{SURF}}$
  i.e. mirror field $B_M$ exceeds that at planet’s surface.

- **Represents a loss cone** at any location where particles are lost to atmosphere before they can mirror (maybe excite *auroral emissions*)
Constants of the motion: ‘Invariants’

- **Guiding principle:** Each invariant is linked to a certain type of motion, provided the field does not change appreciably over the corresponding timescale of that motion.

Types of motion: **Gyration, Bounce, (Azimuthal) Drift**

⇒ ‘Drift shell’ concept

pluto.space.swri.edu/image/glossary/pitch.html, Based on Figure 5-10, "Handbook of Geophysics and the Space Environment," ed. A. S. Jursa (1985)
Collective behaviour: Debye ‘shielding’

- ‘Test’ particles ‘distant’ from a given ‘source ion (or electron) are ‘shielded’ from the source electric field.
- Mobile electrons form a neutralizing ‘sheath’ of charge.

The shielded potential \( \Phi \) is characterised by the Debye length \( \lambda_D \)

\[
\Phi = \left( \frac{q}{4\pi \varepsilon_0 r} \right) \exp\left(-\frac{r}{\lambda_D}\right) \quad \text{‘cuts off’ for } r \gg \lambda_D
\]

\[
\lambda_D = \left( \frac{\varepsilon_0 k T_e}{n_e e^2} \right)^{1/2} \quad \text{colder, denser electrons are better ‘shielders’}
\]

Assumes: quasineutrality (\( n_e \sim n_i \)) and lots of ‘shielding particles’ i.e. for collective behaviour

Plasma ‘lambda’ \( \Lambda = n_e \lambda_D^3 \gg 1 \)
<table>
<thead>
<tr>
<th>Plasma</th>
<th>Density (m$^{-3}$)</th>
<th>Temp. (eV)</th>
<th>Debye Length (m)</th>
<th>Plasma Λ</th>
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<tr>
<td>Interstellar</td>
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<td>0.1</td>
<td>1</td>
<td>$10^6$</td>
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<td>Solar Wind</td>
<td>$10^7$</td>
<td>10</td>
<td>10</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>Solar Corona</td>
<td>$10^{12}$</td>
<td>$10^2$</td>
<td>$10^{-1}$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>Magnetosphere</td>
<td>$10^7$</td>
<td>$10^3$</td>
<td>$10^2$</td>
<td>$10^{13}$</td>
</tr>
<tr>
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<td>$10^{12}$</td>
<td>$10^{-1}$</td>
<td>$10^{-3}$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Fusion Expt.</td>
<td>$10^{22}$</td>
<td>$10^5$</td>
<td>$10^{-5}$</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

Based on Table 2.2 from ‘Physics of Space Plasmas’ by Kivelson, in ‘Introduction to Space Physics’ ed. Kivelson and Russell
Towards MHD

- Particle motions generate electromagnetic fields, but these same fields influence motion of neighbouring particles. A difficult problem.

- The ‘MHD’ (magnetohydrodynamic) approach combines a fluid approach for the plasma (treatment of many particles in terms of average properties) with Maxwell’s equations for the fields (with $J = \text{current density}$ and non-relativistic flow).

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \text{Faraday’s Law} \]

\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad \text{Ampère’s Law} \]

\[ \mathbf{J} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \quad \text{Ohm’s Law} \]
Towards MHD

• Combining these gives the **induction equation** for the B field:

\[
\frac{\partial B}{\partial t} = \nabla^2 B / (\mu_0 \sigma) + \nabla \times (u \times B)
\]

• The first term is ‘diffusive’. For collisionless plasmas ($\sigma \rightarrow \infty$) and/or adequately large length scales, this term will be negligible compared to the second **convective** term.

• If convective term dominates, one can show that the **frozen-in condition** applies and that the magnetic flux threading a moving ‘blob’ of plasma remains constant.

\[
\int \int_S B \cdot dS = \text{const.}
\]
MHD concepts: Magnetic pressure and tension

Using Ampère’s Law:

\[ J \times B = \frac{1}{\mu_0} (\nabla \times B) \times B = -\nabla \left( \frac{B^2}{2\mu_0} \right) + (B \cdot \nabla)B / \mu_0 \]

- Sum of a ‘magnetic pressure gradient’ and a ‘tension force’
- The field-parallel components of these two terms must always add to zero (think of a vacuum dipole field)
- The field-perpendicular component of the tension force is related to field line curvature:
  \[ -\left( \frac{B^2}{\mu_0 R_c} \right) \hat{n} \]
- In rapidly rotating, disc-like outer magnetospheres of Jupiter and Saturn, this curvature force (inward) balances (mainly) the strong centrifugal force plus plasma pressure gradient (outward)
Magnetic merging and reconnection

