Progress in Plasma Physics by Numerical Simulation: Collisionless Shocks

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Examples of Collisionless Shocks I

Coronal Mass Ejection (SOHO-LASCO) in forbidden Fe line

Large CME observed with SOHO coronograph

Schematic of Earth’s bow shock
Examples of Collisionless Shocks II

Schematic of the heliosphere showing the heliospheric termination shock and the bow shock in front of the heliosphere.

Heating of Counterstreaming Ion Beams in an External Magnetic Field

Naval Research Laboratory, Washington, D. C. 20390
(Received 23 June 1970)

Ion Thermalization in the Earth’s Bow Shock

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University of Maryland, College Park 20742, and
Naval Research Laboratory, Washington, D. C.

The Structure of Perpendicular Bow Shocks

M. M. Leroy,1 D. Winske, C. C. Goodrich, C. S. Wu, and K. Papadopoulos
University of Maryland, College Park, Maryland 20742
LETTERS

The purpose of this Letters section is to provide rapid dissemination of important new results in the fields regularly covered by The Physics of Fluids. Results of extended research should not be presented as a series of letters in place of comprehensive articles. Letters cannot exceed three printed pages in length, including space allowed for title, figures, tables, references and an abstract limited to about 100 words.

* Creation of high-energy electron tails by means of the modified two-stream instability

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(Received 11 February 1983; accepted 11 April 1983)

* ELECTRON HEATING IN SUPERHIGH MACH NUMBER SHOCKS*

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(Received 15 July, 1987)

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* A MECHANISM FOR STRONG SHOCK ELECTRON HEATING IN SUPERNova REMNANTS

P. J. Cargill and K. Papadopoulos
Department of Physics and Astronomy, University of Maryland, College Park
Received 1987 October 26; accepted 1988 March 9
Subcritical shock

Dissipation is sufficient to account for temperature jump required by RH relations

Supercritical shock

Additional process of reflection of part of incident ions is needed

(First critical Mach number: fast magnetosonic Mach number at which downstream flow speed equals flow speed)
Specularly reflected ions in the foot of the quasi-perpendicular bow shock – in situ observations (ISEE)

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.
Hybrid simulation of a perpendicular shock by the Maryland group (Papadopoulos, Leroy, Goodrich, Winske, Wu)
Schematic of ion reflection and downstream thermalization at supercritical perpendicular shocks.
Classification of Computer Simulation Models of Plasmas

Kinetic Description

- Vlasov Codes
- Full particle codes
- PIC

Hybrid Code

Fluid Description

- MHD Codes
Simulation Methods

1. Hybrid Method

Ions are (macro) particles
Electrons are represented as a charge-neutralizing fluid

Electric field is determined from the momentum equation of the electron fluid

\[ nm_e \frac{d\vec{V}_e}{dt} = -en(\vec{E} + \frac{\vec{V}_e \times \vec{B}}{c}) - \nabla p_e \]
2. Particle-In-Cell (PIC) Method

Both species, ions and electrons, are represented as particles

Poisson’s equation has to be solved

Spatial and temporal scales of the electrons (gyration, Debye length) have to be resolved

Disadvantage:

Needs huge computational resources

Advantage:

Gives information about processes on electron scales
Describes self-consistently electron heating and acceleration
Parameters in PIC Simulations of Collisionless Shocks

1. Mass ratio \( \frac{m_i}{m_e} \)

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

<table>
<thead>
<tr>
<th>Solar Wind</th>
<th>( \frac{m_i}{m_e} )</th>
<th>( \frac{\omega_{pe}}{\Omega_{ce}} )</th>
<th>( \frac{c}{V_A} )</th>
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<td>Biskamp and Welter, 1973</td>
<td>124</td>
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<td>Lembege and Dawson, 1987</td>
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<td>Liewer et al., 1991</td>
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<td>Krasnoselskikh et al., 2002</td>
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<td>Hada, Oonishi, Lembege, Savoini 2003</td>
<td>84</td>
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<td>Scholer, Shinohara, Matsukiyo, 2003</td>
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<td>Muschietti and Lembege, 2005</td>
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<td>Matsukiyo, Scholer, 2006</td>
<td>1860</td>
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<tr>
<td>Scholer, Comisel, Matsukiyo, 2007</td>
<td>1000</td>
<td>5</td>
<td>1-D</td>
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</tbody>
</table>
2-D Hybrid Simulation of Perpendicular Shock - B in Simulation (x-y) Plane

