Heliophysics Shocks

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Outline

1. Why Shocks Happen: Non Linear Steepening
2. MHD jump conditions: Rankine-Hugoniot jump conditions
3. Definition and Classification of Shocks
4. Perpendicular shocks
5. Parallel shocks
6. Examples: Coronal Shocks; CME Driven Shocks; Planetary Shocks; Termination Shock Heliopause
References

• Opher, M.- Lectures 11,12,13 of “Space Physics” http://physics.gmu.edu/~mopher
• Space Physics, An introduction to plasma and particles in the heliopshere and magnetosphere by May-Britt Kallenrode
• Interplanetary Magnetohydrodynamics by Len F. Burlaga
• Introduction to Plasma Physics with Space and Laboratory Applications by Donald A. Gurnett and Amitava Bhattacharjee
Why Shocks Happen: Non Linear Steepening

- When waves moves faster than the ambient medium there is a steepening of front portion of the wave mode. Small amplitude limit the profile of an MHD wave doesn't change as it propagates.
- But even a small-amplitude wave will eventually distort due to "steepening" or "wave-steepening"
Example: propagation of sounds wave in an adiabatic medium

- Propagation of a sound wave is

For an adiabatic equation of state:

\[ v_s^2 = \frac{dP}{d\rho} \]

\[ \frac{P}{\rho^\gamma} = \text{constant} \]

So: \( v_s \propto P^\alpha \) where \( \alpha = \frac{\gamma + 1}{2\gamma} \)
A propagating wave solution of the ideal fluid equations leads to infinite gradients in a finite time. There is no solution for the ideal MHD equations.

This is not surprising: ideal equations are valid when scales of variations are larger than mean free path.

The breakdown in ideal equations occurs in a very thin region and the fluid equations are valid everywhere else. On in this very thin region is difficult to describe the plasma in details.

The simple picture: is a discontinuity dividing two roughly uniform fluids.

Region 2 (downstream)    Region 1 (upstream)

The transition must be such as to conserve MASS, Magnetic Flux and Energy.
Jump Conditions which are independent of the physics of the shock itself: Rankine-Hugoniot Relations

(a) Conservation of Mass: \[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \]

through regions 1 and 2 gives:

\[ \rho_1 \mathbf{u}_1 \cdot \mathbf{n} = \rho_2 \mathbf{u}_2 \cdot \mathbf{n} \]

that can be written as \( \{\rho \mathbf{u} \cdot \mathbf{n}\} = 0 \) where the symbol \( \{\} \)

represent differences between the two sides of the discontinuity.
(b) Conservation of Momentum

\[
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot [\rho uu + \left( p + \frac{B^2}{2\mu_0} \right) I - \frac{BB}{\mu_0}] = 0
\]

gives

\[
\left\{ \rho u (u \cdot n) + \left( p + \frac{B^2}{2\mu_0} n - \frac{B}{\mu_0} (B \cdot n) \right) \right\} = 0.
\]

(c) Conservation of energy

\[
\frac{\partial}{\partial t} \left( \frac{1}{2} \rho U^2 \frac{P}{\gamma - 1} + \frac{B^2}{2\mu_0} \right) + \nabla \cdot \left( \frac{1}{2} \rho U^2 u + \frac{\gamma P}{\gamma - 1} u + \frac{1}{\mu_0} E \times B \right) = 0
\]

gives

\[
\left\{ \left( \frac{1}{2} \rho U^2 + \frac{\gamma P}{\gamma - 1} \right) (u \cdot n) + \frac{1}{\mu_0} (E \times B) \cdot n \right\} = 0.
\]
(d) The Magnetic flux conservation

\[ \nabla \cdot \mathbf{B} = 0 \]

gives

\[ \{ \mathbf{B} \cdot \mathbf{n} \} = 0 \]

and

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]

gives

\[ \{ \mathbf{E} \times \mathbf{n} \} = 0 \]

