Flow Streamlines - Northward IMF

ESS 200C
Lecture 8
The Bow Shock and Magnetosheath

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The Bow Shock and Magnetosheath
• A shock is a discontinuity separating two different regimes in a continuous media.
  - Shocks form when velocities exceed the signal speed in the medium.
  - A shock front separates the Mach cone of a supersonic jet from the undisturbed air.

• Characteristics of a shock:
  - The disturbance propagates faster than the signal speed. In gas the signal speed is the speed of sound, in space plasmas the signal speeds are the MHD wave speeds.
  - At the shock front the properties of the medium change abruptly. In a hydrodynamic shock, the pressure and density increase while in a MHD shock the plasma density and magnetic field strength increase.
  - Behind a shock front a transition back to the undisturbed medium must occur. Behind a gas-dynamic shock, density and pressure decrease, behind a MHD shock the plasma density and magnetic field strength decrease. If the decrease is fast a reverse shock occurs.

• A shock can be thought of as a non-linear wave propagating faster than the signal speed.
  - Information can be transferred by a propagating disturbance.
  - Shocks can be from a blast wave - waves generated in the corona.
  - Shocks can be driven by an object moving faster than the speed of sound.
• Shocks can form when an obstacle moves with respect to the unshocked gas.

• Shocks can form when a gas encounters an obstacle.
• The Shock’s Rest Frame
  – In a frame moving with the shock the gas with the larger speed is on the left and gas with a smaller speed is on the right.
  – At the shock front irreversible processes lead the compression of the gas and a change in speed.
  – The low-entropy upstream side has high velocity.
  – The high-entropy downstream side has smaller velocity.

• Collisionless Shock Waves
  – In a gas-dynamic shock collisions provide the required dissipation.
  – In space plasmas the shocks are collision free.

- Microscopic Kinetic effects provide the dissipation.
- The magnetic field acts as a coupling device.
- MHD can be used to show how the bulk parameters change across the shock.

Shock Front

<table>
<thead>
<tr>
<th>Upstream (low entropy)</th>
<th>Downstream (high entropy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_u</td>
<td>V_d</td>
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</tbody>
</table>
• Shock Conservation Laws

– In both fluid dynamics and MHD conservation equations for mass, energy and momentum have the form: \( \frac{\partial Q}{\partial t} + \nabla \cdot \vec{F} = 0 \) where \( Q \) and \( \vec{F} \) are the density and flux of the conserved quantity.

– If the shock is steady (\( \partial / \partial t = 0 \)) and one-dimensional \( \frac{\partial F_n}{\partial n} = 0 \) or \( (F_u - F_d) \cdot \hat{n} = 0 \) where \( u \) and \( d \) refer to upstream and downstream and \( \hat{n} \) is the unit normal to the shock surface. We normally write this as a jump condition \([F_n] = 0\).

– Conservation of Mass \( \frac{\partial}{\partial n}(\rho v_n) = 0 \) or \([\rho v_n] = 0\). If the shock slows the plasma then the plasma density increases.

– Conservation of Momentum \( \rho v_n \frac{\partial v_n}{\partial n} + \frac{\partial p}{\partial n} + \frac{\partial}{\partial n} \left( \frac{B^2}{2\mu_0} \right) = 0 \) where the first term is the rate of change of momentum and the second and third terms are the gradients of the gas and magnetic pressures in the normal direction.

\[
\left[ \rho v_n^2 + p + \frac{B^2}{2\mu_0} \right] = 0
\]
Conservation of momentum
\[ \rho v_n \vec{v}_t - \frac{B_n}{\mu_0} \vec{B}_t = 0 \]

The subscript \( t \) refers to components that are transverse to the shock (i.e. parallel to the shock surface).

Conservation of energy
\[ \rho v_n \left( \frac{1}{2} v^2 + \frac{\gamma}{\gamma-1} \frac{p}{\rho} \right) + v_n \frac{B^2}{\mu_0} - \vec{v} \cdot \vec{B} \frac{B_n}{\mu_0} = 0 \]

There we have used \( p \rho^{-\gamma} = \text{const.} \).