Winske and Quest  1988

By magnetic field in x-y plane                      Density in x-y plane

Oblique propagating Alfven Ion Cyclotron waves produced
by the perpendicular/parallel temperature anisotropy
(large perp temperature due to reflected gyrating ions)

$B_y$ magnetic field in x-y plane

Density in x-y plane
Gray-shaded: magnetic field $B_x$ component

Ripples are surface waves on shock front
Move along shock surface with Alfven velocity given by magnetic field in overshoot

Shocks without ripples
$B$ perp to simulation plane
Subcritical

Shock with ripples

Ion scale structures produce efficient electron scattering
Electron acceleration (test particle electrons in hybrid code shock)
Cluster Observations of Bow Shock Ripples

Moullard et al. 2006

From Top: Magnetic field magnitude, low pass, band pass (0.025-0.83 Hz), and high pass filter

16 sec fluctuations - ripples with wavelengths of about 30 ion inertial lengths

Low pass + band pass filtered magnetic field (top) and density (bottom) at the four S/C
Nonstationary Shocks (Self-Reformation)

Four-spacecraft Cluster observations of three quasi-perpendicular bow shock crossings

Horbury et al. 2002
Oblique Shocks and Whistler Precursor

Whistler critical Mach number

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

Condition:
1. Phase velocity = shock velocity (phase standing)
2. Wave length = electron inertial length (smallest wave length)

Below \( M_w \) exists phase standing small amplitude upstream whistler with upstream directed group velocity
1. Whistler excited nonlinear instability between incoming solar wind and reflected ions

Incoming and reflected ion beams are stable when velocity difference large

A nonlinear beam-instability between incoming and reflected ions is triggered by the electric field of the upstream whistler and results in dissipation
Fig. 2. Ion phase space $x$ and $v_x$, 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 $m_i/m_e = 128$. $M_a = 5.0$

$$M_w = \frac{|\cos \Theta_{B_0}|}{2(m_e/m_i)^{1/2}} = 4.0$$
PIC simulation of a $\Theta_{Bn} = 90^\circ$ shock

$(m_i / m_e = 84)$

Shock reformation on time scale of about 300 inverse electron gyrofrequencies (about 3 inverse ion gyrofrequencies)
2. Self-reformation by ion accumulation at the upstream edge of the foot

Hada et al. 2003
Iteration of time-dependent hybrid equations (ions kinetic, electrons as fluid) for initial state with constant magnetic field, zero potential, incoming ions and reflected (gyrating) ions.

Ion phase space and field variables as number of iterations increases

10% reflected ions:  
time-stationary configuration

20% reflected ions:  
Iterations do not converge  
non-stationary
3. Instabilities in the foot

Scholer et al. 2003

Source of instabilities

\[ u_r \neq u_e \]
\[ u_i \neq u_e \]
Situation in the foot region of a perpendicular shock

Ion and electron distributions in the foot:
- Ions: unmagnetized
- Electrons: magnetized
## Microinstabilities in the Foot Region of Quasi-Perpendicular Shocks

<table>
<thead>
<tr>
<th>Wave type</th>
<th>Necessary condition</th>
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<tr>
<td>Buneman inst.</td>
<td>Upper hybrid</td>
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<tr>
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<td>(Langmuir)</td>
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<td>Ion acoustic inst.</td>
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<td>Bernstein inst.</td>
<td>Cyclotron harmonics</td>
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<td>Modified two-stream inst.</td>
<td>Oblique whistler</td>
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</tbody>
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Modified Two-Stream Instability

\[ \Omega_e \cos \Theta_{Bn} - \omega \]

- Langmuir
- oblique whistler
- MTSI

\[ \Omega_i << \omega << \Omega_e \]

- unmagnetized ions \rightarrow perpendicular trapping
- strongly magnetized electrons \rightarrow parallel trapping

\[ u_{ix} \rightarrow v \]

- shock
Growth rate and real frequency of the modified two-stream instability for

(a) reflected ions

(b) transmitted ions

for various angles $\Theta_{Bk}$
Mass dependence of the maximum linear growth rate of MTSI