Let us consider the normal \( n \) and tangential \( t \) component relative to the discontinuity surface so the JUMP conditions can be written as:
\( (a) \quad \left\{ \rho_m \mathbf{u} \cdot \hat{n} \right\} = 0 \Rightarrow \left\{ \rho_m \mathbf{u} \right\} = 0 \quad * \\
(b) \quad \left\{ \rho_m \mathbf{u} (\mathbf{u} \cdot \hat{n}) + \left( \frac{p + B^2}{\mu_0} \right) \hat{n} - \frac{B}{\mu_0} (\hat{B} \cdot \hat{n}) \right\} = 0 \\
\Rightarrow \left\{ \rho_m \mathbf{u} \mathbf{u} + \mathbf{p} + \frac{B^2}{2\mu_0} \right\} = 0 \quad * \\
\Rightarrow \left\{ \rho_m \mathbf{u} \mathbf{u} - \frac{B}{\mu_0} \mathbf{B} \right\} = 0 \quad * \\
(c) \quad \left\{ \left( \frac{1}{2} \rho_m \mathbf{u}^2 + h \right) (\mathbf{u} \cdot \hat{n}) + \frac{1}{\mu_0} (\mathbf{E} \times \mathbf{B}) \cdot \hat{n} \right\} = 0 \\
\left\{ \left( \frac{1}{2} \rho_m \mathbf{u}^2 + h + \frac{B^2}{\mu_0} \right) \mathbf{u} - (\mathbf{u} \cdot \mathbf{B}) \frac{\mathbf{B}}{\mu_0} \right\} = 0 \quad * \\
(d) \quad \left\{ \mathbf{B} \right\} = 0 \quad * \\
(e) \quad \left\{ \mathbf{u} \times \mathbf{B} + \mathbf{u} \times \frac{\mathbf{B}}{\mu_0} \right\} = 0 \quad * \\
\frac{1 - s^2 \rho}{s^2 - 1} \\

The equations (*) are called the Rankine-Hugoniot jump conditions.
Types of Discontinuities & Shocks

<table>
<thead>
<tr>
<th></th>
<th>$U_n = 0$</th>
<th>$U_n \neq 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>${\rho} = 0$</td>
<td>trivial</td>
<td>rotational discontinuity</td>
</tr>
<tr>
<td>${\rho} \neq 0$</td>
<td>contact discont.</td>
<td>shock wave</td>
</tr>
</tbody>
</table>
Contact Discontinuity

- Happens where there is no flow across the discontinuity, i.e., $U_n=0$ and $\{\rho\} \neq 0$

E.g. classic contact discontinuity

(a) If $B_n \neq 0$ contact discontinuity -> only the density changes across the discontinuity (rarely observed in plasmas)
Tangential Discontinuity

(b) When $B_n=0 \Rightarrow \{U_T\} \neq 0$

$\{B_T\} \neq 0$

and $\{p+B^2/2\mu_0\}=0$

The fluid velocity and magnetic field are parallel to the surface of the discontinuity but change in magnitude and direction. The sum of thermal and magnetic pressure is constant also.
Heliopause: Tangential Discontinuity

The interstellar magnetic field is distorting the heliosphere.
If there is no much reconnection so $U_n \sim 0; B_n \sim 0$ so solar wind plasma and magnetic field do not penetrate into the magnetosphere.
Rotational Discontinuity: $U \neq 0$ and $\{\rho\} = 0$

From jump conditions 

(a) $\Rightarrow \begin{cases} U_n^2 = 0 \\ \nabla \cdot \mathbf{v} = \nabla \cdot \mathbf{v} = V_n \\ \rho_1 = \rho_2 \end{cases}$

and

$\int \left( \frac{B_i^2}{\mu_0} \right) = 0$

..some math...we get that if $U_n^2 = \frac{B_i^2}{\mu_0} f_n$

$B_i$ remain constant in magnitude but rotates in the plane of the discontinuity.

Example: if the reconnection rate between the solar wind Magnetic field and the planetary magnetic field is substantial; then The plasma can penetrate significantly into the magnetosphere: The magnetopause becomes a rotational discontinuity
Shock waves are characterized by a fluid flows across the Discontinuity $U_n \neq 0$ and a non zero jump discontinuity $\{\rho\} \neq 0$

Frames of reference for MHD shocks:
(I) normal incident frame (coordinate system moving along the shock front with speed $U_t$)
(II) de Hoffman-Teller frame (the plasma is parallel to the magnetic field on both sides and the reference frames moves parallel to the shock front with the de Hoffman-Teller speed)
Question for class: which type of shock those are?

\[ \{p + B^2/2\mu\} = 0 \text{ for TD} \]

\[ \{\rho\} = 0 \text{ but } U_n \neq 0 \text{ RD} \]
Observations of MHD Shocks

Earth Bow Shock (plot at a distance 15.4$R_E$ upstream from Earth)
This example $\theta_1=76^\circ$
(between B and n)
$U_1=294$km/s $> v_A=37.8$km/s