- In a simple ‘dimensional’ form, the Induction Equation is:
  \[ \frac{B}{\tau} = \frac{1}{\mu_0 \sigma} \frac{B}{L^2} + V_{\text{perp}} \frac{B}{L} \]
  So ratio of convective to diffusive terms scales as
  \[ R_M = V_{\text{perp}} \mu_0 \sigma L \] - known as the ‘magnetic Reynolds number’
  It is high for collisionless, fast-flowing plasmas

- A current sheet with converging flows will show magnetic merging where \( R_M \approx 1 \) e.g. ‘magnetic X line’ at magnetopause

(Messer)
Different plasma ‘regimes’

- Tail Lobe: Open field
- PSBL: Prob. Closed field, thermal $<<$ flow energy
- PS: hot ~keV particles, flow $<<$ thermal energy
- Reconnection: antisunward plasma streaming to thermal energy of PS
- More PS particles from ionosphere (O+) rel. to solar wind (H+) at ‘active’ times

$\beta = \frac{P_{\text{PLAS}}}{P_{\text{MAG}}}$

### Table

<table>
<thead>
<tr>
<th></th>
<th>Magneto-sheath</th>
<th>Tail Lobe</th>
<th>PS Boundary Layer</th>
<th>Central Plasma Sheet</th>
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<tr>
<td>$n$ ($\text{cm}^{-3}$)</td>
<td>8</td>
<td>0.01</td>
<td>0.1</td>
<td>0.3</td>
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<td>$T_i$ (eV)</td>
<td>150</td>
<td>300</td>
<td>1000</td>
<td>4200</td>
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<tr>
<td>$B$ (nT)</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>10</td>
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<tr>
<td>$\beta$</td>
<td>2.5</td>
<td>0.003</td>
<td>0.1</td>
<td>6</td>
</tr>
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(From chapter by Hughes in ‘Intro to Space Phys’)
• **Homework Problems:** You can download these (pdf) - Look for the link ‘Planetary Magnetospheres: Homework Problems’ at: https://www.ucl.ac.uk/~ucapnac

• For those who attempt the problems, I will post solutions in 1-2 weeks from now. Any questions / concerns, email me at nicholas.achilleos@ucl.ac.uk

• **In this session:** We draw on some of the concepts we have encountered so far to look at:

- The size of magnetospheres
- Internal sources of plasma (Jupiter and Saturn)
- Magnetic observations of plasma transport
- How aurorae are linked to patterns of plasma flow
Magnetospheric ‘Pressure Balance’

adapted from Tsyganenko and Usmanov 1982

- Magnetopause currents act to ‘hold off’ the solar wind flow. At ‘nose’, the magnetic force is equivalent to an internal magnetic pressure, which balances the external solar wind dynamic pressure $P_{SW}$.

- If we simplify using dipole $B \sim 1/r^3$, then we expect subsolar location of MP to satisfy:

$$R_{MP} \propto P_{SW}^{-1/6}$$

- Q: Why don’t we consider curvature force in this balance condition?
Magnetospheric ‘Pressure Balance’

adapted from Tsyganenko and Usmanov 1982

Magnetopause currents act to ‘hold off’ the solar wind flow. At ‘nose’, the magnetic force is equivalent to an internal \textit{magnetic}, which balances the external solar wind \textit{dynamic pressure} \( P_{SW} \).

If we simplify using dipole \( B \sim 1/r^3 \), then we expect subsolar location of MP to satisfy:

\[
R_{MP} \propto P_{SW}^{-1/6}
\]

A: Compare the length scales: MPCL width \(<<\) field line \( R_C \)
Magnetospheres scaled by stand-off distance of dipole field

<table>
<thead>
<tr>
<th></th>
<th>( M/M_\oplus )</th>
<th>( M_{\text{Dipole}} )</th>
<th>( M_{\text{mean}} )</th>
<th>( M_{\text{Range}} )</th>
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</thead>
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<tr>
<td>Mercury</td>
<td>( \sim 4 \times 10^{-4} )</td>
<td>1.4 ( R_M )</td>
<td>1.4 ( R_M )</td>
<td></td>
</tr>
<tr>
<td>Earth</td>
<td>1</td>
<td>10 ( R_E )</td>
<td>10 ( R_E )</td>
<td></td>
</tr>
<tr>
<td>Saturn</td>
<td>600</td>
<td>20 ( R_S )</td>
<td>24 ( R_S )</td>
<td>22-27* ( R_S )</td>
</tr>
<tr>
<td>Jupiter</td>
<td>20,000</td>
<td>46 ( R_J )</td>
<td>75 ( R_J )</td>
<td>63-92* ( R_J )</td>
</tr>
</tbody>
</table>

