Study of shock non-stationarity with 1-D and 2-D hybrid simulations

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Controversy: Do shocks reform in > 1D?

1. Observational evidence
2. Previous simulations
3. Simulation code
4. Demonstrations that shocks reform in > 1D
5. Wave spectra
6. Summary & implications for STEREO
1. Observational evidence that shocks reform

- Low frequency oscillations of the ion flux in shocks observed [Vaisberg et al., 1984; Bagenal et al., 1987].

- Strong support claimed for shock reformation recently [Horbury et al., 2001; Lobzin et al., 2007].

- But, all indirect.
2. Theory & simulations: Steady-state or Reforming?

- 1-D hybrid/PIC simulations ➔ fronts of perpendicular & quasi-perp shocks vary with time and reform [Leroy et al., 1982; Quest, 1986; Hellinger, 2002; Scholer 2003; Yuan et al., 2007].

- 2-D PIC simulations ➔ reformation for high $M_A$ q-perp shocks [Lembege and Dawson, 1987; Lembege and Savoini, 1992].

- Whistler-breaking theory ➔ q-perp shocks unsteady at high enough $M_A$ [Krasnoselskikh et al., 2002].

- However, recent 2D PIC/hybrid simulation analysis claims shock reformation stops because of large amplitude whistler waves [Hellinger et al., 2007].

- Controversy: are shocks steady or reforming in 2D?
3. Hybrid Simulation code

- 1D3V and 2D3V parallel hybrid codes were developed: kinetic ions, massless fluid electrons.
- Darwin approximation for EM waves.
- Injection method to generate the shocks.
- Predictor-corrector method to advance ions.
- Less diffusive algorithm.
- The Fortran 90 code parallelized using 1D domain decomposition with MPI library.
4. Shock reformation in 2D

1. Recovery of Hellinger et al. [2007] results at low $M_A$ and high $\theta_{bn}$.
2. Reformation shown at higher $M_A$.
4. Reformation slows in 2D and as $M_A \downarrow$. 
4.1. Recovery of Hellinger et al. at low $M_A$

- In 1-D find clear self-reformation for these parameters.
- 2-D: confirm quasi-stationary shock front with whistlers.

Our results: $\theta_{bn} = 90^\circ$ & $85^\circ$

$M_A = 3.6$
$\beta_i = 0.2$
$\beta_e = 0.5$

But note almost periodic ripples / spatial inhomogeneities near threshold for self-reformation.
4.2. Clear evidence for 2D reformation

\[ M_A = 6.2 \]
\[ \beta_i = 0.15 \]
\[ \beta_e = 0.2 \]
\[ \theta_{bn} = 85^\circ \]
4.3 1D & 2D reforming shocks

1D hybrid: reforming shock with period about 1.6 upstream $\Omega_{ci}^{-1}$

2D hybrid: reforming shock with period about 2.1 $\Omega_{ci}^{-1}$ (upstream)

Shock reformation processes clearly observed in 1D & 2D hybrid simulations → Reforming Shocks in 2D!!
4.4 Different waves in 1D and 2D

1D snapshots after $6.0 \, \Omega_{ci}^{-1}$

No waves in the foot region

2D snapshots after $3.0 \, \Omega_{ci}^{-1}$

- Whistler waves
- $\omega \approx 5 \, \Omega_{ci} \, , \, \lambda \approx 0.2V_A / \Omega_{ci}.$
Wave spectra

- FFT in y-direction, wavelet transform in x for \( <y> \) quantities.
- Similar wave spectra despite “stationary” vs reforming.
- \( \approx \) consistent if “stationary” case is near reformation threshold

Whistlers with \( \omega \approx 5 \Omega_{ci} \) in simulation frame & \( \lambda \approx 0.2V_A/\Omega_{ci} \)
4.5 Slower reformation in 2D

\[ T \Omega_{ci} \]

\[ M_A \]

\[ \beta_i = 0.15 \]
\[ \beta_e = 0.2 \]
\[ \theta_{bn} = 85^\circ \]

\( 2D \quad \text{■} \)
\( 1D \quad \text{○} \)
5. Summary and implications for STEREO

- Resolved controversy: in general, shocks undergo self-reformation in 2D for high enough $M_A$ and $\theta_{bn}$.
- Hellinger et al. case verified to be time-steady but near threshold $(M_A, \theta_{bn}, \beta)$ for reformation.
- Shock reformation period increases in 2D as $M_A \downarrow$.
- Whistlers generated in foot in 2D, not 1D.

- Could STEREO test reformation via whistlers/waves?
- Extensive parameter search & understanding of role of whistlers in shock reformation needed.
4.5 Wave spectra

FFT transform in y-direction
Wavelet transform in x-direction + y-direction average

Similar wave spectrum but different shock parameters and shock reformation processes

Hellinger et al., GRL, 2007
What is collisionless shock?

- The **collisionless shock** is the nonlinear wave where the solar wind plasma can be heated and decelerated.
- The dissipation processes at the shock depend on the properties of a collisionless plasma, and lead to a rich range of energetic particles and plasma waves.
- Observations of the collisionless shock show a rich source of waves and energetic particles.
- Shock accelerated electrons are mainly responsible for Type II/III radio emissions.