Voyager 2 crossing the Termination Shock in August 2007
Strength of the Shock

- Jump equations: 12 unknowns (4 upstream parameters are specified: $\rho$, $v_S$, $B_t$, $B_n$) so we have 7 equations for 8 unknowns -> we need to specify one more quantity

$$\delta = \frac{\rho_2}{\rho_1}$$

Other quantities:

$$M_A = \frac{U_a}{V_{Aa}} = \frac{U_n}{V_{An}} \sqrt{\frac{\mu}{\gamma m}} \quad \text{Alfvén Mach number}$$

$$M_s = \frac{U_s}{V_s} = \frac{U_n}{V_{An}} \sqrt{\frac{\gamma m}{\rho}} \quad \text{Sonic Mach number}$$

$$\tan \theta = \frac{B_b}{B_n} \quad \text{angle } \theta \text{ between the } B \text{ & shock normal}$$
Shock Adiabatic Equation

• You can combine using the shock equations to a one single equation that gives the shock propagating speed $U_{n1}$ as a function of shock strength $\delta$ and upstream parameters.
Type of Shocks

- Weak Shock Limit $\delta = 1$ (solution of the shock equation are slow, intermediate and fast shocks) (slow correspond to slow MHD wave; fast to fast MHD wave and intermediate to transverse Alfven wave)
- Strong Shock Limit: $\delta \rightarrow \delta_m$

- Parallel Shock: $\theta = 0^\circ$
- Perpendicular Shocks: $\theta = 90^\circ$
- Quasi-perpendicular shocks $\theta > 45^\circ$
Thickness of Shocks

- The thickness of the shocks and the details substructure within the shock depends on the angle $\theta$, $M_{A1}, M_{A2}$
- The transition region of a quasi-perpendicular shock is usually thin and well defined
- The transition region of a quasi-parallel shock is usually more complex and often appears thick

Jupiter’s bow shock

Narrow band at 6kHz:
Electron plasma oscillations
Excited by a beam of electrons that escapes into the region upstream the shock

Broadband electric field noise:
Plasma wave turbulence excited by unstable particle distribution in the shock
Termination Shock: Perpendicular Shock

Voyager 2 crossed the Termination Shock in August 2007- (in-situ measurements of a shock)

J. Richardson et al.
Several Crossings; Shock is colder than expected

J. Richardson et al.
Crossing of TS by V2: closer to the Sun than V1

Voyager 2 Proves Solar System Is Squashed

San Francisco, CA - NASA's Voyager 2 spacecraft has followed its twin Voyager 1 into the solar system's final frontier, a vast region at the edge of our solar system where the solar wind runs up against the thin gas between the stars.

However, Voyager 2 took a different path, entering this region, called the heliosheath, on August 30, 2007. Because Voyager 2 crossed the heliosheath boundary, called the solar wind termination shock, about 10 billion miles away from Voyager 1 and almost a billion miles closer to the sun, it confirmed that our solar system is "squashed" or "condensed" - that the bubble carved into interstellar space by the solar wind is not perfectly round. Where Voyager 2 made its crossing, the bubble is pushed closer to the sun by the local interstellar magnetic field.

"Voyager 2 continues its journey of discovery, crossing the termination shock multiple times as it entered the outermost layer of the giant heliospheric bubble surrounding the Sun and joined Voyager 1 in the last leg of the race to Interstellar space," said Voyager Project Scientist Dr. Edward Stone of the California Institute of Technology, Pasadena, Calif.

The solar wind is a thin gas of electrically charged particles...
Spiral Magnetic Field Crossing V1 and V2

Shock closer to the Sun near nose than in the flanks

In both Northern and Southern Hemisphere the cones intersect the Termination Shock closer to the equator near the nose.
The distortion of the shock is such that the shock is closer to the Sun counterclockwise from Voyager 1.

2AU inside the shock.

Voyager 1 was connected to the shock along a field line in the direction toward the Sun. Particles streaming outward along the field.
The distortion is such that the shock is closer to the Sun clockwise from V2 -> TSPs streaming *inward* along the field line.

The distortion is larger in the southern hemisphere -> field lines 5AU from the shock are connected to V2.
Inward TSPs

Outward TSPs
Shocks Driven by Coronal Mass Ejections

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
Propagating Shocks

- Shock geometry can vary if near the nose or flanks
Shocks Geometry: Magnetic Connectivity
CMEs and Composition of SEPs

Modified from Lee, 2005
CME: near the nose: Quasi-Parallel Shocks

Liu, Opher et al. 2008
Initial Steady State in the Corona

• Solar surface is colored with the radial magnetic field.

• Field lines are colored with the velocity.

• Flux rope is shown with white field lines.
Two Hours After Eruption in the Solar Corona
65 Hours After Eruption in the Inner Heliosphere
Synthetic Coronagraph
Images of the CME: LASCO C2 and HI2

Lugaz, Manchester and Gombosi
Fine Shock Structure

Manchester et al. 2004
Evolution of Magnetized Shocks

How magnetic effects affect shock evolution?
Which type of flows we get in shocks?
MHD instabilities?
How reconnection affect shock structures?