Inflated magnetospheres of Jupiter & Saturn due to HOT PLASMAS

Note bimodal average locations
* Achilleos et al. 2008  # Joy et al. 2002

Orig. Images / Text Credit: Bagenal / Bartlett
(Mercury mag. moment has been updated)
Internal mass sources: Moons

**Enceladus** (icy satellite): Mass source for Saturn’s E ring, magnetosphere (~10-100 kg/s of plasma) **First discovered by MAG** (*Dougherty et al, Science, 2006*)

**Io**: Mass source for Jupiter’s magnetosphere (~1000 kg/s of plasma)
Jupiter: A Rapidly Rotating Magnetosphere

- $P_{\text{ROT}} \approx 9.9 \text{ hr}$
- $R_J \approx 71500 \text{ km} \approx 11 \, R_E$
- $B_{J,\text{EQ}} \approx 428000 \text{ nT} \approx 14 \, B_{\text{E,EQ}}$
- $\mu_J = B_{J,\text{EQ}} \, R_J^3 \approx 18000 \mu_E$
- A ‘cavity’ in the solar wind.
- Boundaries in field / flow
- Magnetopause on dayside extends to $60-90 \, R_J$ (c.f. Earth, $10 \, R_E \approx 1 \, R_J$)

Image Credit: Fran Bagenal / Steve Bartlett
Jupiter: A Rapidly Rotating Magnetosphere

- Subsolar MP location pressure balance

\[(1+\beta) \frac{B^2}{2\mu_0} \approx \rho_{sw} v_{sw}^2\]

- Large \(\mu_J\) and plasma \(\beta\) – large magnetosphere

- ‘Disc-like’ field-Jovian system ‘squishy’ \(R_{MP} \sim P_{SW}^{-1/4}\) cf Earth \(P_{SW}^{-1/6}\)

- Disc-like obstacle – ‘polar-flattened shape’ (e.g. Saturn: Pilkington et al JGR 2014)
An internal plasma source: Io

- Adds ~500-1000 kg/s of sulphur and oxygen plasma to the system
- The plasma does not ‘build up’ indefinitely – radial transport
In this work, we have excluded such chaotic periods from our database of current sheet crossings.

The height of a rigid tilted magnetodisc located in a dipole equator is given by

\[ Z_{cs} = r \tan q_{cs} \cos f \left/ \cos f_0 \right. \quad (1) \]

where \( Z_{cs} \) is the height of the current sheet in sIII (right-hand) coordinates, \( r \) is the cylindrical radial distance of the observer from Jupiter’s spin axis, \( q_{cs} \) is the tilt of the magnetodisc with respect to the planetary equator, and \( f_0 \) is the azimuthal direction (called the prime meridian) in which the elevation of the current sheet is maximum. From the VIP4 model of Jupiter’s internal field [Connerney et al., 1998], \( q_{cs} = 9.52/176 \) and \( f_0 = 339.4/176 \) (east longitude).

As discussed above, observations from Pioneer and Voyagers space crafts show that the current sheet crossings at radial distances >25 \( R_J \) are delayed from the expected dipole equator crossings in proportion to the radial distance of the observer (see Figure 4, where we show current sheet crossing longitudes from Voyager 1). This has been traditionally understood in terms of a signal delay required for the information about the motion of the dipole to propagate to the outer magnetosphere. Northrop et al. [1974] provide a more accurate description of the situation by using the concept of a wave packet traveling in a subcorotating magnetosphere in the presence of a radial outflow (\( u_r \)).

Northrop et al. showed that the incremental delay \( d/dr \) in the arrival of information about the magnetic equator at a radial distance \( r \) is given by

\[ d/dr = V_{A} B f_0/C_0 r B W_{J}/C_0 W_m(1) u_r + V_{A} B r/C_0/C_1 \quad (2) \]

where \( W_J \) and \( W_m \) are the angular rotation rates of Jupiter and the magnetosphere, respectively, and \( V_{A} \) is the local Alfvén wave velocity. Northrop et al. used Mestel’s [1961, 1968] MHD solution to relate the magnetic field configuration to the plasma flow:

\[ u = k B + m r \hat{j} \quad (3) \]

where \( k \), an arbitrary scalar function, quantifies the relationship between the field-aligned flow and the magnetic field and \( m \) is a constant along a field line. In the ionosphere of Jupiter, \( B_j \) is close to zero; therefore \( m \) can be identified as the angular velocity of the ionospheric plasma (\( W_i \)). Following Goertz [1981], equation (2) can then be rearranged with the help of (3) as

\[ d/dr = B f_0 r B r/C_0 W_{J}/C_0 W_i(1) u_r + V_{A} B r/C_0/C_1 \quad (4) \]

