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

• **Fri Feb 3, 3:30-~4:40 pm** – Lecture

• **Fri Feb 10, 3:30-~4:40 pm** – May have to do a Zoom session (TBC)

• 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)
• 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. 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)

http://helios.gsfc.nasa.gov
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 $\rightarrow$ 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

http://helios.gsfc.nasa.gov
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.

http://helios.gsfc.nasa.gov

http://pluto.space.swri.edu
Fig. 00: The development of a magnetospheric substorm in the magnetotail according to the near-Earth neutral line hypothesis (after Hones, 1983).

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 angle between September 12 1979 UT indicates a positive $B_z$ 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).

(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 Figure 3. Monoenergetic aurora electron energy/uniFB02ux 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 $t = 0$ min.

‘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.

(Wing, 2013)
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).
**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

$$\Omega_C = \frac{|qB|}{m} \quad \text{(cyclotron or gyrofrequency)}$$

the radius of the circle is

$$r_C = \frac{|mv_{\perp}|}{|qB|} \quad \text{(also called Larmor radius)}$$

where $v_{\perp} =$ speed perpendicular to $\mathbf{B}$

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

\[\text{ExB}\]  

(\text{relative gyroradii not to scale})

• **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.
  \[ u_g = \left( W_\perp / (qB^3) \right) B \times \nabla B \]

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

- **‘W’ terms:** Kinetic energy

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

C: Centre of curvature
Question

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

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

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

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

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

**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*
• Gradient Drift:
\[ u_g = \left( \frac{W_\perp}{qB^3} \right) B \times \nabla B \]

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

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

\textbf{A:} Drift currents come from long-range drift of the particle’s guiding centre. Another type of motion which can create current is \textit{collective motion} of many gyrating particles – \textit{magnetization current}. 

adapted from Tsyganenko and Usmanov 1982
Diamagnetic 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.

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

First adiabatic invariant - ‘magnetic moment’ $\mu = W_\perp / B$

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)
Sessions

• Fri Feb 3, 3:30-~4:40 pm – Lecture

• Fri Feb 17, 3:30-~4:40 pm

• 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
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 $\lambda_D$

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

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

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

Plasma ‘lambda’ $\Lambda = n_e \lambda_D^3 \gg 1$
## Properties of Various Plasmas in Nature

<table>
<thead>
<tr>
<th>Plasma</th>
<th>Density (m⁻³)</th>
<th>Temp. (eV)</th>
<th>Debye Length (m)</th>
<th>Plasma Λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstellar</td>
<td>10⁶</td>
<td>0.1</td>
<td>1</td>
<td>10⁶</td>
</tr>
<tr>
<td>Solar Wind</td>
<td>10⁷</td>
<td>10</td>
<td>10</td>
<td>10¹⁰</td>
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<tr>
<td>Solar Corona</td>
<td>10¹²</td>
<td>10²</td>
<td>10⁻¹</td>
<td>10⁹</td>
</tr>
<tr>
<td>Magnetosphere</td>
<td>10⁷</td>
<td>10³</td>
<td>10²</td>
<td>10¹³</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>10¹²</td>
<td>10⁻¹</td>
<td>10⁻³</td>
<td>10³</td>
</tr>
<tr>
<td>Fusion Expt.</td>
<td>10²²</td>
<td>10⁵</td>
<td>10⁻⁵</td>
<td>10⁷</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
Signs of ‘Collective Behaviour’

7.3.1 Plasma Frequency

Figure 7.2: A slab of plasma in which the electrons have been displaced by a small amount $x$.

- Consider a slab of plasma, width $s$, area $A$ (as a face on a plane orthogonal to the sheet of paper).
- Displace all electrons in slab by $x$
- Produces charge build-up $Q = N_e x A$ (related to dipole moment density $P$)
- Equivalent to a capacitor with $Q = \pm N_e x A$ on each plate
- We will see that there are oscillations with frequency $\omega_P = \sqrt{N_e e^2 / m_e \varepsilon_0}$

- The ‘thought experiment’ of displacing electrons then allowing them to respond to the resulting charge separation.

- Results in oscillation about an equilibrium position with frequency given by $\omega_P = \sqrt{N_e e^2 / m_e \varepsilon_0}$
Signs of ‘Collective Behaviour’

- The plasma frequency shows up again when we look at how electrons respond to the oscillating electric field of a passing wave in the plasma.

- If the wave frequency $\omega \gg \omega_p$ the electron fluid is not efficient at responding to and neutralizing the perturbation in field/charge – the wave propagates without being affected.

- If the wave frequency $\omega \ll \omega_p$ the electron fluid has plenty of time to ‘act’ – wave cannot propagate far without being damped.
Signs of ‘Collective Behaviour’

- The plasma frequency shows up again when we look at how electrons respond to the oscillating electric field of a passing wave in the plasma.

- If the wave frequency $\omega > \omega_p$ the electron fluid is not efficient at responding to and neutralizing the perturbation in field / charge – the wave propagates without being affected.

- If the wave frequency $\omega < \omega_p$ the electron fluid has plenty of time to ‘act’ – wave cannot propagate far without being damped.

- Nicely summarized by the dispersion relation for an idealized plasma (exp(ik) is a decaying function for imaginary k):

$$k^2 = \frac{\omega^2}{c^2} \left( 1 - \frac{\omega_p^2}{\omega^2} \right)$$
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:

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

• The first term is ‘diffusive’. For collisionless plasmas \((\sigma \to \infty)\) 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.

