# Two-dimensional hybrid models of ion dynamics in collisionless quasi-perpendicular shocks

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# Motivation and objectives

Early subcritical shock observations: no structure

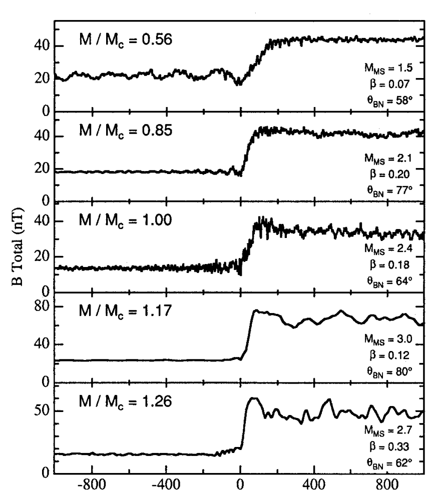
Recent subcritical shock observations: downstream oscillations

1D stationary theory and simulations: gyrating ions

**Questions**

2D simulations: how wide ?

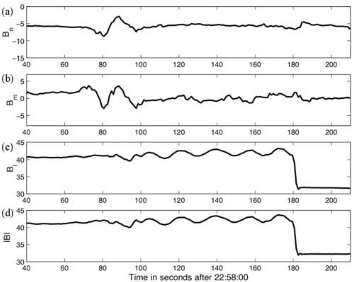
# Sub- vs super-critical: structure develops



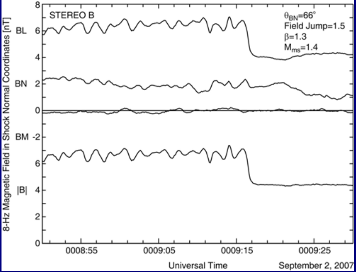

From Farris et al. (1993)

Overshoot appears when reflected ions appear

# Recent: downstream oscillations at low Mach numbers




Very low-Mach number Venusian shock (Venus Express).
From Balikhin et al. (2008)

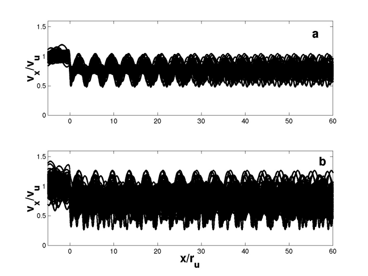



Low-Mach number interplanetary shocks (STEREO).
From Russell et al. (2009)

# Theory: gyration of directly transmitted ions

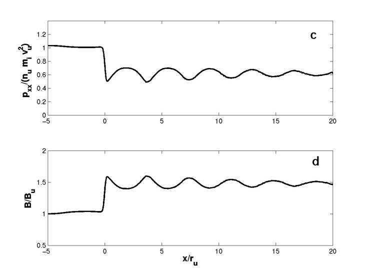
- Thin shock transition: crossing ions are decelerated by the cross-shock potential
- Downstream ions drift and gyrate
- Total pressure $p_{xx} = \int m v_x^2 f(\mathbf{v}) d\mathbf{v}$ spatially periodic
- Pressure balance $p + B^2/8\pi =$ const throughout the shock
- Ergo: magnetic pressure spatially periodic

# Theory: test particle, 1D



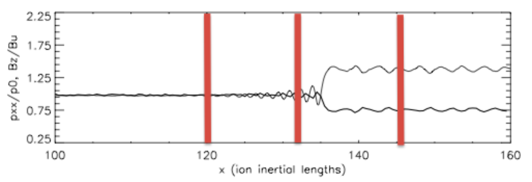

Ion trajectories for different $\beta$

From Balikhin et al. (2008)




Ion pressure and derived magnetic field

# 1D hybrid simulations




Normalized ion pressure and magnetic field. Shock parameters are $\beta_i = \beta_e = 0.2, \theta = 77^\circ, M = 1.48$.

movie

From Ofman et al. (2009)

# Open questions and problems with 1D

1D simulations suppress inhomogeneities along the shock front: whether 1D structure is artificially enforced ?

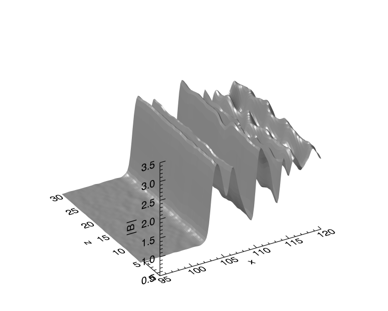
What is the dependence on $M$ and $\beta$ ?

What is the relative contribution of directly transmitted and reflected ions ?