Equation (4) shows that the delay in the current sheet crossing time arises as a consequence of the nonrigid...
Jupiter and Saturn are large, rapid rotators, carrying much angular momentum. This angular momentum is imposed on the surrounding magnetosphere – flow is dominated by rotation. Flows generally arise from the competition between the solar wind and the planetary rotation ‘forcing’ the plasma in the system.

Earth shows a rotational ‘core’ magnetosphere surrounded by a layer of solar-wind-driven flows.
• Jupiter’s main oval also linked to flow shear – but here, that ‘shear’ arises from the different rotation periods of the planet (~10 hr) and the plasma disc (~10 up to ~30 hr).
• Source of disc plasma is the moon, Io – adds ~500-1000 kg/s of sulphur / oxygen plasma (e.g. Bagenal and Sullivan, 1981, JGR).
• Diagram shows the general sense of the currents.
• Usually, main oval emissions map to ~20-30 RJ in the equatorial plane – location of ‘breakdown in corotation’ of plasma.
• Global energy dissipated is ~90-200 TW (Joule heating + precip’n), ~1000 times the energy range for the Earth.
• Ray et al (e.g. JGR, 2010) considered effect of field-aligned E
Models of plasma rotation using the theory of Hill (1979)

- Note that gravity has very little direct influence here …
- Important advances / refinements to this theory in much of the literature.
Auroral Oval: Jupiter

- UV image of Jupiter’s aurora taken by HST ACS instrument.

Youtube Jupiter UV movie
https://www.youtube.com/watch?v=oFsoXjFoKf4

Main oval – corotates with the planet, it is not Sun-aligned.

Io ‘spot’

Cusp?
Some simple considerations:

• The ‘average’ Jovian configuration is a plasma concentrated into a relatively thin, near-equatorial sheet.

• In an average sense, of order ~1 tonne/s of plasma must be lost from the system, to balance the logenic source.

• The net transport of this material from Io orbit must be achieved in the ‘quasi-dipolar’ region ($r <\sim 10-15$ RJ), where the field strongly resists ‘deformation’.

• Thus we need a ‘mode’ of transport where plasma mass is displaced, but magnetic flux is not ‘interchange’ – a process which relies on the development of ‘texture’
Galileo observed field enhancements of 1-2% (10-25 nT) over 6-7.7 RJ (e.g. Kivelson et al, GRL, 1997)

- Event shown is at 6.03 RJ, lasts 10s, has density depletion Ni/No >~ 0.53
- Estimated distance of origin: 7.2 RJ
- Note also disappearance of ion-cyclotron waves: consistent with Vr~100 km/s to ‘avoid’ growth due to ion pickup (Russell et al, 1997)

**Figure 4.** The field magnitude and components in the interval of enhanced field at ~17:34 UT. Shading emphasizes the 1 s intervals during which the field increased and decreased abruptly. The marked decrease of the power in the ion cyclotron waves during the interval of interest is evident.
Interchange Properties

- Heavier tubes are outward-moving.
- Close to Io, magnetic data indicates outward motions dominant (balanced by inward motions at other longitudes)
- Further away, motions ‘combine’ to achieve overall transport

• Kivelson et al (GRL, 1997)
Interchange Properties

- **Interchange concept** first proposed by Ionnadis and Brice (1971), further developed by e.g. Siscoe and Summers (1981), Southwood and Kivelson (1987), Yang et al (1994).
- **More recently** e.g. André and Ferrière (2008, JGR, effect of pressure anisotropy); Kidder et al (2009, JGR, Saturn multifluid model, effect of Enceladus and solar wind); Observations by Cassini at Saturn (e.g. Hille et al 2005, Rymer et al 2009)
What goes in must (eventually) come out

- Flux tubes cannot maintain integrity
- The process of mass-loading leads to strong radial expansion of tubes in the tail region
- Formation of plasmoids, dipolarizations – à la Vasyliunas (1983)
- Importance of Kivelson and Southwood (2005) analysis: Must combine MHD and kinetic framework
- ~1 keV heavy ions can ‘pick up’ ~20 keV from centrifugal acceleration, moving 45-50 RJ in cyl. radial dist.
- Significant rotation / expansion of tube during bounce period - unstable plasma sheet.