(Cold plasma dispersion relation)

\[ \frac{\tau}{\tau_{\max}} = \frac{\omega^2_{\text{pe}}}{\Omega^2_{\text{ce}}} \]

\[ \tau = \frac{\omega^2_{\text{pe}}}{\Omega^2_{\text{ce}}} \]

Matsukiyo and Scholer 2003
Reformation of almost perpendicular medium Mach number shocks: Mass ratio and ion beta effect

$\beta_i = 0.1$, $\Theta_{Bn} = 87^\circ$

Higher beta: electron & ion Landau damping stabilizes
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

\[ t \, \Omega_{ci} = 4.6 \]
$M_A = 8 \quad \beta_i = 0.5$

Cluster magnetic and electric field observations of shock reformation

Steepend magnetic field and large electric field spike

Seki et al. in press 2009
Future of Shock Simulations

2-D PIC Simulations of Shocks - Instability-Induced Nonstationarity

2-D, 3-D (Hybrid) Global Bow Shock Simulations

Very High Mach Number Shock PIC Simulations – Electron acceleration
1. 2-D PIC Simulations of Ion/Ion Beams in a Periodic System

Number of grids $1,024 \times 1,024$
Number of particles $100$/cell
Time step $0.02 \omega_{pe}^{-1}$
System length $40.96 \ c/\omega_{pe}$

$\omega_{pe}^2/\omega_{ce}^2 = 4$
$mi/m_e = 1836$
$\beta_i = \beta_r = 0.05$
$\beta_e = 0.05$
$M_A \sim 10$

Matsukiyo and Scholer 2006
Two-Step Instabilities

1. MTSI between reflected/transmitted ions and electrons \( \rightarrow \) Parallel electron acceleration

2. Electron acoustic instability – electron heating

Electron phase space \( v_y \) at a certain \( x \)

Power spectrum of \( E_y \) electric field component (broad-band fluctuations typical for EAI)

The double peaked electron distributions (due to the modified two-stream instab.) are free energy source for electron acoustic instability. Small scale vortices – parallel electron heating.
2. 2-D Global Hybrid Simulation

Omidi, Blanco-Cano, Russell 2005

\[ D_p = 64 \]

\[ D_p = \text{magnetopause standoff distance/ ion inertial length} \]

(at 1 AU inertial length is about 100 km)
3. Very High Mach Number Shocks - SNRS

ELECTRON HEATING IN SUPERHIGH MACH NUMBER SHOCKS*

K. PAPADOPOULOS

Department of Physics and Astronomy, University of Maryland, College Park, MD, U.S.A.

(Received 15 July, 1987)

1. Excitation of the Buneman Instability in the foot \(\rightarrow\) Electron heating

2. Excitation of Ion-Acoustic Instability \(\rightarrow\) Further strong electron heating

Cargill and Papadopoulos 1988: hybrid simulation of a Mach number \(M_A = 50\) shock with phenomenological resistivity
Buneman Instability

\[ \Delta u >> v_{the} \]

Suppressed when

\[ \beta_e > 4 \left( 1 - \alpha \right) M_A^2 / \mu \quad \text{where } \mu = \text{ion/electron mass ratio} \]
\[ \alpha = \text{ratio of reflected ions} \]

with \( \mu = 1836, \alpha = 0.2 \) this results in

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

(always fullfilled at Earth's bow shock)

But: when using in PIC simulations small mass ratio \( \mu \) the Buneman Instability can get excited at smaller Mach number
\( \frac{\omega_{pe}}{\Omega_e} = 50, \frac{m_i}{m_e} = 1836, \Theta_{Bn} = 90^\circ \)
PIC Simulations: Buneman-Instability (BI) in the Foot and Electron Acceleration

Shimada and Hoshino 2000

$M_A = 10.5 \quad m_i / m_e = 20$

$$V = \frac{\omega_{pe}}{\Omega_{ce}} = \frac{c}{V_A} \sqrt{\frac{m_e}{m_i}} = 20$$

Nonlinear state of the BI: electron holes

Downstream electron energy spectra for (a) low and (b) high Mach Number run
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.
Numerical simulations have led to better understanding of features observed in situ at Earth's bow shock (ISEE).

Simulations have predicted new features/processes at shocks which have subsequently been verified by in situ observations at Earth's bow shock (Cluster).

Comparison of simulation and in situ observations allows verification of the validity of the simulation model/method.

Simulations allow access to parameter regimes (in astrophysical settings) not directly accessible by observations.