# 2.5D hybrid simulations setup

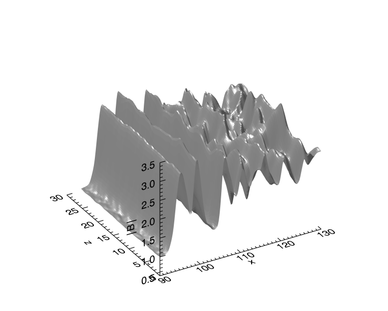
- Box size: 1024×128 cells with grid size of 0.2×0.2 in units of the ion inertial length.
- 200 particles per cell on average.
- Almost perpendicular geometry, $\cos\theta = 0.05$.
- Shock formation by the wall reflection.
- Periodic boundary conditions across.
- In-plane magnetic field.

# Shock: magnetic field



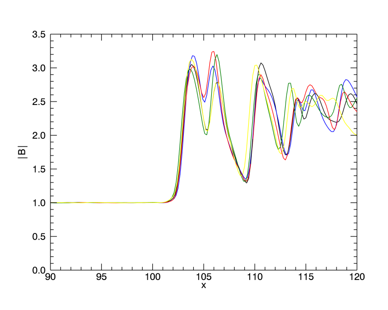

$\beta_i = 0.4,\ M = 3.4$

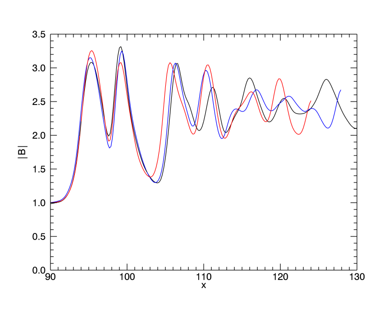
Magnetic field surface plot




$\beta_i = 1.5,\ M = 5.3$

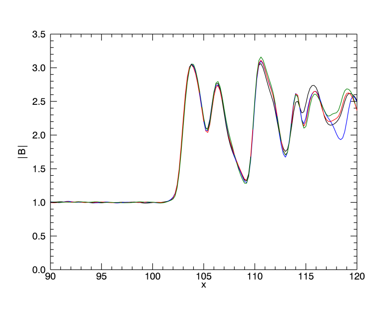
# Shock diagnostics: stationarity



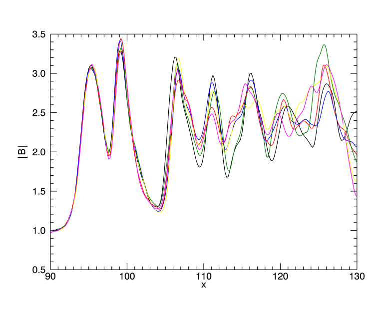




$\beta_i = 0.4,\ M = 3.4$ $\beta_i = 1.5,\ M = 5.3$

Successive magnetic field profiles (averaged across the box)




$\beta_i = 0.4,\ M = 3.4$




$\beta_i = 1.5,\ M = 5.3$

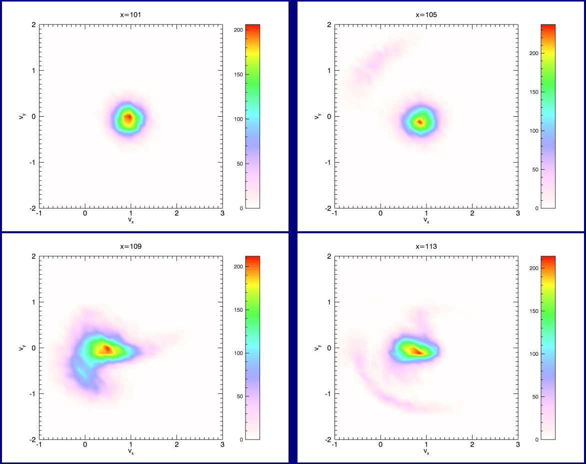
Several simultaneous cuts across the shock

# Ions crossing the shock

movie

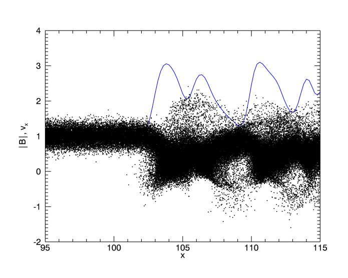
Left: $\beta_i = 0.4$, $M = 3.4$, right: $\beta_i = 1.5$, $M = 5.3$

# Shock with $\beta_i = 1.5$, $M = 5.3$: ion distribution

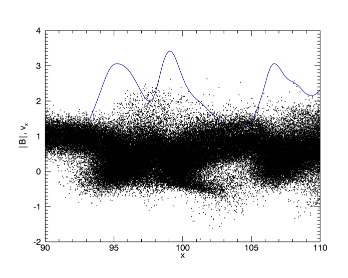



Successive ion distributions throughout the shock

# Distribution vs magnetic field




$\beta_i = 0.4, \; M = 3.4$




$\beta_i = 1.5, \; M = 5.3$

# Conclusions

Downstream magnetic oscillations are due to ion gyration

The main contribution is due to directly transmitted ions

Basic parameter: $v_T/v_u = \sqrt{0.5\beta_i}/M$

Reflected ion contribution increases with the increase of Mach number

No periodicity of the magnetic field because of different spatial periods for directly transmitted and reflected ions