Krupp et al, 2004

Kivelson and Southwood 2005
What about the Earth’s aurora and flows?

- Here we consider following the motion of the ionospheric ‘feet’ of flux tubes which march across the Earth’s polar cap.
- Vortices of flow carry field between closed and open topology.
What about the Earth’s aurora and flows?

- Plasma flow just above the ionosphere determines the electric field.
- \( E \) changes direction across regions where flow velocity changes.
What about the Earth’s aurora and flows?

- Thus the currents (driven by $E$) converge or diverge across the OCB.
- Current must close – get sheets of field-aligned current (FAC)
- Upward FAC is supported by downgoing auroral electrons
- Forms a persistent auroral oval.
Auroral Oval: Saturn – an ‘Earth-like’ aurora

- HST images of Saturn’s southern UV aurora presented by Badman et al (JGR, 2005).
- Concurrent observations by Cassini → planet’s auroral response to the passage of a solar wind compression / shock.
- Polar cap boundary (main oval) strongly contracts to higher latitudes, an ‘Earth-like’ response.
- Compression → magnetic reconnection on the nightside, which closes of order 10 GWb of open magnetic flux (~20x Earth value).
| Summary |
|-----------------|-------------|-------------|-------------|
| **Earth**       | **Jupiter** | **Saturn**  |
| Dipole moment   | $1\mu_E$   | $18000\mu_E$| $550\mu_E$ |
| M’pause standoff | $1R_{MP,E}$| $80R_{MP,E}$| $20R_{MP,E}$|
| distance $R_{MP}$|            |             |             |
| $P_{ROT}/(R_{MP}/V_{SW})$ | ~500 | ~2.5 | ~8 |
| Auroral energy  | ~10s of GW | ~100 TW | ~20 TW |
| dissipated      |            |             |             |
| Main auroral ‘oval’ due to: | Solar wind-driven | Planetary rotation | Solar wind-driven*, with fainter rot’n oval |
| Other examples of | Transpolar arc | Polar dawn | Oscillations in |
| transient aurora | ($change in IMF$ | ‘spots’ (tail | oval location |
|                  | $B_Y$) (e.g. Milan | reconn.) | (‘camshaft’ |
|                  | et al, 2005)      | (Radioti et al, | currents) (Nichols |
• Without a magnetic field, accretion between two stars in a binary system occurs via a stream.
• The stream intersects itself, spreads out and forms a ‘classical’ accretion disc.

*Lubow and Shu, 1975*
Brief Glimpse of a Stellar Magnetosphere

- Add a magnetic field now to the accreting star.

- If it is strong enough, magnetic pressure interrupts dynamic pressure of the stream flow before disc has fully formed – ‘truncated’ disc (intermediate polars).

- For very strong fields, no disc – only an accretion column (polars).

For more details, see the notes on ‘Astrophysical Discs’ at https://www.ucl.ac.uk/~ucapnac/
Summary

- Magnetospheres are natural laboratories for \textit{plasma physics}.
- We may describe plasma motion in terms of individual particle \textit{drifts}.
- When we consider \textbf{collective behaviour}, MHD provides a framework for treating the plasma as a \textit{fluid} permeated by electromagnetic \textit{fields}. Concepts of \textbf{magnetic ‘pressure’ and ‘tension’} are useful.
- The magnetic field structure plays an important role in \textbf{force balance} and \textbf{plasma transport and dynamics}. Reconnection is an important means of ‘solar wind – magnetosphere coupling’.
- \textbf{Magnetosphere-ionosphere coupling} ‘transmits’ energy and momentum by means of \textit{field-aligned current} systems. These are often associated with \textit{auroral emissions}.
- \textbf{MISSIONS} to Jupiter: \textit{Juno} (JOI 2016), \textit{JUICE} (JOI planned 2030)

- \textbf{Further recommended reading} for those interested (not exhaustive!):
  - ‘Heliophysics’ series (ed. Schrijver / Siscoe / Bagenal / Sojka);
  - ‘Introduction to Space Physics’ (ed. Kivelson and Russell);
  - ‘Basic Space Plasma Physics’ (Baumjohann / Treumann);
  - ‘Jupiter’ book (ed. Bagenal, Dowling, McKinnon);
  - ‘Physics of the Jovian Magnetosphere’ (ed. Dessler)
  - Special issue of SSR / ISSI book ‘Giant Planet Magnetodiscs and Aurorae’ (ed. Szego et al)