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

Using Ampère’s Law:

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

- 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:

\[ -\left( \frac{B^2}{2\mu_o R_C} \right) \hat{n} \]

- 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 \textit{collisionless, fast-flowing} plasmas

- A \textit{current sheet} with converging flows will show magnetic merging where \( R_M \sim 1 \) e.g. ‘magnetic X line’ at magnetopause
Different plasma ‘regimes’

- Tail Lobe: Open field
- PSBL: Prob. Closed field, thermal << flow energy
- PS: hot ~keV particles, flow<<thermal energy

<table>
<thead>
<tr>
<th></th>
<th>Magneto-sheath</th>
<th>Tail Lobe</th>
<th>PS Boundary Layer</th>
<th>Central Plasma Sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (cm⁻³)</td>
<td>8</td>
<td>0.01</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>T_i (eV)</td>
<td>150</td>
<td>300</td>
<td>1000</td>
<td>4200</td>
</tr>
<tr>
<td>B (nT)</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>β</td>
<td>2.5</td>
<td>0.003</td>
<td>0.1</td>
<td>6</td>
</tr>
</tbody>
</table>

\( \beta = \frac{P_{\text{PLAS}}}{P_{\text{MAG}}} \)

(From chapter by Hughes in ‘Intro to Space Phys’)
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 pressure}, 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:

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

• 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 **magnetic**, 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:

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

- 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_E</th>
<th>MP_{Dipole}</th>
<th>MP_{mean}</th>
<th>MP_{Range}</th>
</tr>
</thead>
<tbody>
<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
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

- $P_{\text{ROT}} \approx 9.9$ hr
- $R_J \approx 71500$ km $\approx 11 \, R_E$
- $B_{J,\text{EQ}} \approx 428000$ nT $\approx 14 \, B_{E,\text{EQ}}$
- $\mu_J = B_{J,\text{EQ}} \, R_J^3 \approx 18000 \, \mu_E$
- 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
  \[(1+\beta) \frac{B^2}{2\mu_0} \sim \rho_{sw} v_{sw}^2\]
- 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)
Jupiter: A Rapidly Rotating Magnetosphere

- 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
quiet field regions are absent. In this work, we have excluded such chaotic periods from our database of current sheet crossings.

4. Current Sheet Description

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

\[ Z_{cs} = r \tan(q_{cs} \cos(f)) / C_0(f) \]

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 \( j_0 \) 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], \( q_{cs} = 9.52 \)° and \( j_0 = 339.4 \)° (east longitude).

As discussed above, observations from Pioneer and Voyagers spacecraft show that 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 in the arrival of information about the magnetic equator at a radial distance \( r \) is given by:

\[ d = V_A B f / C_0 r B W J / C_0 W m(\Pi) u_r + V_A B r / C_0 / C_1 \]

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:

\[ u = k B + m r \hat{j} \]

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:

\[ d = B f r B r / C_0 W J / C_0 W i(\Pi) u_r + V_A B r / C_0 / C_1 \]

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

Io ‘spot’

Cusp?

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

Youtube Jupiter UV movie

https://www.youtube.com/watch?v=oFsoXjFoKf4
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 <~ 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)
• 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

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.

Figure 8. The equatorial plane of Jupiter’s magnetosphere as represented by Vasyliunas [1983]. Labels indicate the interpretation of the dynamics in the schematic in terms of the processes discussed in this paper.

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.
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

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Jupiter</th>
<th>Saturn</th>
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<tbody>
<tr>
<td>Dipole moment</td>
<td>$1\mu_E$</td>
<td>$18000\mu_E$</td>
<td>$550\mu_E$</td>
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<tr>
<td>M’pause standoff</td>
<td>$1R_{MP,E}$</td>
<td>$80R_{MP,E}$</td>
<td>$20R_{MP,E}$</td>
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<td>distance $R_{MP}$</td>
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<tr>
<td>$P_{ROT}/(R_{MP}/V_{SW})$</td>
<td>$\sim500$</td>
<td>$\sim2.5$</td>
<td>$\sim8$</td>
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<tr>
<td>Auroral energy</td>
<td>$\sim10$s of GW</td>
<td>$\sim100$ TW</td>
<td>$\sim20$ TW</td>
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<tr>
<td>dissipated</td>
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<td>Main auroral ‘oval’</td>
<td>Solar wind-driven</td>
<td>Planetary rotation</td>
<td>Solar wind-driven*, with fainter rot’n oval</td>
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<td>due to:</td>
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* All main ovals involve spatial gradients in plasma flows

Other examples of transient aurora:

- Transpolar arc *(change in IMF $B_Y$) (e.g. Milan et al, 2005)*
- Polar dawn ‘spots’ *(tail reconnn.) (Radioti et al, 2010)*
- Oscillations in oval location *(‘camshaft’ currents) (Nichols et al. 2010)*
• 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 plasma physics.
- We may describe plasma motion in terms of individual particle drifts.
- When we consider collective behaviour, MHD provides a framework for treating the plasma as a fluid permeated by electromagnetic fields. Concepts of magnetic ‘pressure’ and ‘tension’ are useful.
- The magnetic field structure plays an important role in force balance and plasma transport and dynamics. Reconnection is an important means of ‘solar wind – magnetosphere coupling’.
- Magnetosphere-ionosphere coupling ‘transmits’ energy and momentum by means of field-aligned current systems. These are often associated with auroral emissions.
- MISSIONS to Jupiter: Juno (JOI 2016), JUICE (JOI planned 2030)

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)