The first two terms are the flux of kinetic energy (flow energy and internal energy) while the last two terms come from the electromagnetic energy flux \( \vec{E} \times \vec{B} / \mu_0 \).

- Gauss Law \( \nabla \cdot \vec{B} = 0 \) gives \( [B_n] = 0 \)

- Faraday’s Law \( \nabla \times \vec{E} = -\partial \vec{B} / \partial t \) gives \( [v_n \vec{B}_t - B_n \vec{v}_t] = 0 \)
• The jump conditions are a set of 6 equations. If we want to find the downstream quantities given the upstream quantities then there are 6 unknowns \((\rho, v_n, v_t, p, B_n, B_t)\).

• The solutions to these equations are not necessarily shocks. These are conservation laws and a multitude of other discontinuities can also be described by these equations.

<table>
<thead>
<tr>
<th>Types of Discontinuities in Ideal MHD</th>
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</thead>
<tbody>
<tr>
<td>Contact Discontinuity</td>
</tr>
<tr>
<td>(v_n = 0, B_n \neq 0)</td>
</tr>
<tr>
<td>Density jumps arbitrary, all others continuous. No plasma flow. Both sides flow together at (v_t).</td>
</tr>
<tr>
<td>Tangential Discontinuity</td>
</tr>
<tr>
<td>(v_n = 0, B_n = 0)</td>
</tr>
<tr>
<td>Complete separation. Plasma pressure and field change arbitrarily, but pressure balance</td>
</tr>
<tr>
<td>Rotational Discontinuity</td>
</tr>
<tr>
<td>(v_n \neq 0, B_n \neq 0)</td>
</tr>
<tr>
<td>(v_n = B_n / (\mu_0 \rho)^{\frac{1}{2}})</td>
</tr>
<tr>
<td>Large amplitude intermediate wave, field and flow change direction but not magnitude.</td>
</tr>
<tr>
<td>Types of Shocks in Ideal MHD</td>
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<td>--------------------------------</td>
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<tr>
<td><strong>Shock Waves</strong></td>
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<tr>
<td><strong>Parallel Shock</strong> (along shock normal)</td>
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<tr>
<td><strong>Perpendicular Shock</strong></td>
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<td><strong>Oblique Shocks</strong></td>
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<tr>
<td><strong>Fast Shock</strong></td>
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<td><strong>Slow Shock</strong></td>
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<tr>
<td><strong>Intermediate Shock</strong></td>
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</table>
- Configuration of magnetic field lines for fast and slow shocks. The lines are closer together for a fast shock, indicating that the field strength increases.
• Quasi-perpendicular and quasi-parallel shocks.
  
  – Call the angle between $\vec{B}$ and the normal $\theta_{Bn}$.
  
  – Quasi-perpendicular shocks have $\theta_{Bn} > 45^0$ and quasi-parallel have $\theta_{Bn} < 45^0$.
  
  – Perpendicular shocks are sharper and more laminar.
  
  – Parallel shocks are highly turbulent.
  
  – The reason for this is that perpendicular shocks constrain the waves to the shock plane while parallel shocks allow waves to leak out along the magnetic field.
  
  – In these examples of the Earth’s bow shock – N is in the normal direction, L is northward and M is azimuthal.
• Examples of the change in plasma parameters across the bow shock
  – The solar wind is supersonic so the purpose of the shock is to slow the solar wind down so the flow can go around the obstacle.
  – The density and temperature increase.
  – The magnetic field (not shown) also increases.
  – The maximum compression at a strong shock is 4 but 2 is more typical.
- Particles can be accelerated in the shock (ions to 100’s of keV and electrons to 10’s of keV).
- Some can leak out and if they have sufficiently high energies they can out run the shock. (This is a unique property of collisionless shocks.)
- At Earth the interplanetary magnetic field has an angle to the Sun-Earth line of about 45°. The first field line to touch the shock is the tangent field line.
  - At the tangent line $\theta_{Bn}$ the angle between the shock normal and the IMF is 90°.
  - Lines further downstream have $\theta_{Bn} < 90°$
- Particles have parallel motion along the field line ($\vec{v}_||$) and cross field drift motion ($\vec{v}_d = (E \times \vec{B}) / B^2$).
  - All particles have the same $\vec{v}_d$
  - The most energetic particles will move farther from the shock before they drift the same distance as less energetic particles
- The first particles observed behind the tangent line are electrons with the highest energy electrons closest to the tangent line – electron foreshock.
- A similar region for ions is found farther downstream – ion foreshock.
• For compressive fast-mode and slow-mode oblique shocks the upstream and downstream magnetic field directions and the shock normal all lie in the same plane. (Coplanarity Theorem)

