Collisionless Nonrelativistic Shocks – Overview

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Tom Gold, 1953: Solar flare plasma injection creates a thin collisionless shock

Norman F. Ness, 1964: Discovery of Earth's bow shock from IMP-1 magnetic field data
Important Parameters

Shock normal angle $\Theta_{Bn}$

Trajectories of specularly reflected ions

Mach number $M_A$

Ion/electron beta

Composition, anisotropy
Above first critical Mach number resistivity (by whatever mechanism, e.g. ion sound anomalous resistivity) cannot provide all the dissipation required by the Rankine-Hugoniot conditions. Conclusion: additional dissipation needed - particle reflection.

**Whistler critical Mach number**

\[
M_w = \frac{\left| \cos \Theta_{Bn} \right|}{2(m_e / m_i)^{1/2}}
\]

Upper limit fast Mach number for which a (linear) whistler can phase stand in the flow.
Quasi-Parallel Collisionless Shocks

Parker (1961): Collisionless parallel shock is due to firehose instability when upstream plasma penetrates into downstream plasma

Golden et al. (1973) Group standing ion cyclotron mode excited by interpenetrating beam produces turbulence of parallel shock waves

Early papers did not recognize importance of backstreaming ions

1. Excitation of upstream waves and downstream convection
2. Upstream vs downstream directed group velocity
3. Mode conversion of waves at shock
4. Interface instability
5. Short Large Amplitude Magnetic Structures (SLAMSs)
6. Injection and diffusive acceleration
Ion phase space $v_x - x$

(velocity in units of Mach number)

Transverse magnetic field component

Large amplitude waves

$\delta B/B \sim 1$

Hybrid Simulation of 1-D or 2-D Planar Collisionless Shocks

Inject a thermal distribution from the left hand side of a numerical box.

Let these ions reflect at the right hand side.

The (collective) interaction of the incident and reflected ions results eventually in a shock which travels to the left.

$M_A = 5.1 \quad \Theta_{Bn} = 5^\circ$
Electromagnetic Ion/Ion Instabilities

Gary, 1993

Ion/ion right hand resonant (cold beam) propagates in direction of beam resonance with beam ions right hand polarized fast magnetosonic mode branch

Ion/ion nonresonant (large relative velocity, large beam density) Firehose-like instability propagates in direction opposite to beam

Ion/ion left hand resonant (hot beam) propagates in direction of beam resonance with hot ions flowing antiparallel to beam left hand polarized on Alfven ion cyclotron branch

Ion distribution functions and associated cyclotron resonance speed.
Backstreaming ions excite upstream propagating waves by a resonant ion/ion beam instability.

Cyclotron resonance condition for beam ions:

\[ \omega - k_r v_b = -\Omega_c \]

dispersion relation

\[ \omega = kv_A \]

assume beam ions are specularly reflected

\[ v_b = 2v_{sw} \]

( \( \omega \) in units of \( \Omega_c \), \( k \) in units of \( \Omega_c / v_A \))

\[ \omega_r = k_r = 1/(2M_A - 1) \]

Wavelength (resonance) increase with increasing Mach number.
Dopplershift into Shock Frame

(positive $\omega$ phase velocity directed upstream)

Dispersion relation of upstream propagating whistler in shock frame.

Dispersion curve is shifted below zero frequency line.

At low Mach number waves (with large $k$) have upstream directed group velocity; they are phase-standing or have downstream directed phase velocity.

At higher Mach number the group velocity is reduced until it points back toward shock.
Upstream wave spectra (2-D (x-t space) Fourier analysis) for simulated shocks of three different Mach numbers

Krauss-Varban and Omidi 1991

Upstream waves are close to phase-standing. Group velocity directed upstream

Upstream waves are close to group standing.

Group and phase velocity directed towards shock

Shock periodically reforms itself when group velocity directed downstream
Mode Conversion of Upstream Fast Magnetosonic Waves

Krauss-Varban and Omidi 1991

Doppler shifted dispersion relation of upstream propagating fast magnetosonic mode (FM) in upstream region

Doppler shifted dispersion relation of upstream propagating FM and Alfven ion cyclotron mode (AIC) in downstream region

Star * shows position of an upstream wave on the FM branch which is downstream only accessible to the AIC branch (assuming constant wave frequency during shock transmission)
Interface Instability

In the region of overlap between cold solar wind and heated downstream plasma waves are produced by a right hand resonant instability (solar wind is background, hot plasma is beam).

Medium Mach number shock: decomposition in positive and negative helicity
interface waves have small wavelength and are heavily damped

Far downstream only upstream generated F/MS waves survive

F/MS waves are mode converted into AIC waves

Right: wavelet analysis of magnetic field of a $M_A=3.5$ shock. Two different wavelet components.
In high Mach number shocks the right hand resonant and right hand nonresonant instability are excited. The downstream turbulence is dominated by these large wavelength interface waves

(back to Parker and Golden et al.)

