ESS 7
Lecture 9
October 17, 2011
The Bow Shock and Magnetosheath
A Little Bit About Waves

- For a plane wave propagating in the \(x\)-direction with wavelength \(\lambda\) and frequency \(f\), the oscillating quantities can be taken to be proportional to sines and cosines.

  - For example, the pressure in a sound wave propagating along an organ pipe might vary like
    \[ p = p_o \sin(kt - \omega t) \]
    where the wave frequency is \(f\) (and \(\omega = 2\pi f\)) and \(t\) is time.
    \[ k = 2\pi/\lambda \]
    is called the wave number. In general it can be a vector.
How About Beach Waves, what do they have in Common with Shock Waves?

If you move at the speed of the discontinuity you can get energy out. We call it Landau damping in many cases…

• Shallow water waves (wavelength > depth d) move with speed $\sqrt{gd} \approx 3\sqrt{d}$ m/s

• As the beach gets shallower the faster speeds behind the wave cause it to pile up (steepen).

• Normally, waves do not carry the medium along with them, they travel through it.
A LittleWave Math

• $v = \lambda f$ (# waves/second) (called the phase velocity).
• Period is time for one wave so $f = 1/P$
• Here $P = 14\text{s}$ so $f = 0.07\text{ Hz}$
• If $d = 10\text{m}$, $v = 9\text{ m/s}$
  \[ \lambda = \frac{v}{f} = \frac{9}{0.07} = 130\text{m} \]
  If $d = 1\text{m}$, $v = 3\text{ m/s}$
  \[ \lambda = \frac{v}{f} = \frac{3}{0.07} = 40\text{m} \]

The slowing as waves come to shore is why waves always hit any beach straight on
Shock: A Discontinuity Separating Two 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.
  - Shocks can be from a blast wave - waves generated in the corona.

- 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, pressure 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.
How Shocks Form

- Shocks can form when an obstacle moves with respect to the unshocked gas.
- Shocks can form when a gas encounters an obstacle.
A Hydrodynamic (Gas Dynamic) Shock

- Hydrodynamic shocks form on sharp surfaces in a wind tunnel.

- A hydrodynamic shock forms when the velocity (in this case of the wind) exceeds the sound speed.

- The ratio of the gas speed to the sound speed is the Mach number.
A Familiar Shock-like Phenomenon: The Hydraulic Jump

- In water this shallow the wave speed is very low (although surface tension complicates things).
- Note that this “shock” is stationary.

Jump condition \( (vh)_0 = (vh)_1 + \text{other conditions} \)

Note turbulence!

For horizontal flow the depth increases before jump due to fluid friction slowing water.

Rapid Laminar Flow Region

Slower Turbulent Flow Region

Height immediately before jump \( (h_0) \)

Height after jump \( (h_1) \)

wikipedia
Examples of Shocks we Have Seen so far

- CME
- Magnetic cloud
- Corotating Interaction Region
- The Termination Shock
Shocks in Space

- Unlike hydrodynamics which has only one wave speed, plasmas have three.
- The sound speed - \( C_s^2 = \frac{P}{\rho} = \gamma \frac{kT}{m} \)
- The Alfvén speed - \( V_A^2 = \frac{B^2}{\mu_0 \rho} \)
- The magnetosonic speed - \( V_F^2 = C_s^2 + V_A^2 \) for propagation perpendicular to \( \vec{B} \)
- All of the shocks we have seen are magnetosonic shocks.
Collisionless Shocks

- 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 to 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.
- In a gas-dynamic shock collisions provide the required dissipation.
- In space plasmas the density is low ($<10^7 \, \text{m}^{-3}$) shocks are collision free.
  - Microscopic kinetic effects provide the dissipation.
  - The magnetic field acts as a coupling device.

**Shock Front**

Upstream (low entropy) | Downstream (high entropy)

$V_u$ | $V_d$
Changes Across the Bow Shock

- At the Earth the obstacle to the flow is the magnetic field – upstream is the solar wind and downstream is the magnetosheath.
- The velocity must decrease as you go from upstream to downstream so that the flow can go around the obstacle.
- The magnetic field, density and temperature increase as you go from upstream to downstream.

Shock Front

Upstream (low entropy) \( V_u \)

Downstream (high entropy) \( V_d \)
Changes in the Plasma Parameters Across the Bow Shock

- The solar wind is super-magnetosonic 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.
Magnetic Field Observations of the Bow Shock

- The magnetic field may either increase or remain constant in a fast mode shock.

- If the solar wind is perpendicular to the normal to the bow shock the magnetic field will increase.

- If the solar wind is parallel to the normal the magnetic field will be constant.
Why it is Called The Bow Shock

It is analogous to the bow waves of a ship.

Australian Navy
The Shape of the Bow Shock

- Flow streamlines and velocity magnitude in the equatorial plane. (Only half of the equator is shown.)
- A flow streamline is tangent to the velocity vectors.

\[
\frac{dx}{dy} = \frac{V_X}{V_Y}
\]

- The velocity decreases across the shock

Flow Streamlines - Northward IMF
Change in Parameters Across the Bow Shock

- 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 region between the bow shock and magnetopause containing compressed and heated solar wind plasma is the magnetosheath.
Observations of the Magnetosheath and Magnetopause

- 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.

![Diagram showing observations of the magnetopause and magnetosheath with magnetic field data over time.](image-url)
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