\[ \hat{n} \cdot (\vec{B}_d \times \vec{B}_u) = 0 \]

• The transverse component of the momentum equation can be written as

\[ \rho \left[ v_n \vec{v}_t - \frac{B_n}{\mu_0} \vec{B}_t \right] = 0 \quad \text{and Faraday’s Law gives} \quad \left[ v_n \vec{B}_t - B_n \vec{v}_t \right] = 0 \]

• Therefore both \( [v_n \vec{B}_t] \) and \( [\vec{B}_t] \) are parallel to \( [\vec{v}_t] \) and thus are parallel to each other.

• Thus \( [\vec{B}_t] \times [v_n \vec{B}_t] = 0 \). Expanding \( v_{u_n} \vec{B}_{u_t} \times \vec{B}_{u_t} + v_{d_n} \vec{B}_{d_t} \times \vec{B}_{d_t} - v_{d_n} \vec{B}_{u_t} \times \vec{B}_{d_t} - v_{u_n} \vec{B}_{d_t} \times \vec{B}_{u_t} = 0 \)

\( (v_{n,u} - v_{n,d})(\vec{B}_{t,u} \times \vec{B}_{t,d}) = 0 \)

• If \( v_{n,u} \neq v_{n,d} \) \( \vec{B}_{t,u} \) and \( \vec{B}_{t,d} \) must be parallel.

• The plane containing one of these vectors and the normal contains both the upstream and downstream fields.

• Since \( (\vec{B}_u - \vec{B}_d) \cdot \hat{n} = 0 \) this means both \( \vec{B}_d \times \vec{B}_u \) and \( \vec{B}_u - \vec{B}_d \) are perpendicular to the normal and

\( \hat{n} = (\vec{B}_u - \vec{B}_d) \times (\vec{B}_u \times \vec{B}_d) / |(\vec{B}_u - \vec{B}_d) \times (\vec{B}_u \times \vec{B}_d)| \)
• Structure of the bow shock.

- Since both the density and B increase this is a fast mode shock.
- The field has a sharp jump called the ramp preceded by a gradual rise called the foot.
- The field right behind the shock is higher than its eventual downstream value. This is called the overshoot.
• Flow streamlines and velocity magnitude in the magnetosheath. These are results from a global magnetohydrodynamic simulation of the interaction of the solar wind with the magnetosphere when the interplanetary magnetic field is northward.

Flow Streamlines - Northward IMF
- The magnetic field (top), the density (middle) and the temperature of the plasma all increase downstream of the bow shock.

- In the bottom panel the thermal pressure ($P = nkT$) also increases.

- The figures come from a global magnetohydrodynamic simulation of the magnetosphere.

- The region between the bow shock and magnetopause containing compressed and heated solar wind plasma is the magnetosheath.
• Magnetic field lines from a global MHD simulation of the interaction of the solar wind and the magnetosphere for northward IMF.

• The red lines are in the magnetosheath. Note most of magnetosheath field lines are concave away from the Sun.

• Flows in the magnetosheath are accelerated by pressure gradients and the tension on these field lines.
• Observations of the magnetic field near the magnetopause from the ISEE satellites.

• The magnetosphere is on either end of the figure. The region in between is the magnetosheath.

• The magnetic field of the magnetosheath is characterized by oscillations in the magnetic field.