Scholer, Kucharek, Jayanti  1997
Short Large Amplitude Magnetic Structures SLAMSs and Shock Reformation

Oservations of SLAMSs at Earth's bow shock. Top: temporal profile of magnetic field magnitude; bottom: hodogram In one SLAMS.

Schwartz et al. 1992

Hybrid simulation of a quasi-parallel shock showing shock reformation.

Burgess 1989
SLAMs comprise the quasi-parallel shock

Upstream waves – interaction with diffuse ions –
SLAMs – shock structure

A collisionless quasi-parallel shock as
due to formation, convection, growth,
deceleration and merging of short large
amplitude magnetic structures (SLAMs).

SLAMs have a finite transverse extent.
Thus the shock is patchy when viewed,
e.g., over the shock surface.

The downstream state is divided into
plasma within SLAMs and in
inter-SLAMs region.
In 2-D k-vectors of upstream waves are aligned with magnetic field.

When waves convect into region of increasing diffuse ion density they are refracted and wave fronts become aligned with shock front.

Waves steepen and develop into large amplitude magnetic field pulsations.

Scholer, Fujimoto, Kucharek 1997
Diffusive Acceleration

Simulation of a parallel shock in large-scale domain

Giacalone 2004

$M_A = 6.4, \beta = 1.5$

Downstream spectra for different distances from the free escape boundary. Cut-off energy much smaller than predicted by diffusive acceleration theory.
Injection

Trajectory of a typical solar wind proton trapped and accelerated at shock

Energy vs time.
red: tangential electric field is parallel to particle velocity,
blue: tangential electric field is antiparallel to velocity

Scholer et al. 2000
Nonlinear phase trapping in large amplitude monochromatic wave

Sugiyama and Terasawa  1999

Ion is trapped between upstream and downstream wave train and gains energy
Parallel Shock Surfing

Krasnoselskikh et al. 2006

V x B force in x (shock normal) direction is at each point balanced by potential force so that the particle moves with constant velocity into the ramp.

During this trajectory the particle is in cyclotron resonance with an upstream wave and gains perpendicular energy.
Quasi-Perpendicular Collisionless Shocks

1. Specular reflection of part of incident ions
2. Downstream excitation of instabilities by temperature anisotropy
3. Rippling of shock surface
4. Shock reformation
   a) Upstream accumulation of reflected ions
   b) Instabilities in foot
   c) Nonlinear steepening of whistler or whistler triggered instability
5. Field Aligned Beams (FABs)
Schematic of Ion Reflection and Downstream Thermalization at Perpendicular Shocks
Specularly reflected ions in the foot of the quasi-perpendicular bow shock – in situ observations

Sckopke et al. 1983

Ion velocity space distributions for an inbound bow shock crossing. The position of the measurement is shown by dots on the density profile. Phase space density is shown in the ecliptic plane with sunward flow to the left.
Iso-intensity contours of density (left) and energy density (right) in the plane perpendicular to the magnetic field going from upstream of the ramp (top) to downstream.
Oblique propagating Alfvén Ion Cyclotron waves produced by the perpendicular/parallel temperature anisotropy.
Ripples are surface waves on shock front
Move along shock surface with Alfven velocity given by magnetic field in overshoot

Electron acceleration (test particle electrons in hybrid code shock)

Shocks with no ripples
Instability due to speculally reflected ions

Burgess and Scholer 2006

2-D simulation – magnetic field perpendicular to (x-y) simulation plane

Ripples perpendicular to the magnetic field
Time evolution of the magnetic field in the ramp

Pattern moves with constant speed along the shock
Sense of propagation is reversed when sense of magnetic field is reversed
Speed of pattern is the same as average y velocity of specularly reflected ions
Sense of propagation is same as gyromotion of reflected ions
Self-Reformation of Quasi-Perpendicular Shocks

1. Self-reformation by ion accumulation

Hada, Oonishi, Lembege, Savoini 2003

Stationary - Unstationary Transition

\[ V_t = 0.2 \]
Situation in the foot region of a perpendicular shock

Ions: unmagnetized
Electrons: magnetized

Ion and electron distributions in the foot

Ions: unmagnetized
Electrons: magnetized
2. Micro-Instabilities in the foot

Scholer, Shinohara, Matsukiyo 2003

Source of instabilities

\[ u_r \neq u_e \]
\[ u_i \neq u_e \]
### Possible microinstabilities in the foot