Y. Liu et al. 2008b
Evolution of Magnetized Shocks in the Lower Corona

Liu, Opher et al. (2008)

Loesch, Opher, Alves et al. 2008
Coronal Mass Ejection in the Lower Corona: Comparison of Two Initiation Models
(Loesch, C., Opher, M., Alves, M. et al. 2008)

Gibson-Law

Titov-Demoulin
Evolution of the Shock Structures in the Lower Corona

The inserted TD flux rope

Bright Front and Dark Void

2D slice at Z=0.11  

Bright front  

Dark void  

$t=10$ minutes
Shock Speed and the background solar wind speed
Shock and Post Shock Compression Ratio

The post shock acceleration exists in 3-5 Rs
Evolution of Flows, Field Lines in CME sheath

Magnetic Field Lines Rotation

Behavior of the Magnetic Field in the Sheath
Measuring Shocks

Shock brightness to density ($\rho$)
Shock strength, $\gamma = 1 + \rho / \rho_0$
SPM model for the density of the background corona ($\rho_0$).

Vourlidas & Ontiveros 2008
Development of Coronal Shocks Seen in the UV

John Raymond

Smooth, Faint arcs are often seen in White Light. Convincing identification as shocks requires MHD Simulation matching profile (Manchester et al., Vourlidas et al.)


UVCS Shock Observations Analyzed so far

<table>
<thead>
<tr>
<th>Date</th>
<th>Reference</th>
<th>H</th>
<th>V</th>
<th>n₀</th>
<th>Log $T₀$</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/11/98</td>
<td>Raymond et al.</td>
<td>1.75</td>
<td>1200</td>
<td>1x10^6</td>
<td>8.7</td>
<td>1.8</td>
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<td>06/27/99</td>
<td>Raouafi et al.</td>
<td>2.55</td>
<td>1200</td>
<td></td>
<td>&lt;8.2</td>
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<tr>
<td>03/03/00</td>
<td>Mancuso et al.</td>
<td>1.70</td>
<td>1100</td>
<td>1x10^7</td>
<td>8.2</td>
<td>1.8</td>
</tr>
<tr>
<td>06/28/00</td>
<td>Ciaravella et al.</td>
<td>2.32</td>
<td>1400</td>
<td>2x10^6</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>07/23/02</td>
<td>Mancuso &amp; Avetta</td>
<td>1.63</td>
<td>1700</td>
<td>5x10^6</td>
<td>8.0</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Modest heights, Modest compression, High $T₀$

5 other shocks not yet fully analyzed (Ciaravella et al. 2006)
What is the Alfvén Speed Profile in the Lower Corona?

- **Ten Models (Solar Minimum)**
  - **6 Global MHD**: Manchester et al. 2004; Cohen et al. 2007; Roussev et al. 2004; Riley 2006; Lionello et al. 2001; Usmanov & Goldstein 2006
  - **2 Local Studies**: Cranmer et al. 2007; Verdini & Velli 2007
  - **2 Semi-analytic**: Guhathakurta et al. 2006; Mann et al. 2003

- **Different Strategies to Accelerate Solar Wind**
  - Empirical Heating Functions
  - Non-uniform Polytropic Index
  - Inclusion of Alfvén Waves
Profiles vary drastically; Almost none with a clear hump
Need more physical based solar wind to study shocks in lower corona

Voyager 1 in the Northern Hemisphere; and Voyager 2 in the Southern Hemisphere
2-3kHz Radio Emissions were detected each solar cycle

Kurth et al. ‘84
Gurnett et al. ‘93
Gurnett, Kurth and Stone, ‘03

Solar Cycle 21  Solar Cycle 22  Solar Cycle 23
Current accepted scenario: radio emissions are generated when a strong interplanetary shock reaches the vicinity of the heliopause (Gurnett et al. ‘03, Gurnett & Kurth ‘95)
Radio Source Locations

From radio direction-finding measurements from V1 and V2

Kurth & Gurnett ‘2003
Shock Geometry can affect acceleration of particles
E.g: Termination Shock
RESEARCH ON THE EDGE—
OF THE SOLAR SYSTEM

Mason astrophysicist Moshe Opher and his team of researchers have their eyes on the stars—and the space in between. By combining numerical analysis and observational data from Voyagers 1 and 2, Dr. Opher is examining space weather and the edges of our solar system to discover how stars interact with the medium that surrounds them. The results of her work will have an impact on future space exploration and the design of space probes.

Teamwork at Mason—A HABIT OF EXCELLENCE