<table>
<thead>
<tr>
<th>Wave type</th>
<th>Necessary condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buneman inst.</td>
<td>Upper hybrid</td>
</tr>
<tr>
<td></td>
<td>(Langmuir)</td>
</tr>
<tr>
<td></td>
<td>$\Delta u \gg v_{te}$</td>
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<tr>
<td>Ion acoustic inst.</td>
<td>Ion acoustic</td>
</tr>
<tr>
<td></td>
<td>$T_e \gg T_i$</td>
</tr>
<tr>
<td>Bernstein inst.</td>
<td>Cyclotron harmonics</td>
</tr>
<tr>
<td></td>
<td>$\Delta u &gt; v_{te}$</td>
</tr>
<tr>
<td>Modified two-stream inst.</td>
<td>Oblique whistler</td>
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<tr>
<td></td>
<td>$\Delta u / \cos \theta &gt; v_{te}$</td>
</tr>
</tbody>
</table>
Linear Properties of the Modified Two-Stream Instability

(Between incoming ions and incoming electrons
the foot of a quasi-perpendicular shock)

Maximum growth rate (normalized to ion gyrofrequency) for cold plasma
as a function of ion to electron mass ratio $\mu$

$\tau = (\omega_{pe} / \omega_{ce})^2$

Matsukiyo and Scholer 2003
Parameters in PIC Simulations of Collisionless Shocks

1. Mass ratio \( m_i / m_e \)

2. Ratio of electron plasma to gyrofrequency
\[
v = \frac{\omega_{pe}}{\Omega_{ce}} = \frac{c}{V_A} \sqrt{\frac{m_e}{m_i}}
\]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solar Wind</th>
<th>( m_i / m_e )</th>
<th>( \omega_{pe} / \omega_{ce} )</th>
<th>( c / V_A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1836</td>
<td>100 – 200</td>
<td>(5000)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Biskamp and Welter, 1973  
Lembege and Dawson, 1987  
Liewer et al., 1991  
Savoini and Lembege, 1994  
Shimada and Hoshino, 2000, 2003, 2005  
Lembege and Savoini, 2002  
Krasnoselskikh et al., 2002  
Hada, Oonishi, Lembege, Savoini, 2003  
Scholer, Shinohara, Matsukiyo, 2003  
Scholer, Matsukiyo, 2004  
Muschietti and Lembege, 2005  
Matsukiyo, Scholer, 2006  
Scholer, Comisel, Matsukiyo, 2007
Reformation of almost perpendicular medium Mach number shocks: Mass ratio and ion beta effect

\[ \beta_i = 0.1 \quad \Theta_{Bn} = 87^\circ \]

\( m_i / m_e = 400 \quad \tau = 10 \)

\( m_i / m_e = 1840 \quad \tau = 4 \)

\( \beta_i = 0.4 \)
Self-reformation is a high (ion) beta mechanism. More precise: velocity difference between reflected and incoming ions has to be larger than ion thermal velocity.
Instability between incoming ions and incoming electrons leads to perpendicular ion trapping.

\[ \beta_i = \beta_e = 0.05 \]

\[ M_A = 4.5 \quad \theta_{Bn} = 87^\circ \]

Reflected ions not affected.
Phase-mixing – Ion thermalization

\[ \mu = 1840 \]

\[ t \Omega_{ci} = 4.1 \]

Shock reformation
Modified Two-Stream Instability (MTSI)

\( \Omega_i \ll \omega \ll \Omega_e \)

\( \Omega \cos \Theta_{Bn} \)

\( k \)

\( \omega \)

\( \omega \)

\( \Omega \)

\( \Theta \)

\( B_n \)

\( \Omega \)

\( u_i \)

\( u_e \)

\( u_T \)

\( x \)

unmagnetized ions → perpendicular trapping

strongly magnetized electrons → parallel trapping
3. Gradient catastrophe of nonlinear upstream whistler at oblique shocks

Krasnoselskikh et al. 2002

Whistler critical Mach number

\[ M_w = \frac{|\cos \Theta_{Bn}|}{2(m_e / m_i)^{1/2}} \]

Below \( M_w \) exists phase standing small amplitude upstream whistler

Nonlinear whistler critical Mach number

\[ M_{nw} = \frac{|\cos \Theta_{Bn}|}{(2m_e / m_i)^{1/2}} \]

Above \( M_{nw} \) shock nonlinear steepening of waves cannot be canceled anymore by dispersion and/or dissipation and becomes non-stationary
4. Nonlinear instability between incoming solar wind and reflected ions

Biskamp and Welter 1972

Incoming and reflected ion beams are stable if velocity difference large (note: ions are unmagnetized)

A nonlinear beam-instability between incoming and reflected ions is then triggered by the electric field of the large amplitude upstream whistler
Small mass ratio, but also small $\Theta_{Bn}$ of $45^\circ$, therefore $M_w$ reasonable large, i.e., were able to investigate influence of reflected ions (PIC simulation 36 years ago!)

$$M_w = \frac{|\cos \Theta_{Bn}|}{2(m_i/m_e)^{1/2}} = 4.0$$

Fig. 2. Ion phase space $x$ and $v_z$, magnetic field components $B_y$ and $B_z$, total magnetic field $B$, and electric potential $\phi$ of a magnetic shock at (a) $t = 1.25/\Omega_i$ and (b) $t = 3.25/\Omega_i$. The mass ratio is $m_i/m_e = 128$. $M_d = 5.0$
Buneman Instability

Strongly suppressed by Landau damping when relative drift between electrons and reflected ions smaller than electron thermal velocity.

\[ V_{r-e} > \sqrt{2} v_{\text{the}} \]

\[ v_{\text{the}} / V_A = \sqrt{(0.5 \beta_e)(m_i / m_e)} \]

We assume that the reflected ions have the same velocity as the incoming ions and that the incoming electrons are decelerated in order to achieve zero electrical current in the normal direction. The Buneman instability is stabilized if

\[ \beta_e \geq 4 M_A^2 (1 + \alpha)^2 (m_e / m_i) \]

where \( \alpha \) denotes density ratio of reflected and incoming ions.

With \( m_i / m_e = 1840 \), \( \alpha = 0.25 \), the Buneman instability can not grow unless

\[ \beta_e \leq M_A^2 / 720 \]

Buneman instability only at large Mach number or small electron beta.
Importance of Buneman Instability for Electron Acceleration In High Mach Number Shocks

Shimada and Hoshino 2003

\[ \Theta_{Bn} = 90^\circ, M_A = 11 \]

\[ \frac{m_i}{m_e} = 20, \beta_i = \beta_e = 0.5, \frac{\omega_{pe}}{\Omega_{ce}} = 20 \]
Nonlinear state of the Buneman instability – Electron holes

Part of the shock transition region with electron hole

\[ \Theta_{Bn} = 90^\circ, M_A = 11 \]

\[ m_i / m_e = 20, \beta_i = \beta_e = 0.5, \omega_{pe} / \Omega_{ce} = 20 \]

Shimada and Hoshino 2003
Electron hole generation by nonlinear development of Buneman instability. Large-amplitude electron hole couples to ions via ion acoustic fluctuations. Decelerates incoming and reflected ions and leads to further potential increase in the hole.

Hole disappears and electrons are heated and accelerated.

Coupling of hole to the incoming ions.
Field-Aligned Beams (FABs) at the Quasi-Perpendicular Shock

Field lines are convected downstream.

Particles can escape upstream if their velocity parallel to B exceeds convection speed.
No or very small phase space density found downstream of the ramp at position of beam ions

Field-aligned beam seems to emerge from the ramp and NOT from downstream
Test particles in hybrid simulations of a quasi-perpendicular shock

Burgess 1987

Simulation beams in $v_x$-$v_z$ phase space as the angle $\Theta_{Bn}$ is increased. The line is the direction of the upstream magnetic field.
Trajectory of a directly reflected particle plotted in the shock frame. Top left: typical magnetic field trace. Right panels: time history of position and component forces.

Simulation beam density as a function of $\Theta_{\text{Bn}}$ for various values of upstream ion $\beta$ (ratio of incident particle flux to backstreaming beam flux).
Summary

1. Quasi-Parallel Shocks

Upstream waves by r. h. resonant ion/ion beam instability

Waves at higher Mach number downstream directed group velocity

Mode conversion of upstream waves downstream

Interface instability – important at higher Mach number

Oblique shocks: waves develop into short large amplitude magnetic structures

Backstreaming ions: injection by energy gain at shock

2. Quasi-Perpendicular Shocks

Specularly reflected ions – Alfven ion cyclotron instability downstream

Ripples at shock surface parallel and perpendicular to magnetic field

Self-reformation (micro-instabilities in the foot, nonlinear whistler, whistler induced beam Instability)

Buneman instability in the foot of high Mach number shocks – electron acceleration

Field-Aligned Beams
Future Simulations

1. Higher spatial dimensions:
   - 3-D in hybrid (takes into account cross-field diffusion, shock rippling)
   - 2-D in PIC (allow for oblique k vectors of micro-instabilities in foot – many more instabilities – electron heating)

2. Realistic ion/electron mass ratio and large electron plasma/gyrofrequency in PIC simulations

3. Curved shocks (in particular study influence of quasi-perpendicular shock on quasi-parallel foreshock)

4. Minor ions, in particular pickup ions (heliospheric termination shock)