STEREO SWG 21/4/08

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

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Outline

- Controversy: Do shocks reform in > 1D?

1. Observational evidence
2. Previous simulations
3. Simulation code
4. Demonstrations that shocks reform in > 1 D
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?

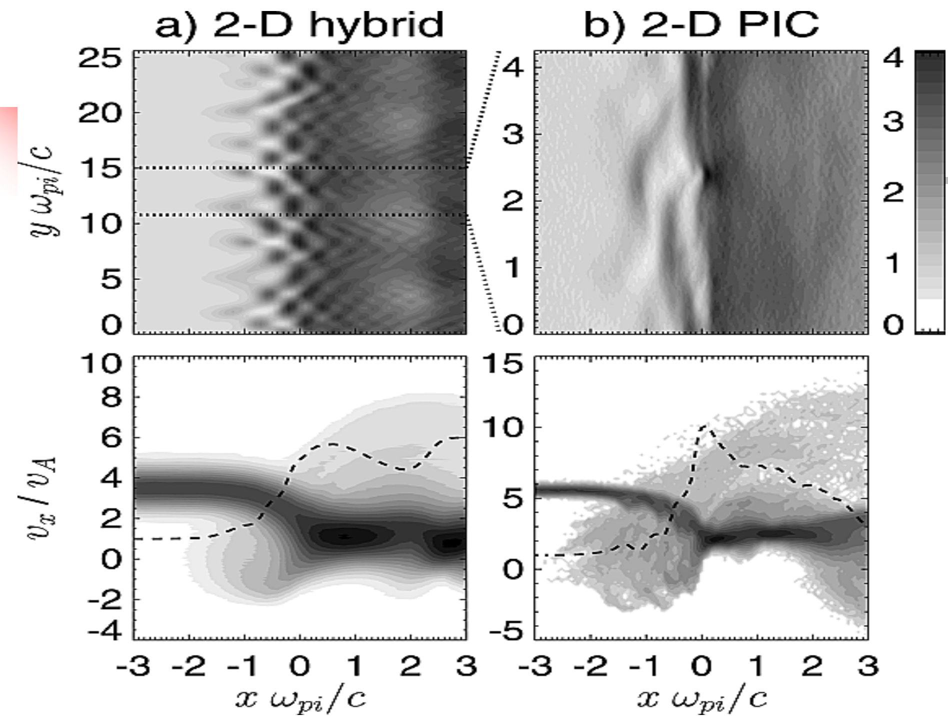
3. Hybrid Simulation code

- 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 algorithim.
- The Fortran 90 code parallelized using 1D domain decomposition with MPI library.

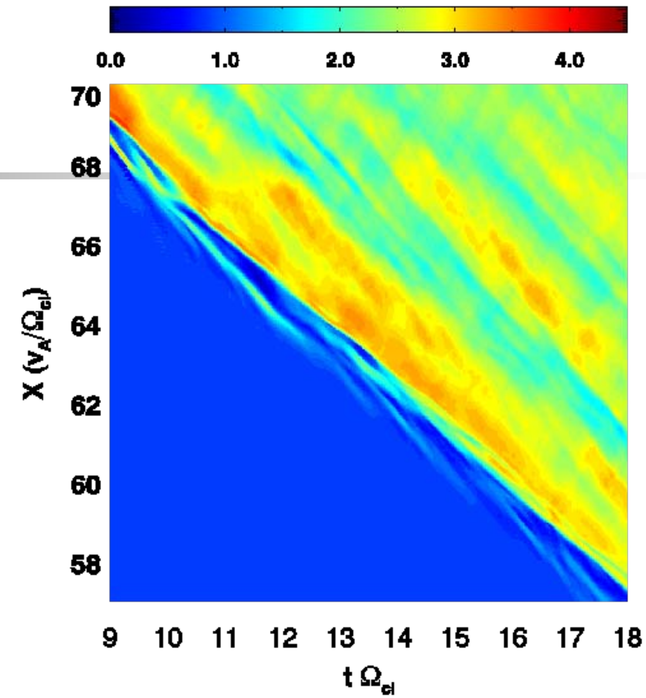
4. Shock reformation in 2D

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

4.1. Recovery of Hellinger et al. at low M_A



[Hellinger et al., GRL, 2007; θ_{bn} = 90]



$M_A = 3.6$

$\beta_i = 0.2$

$\beta_e = 0.5$

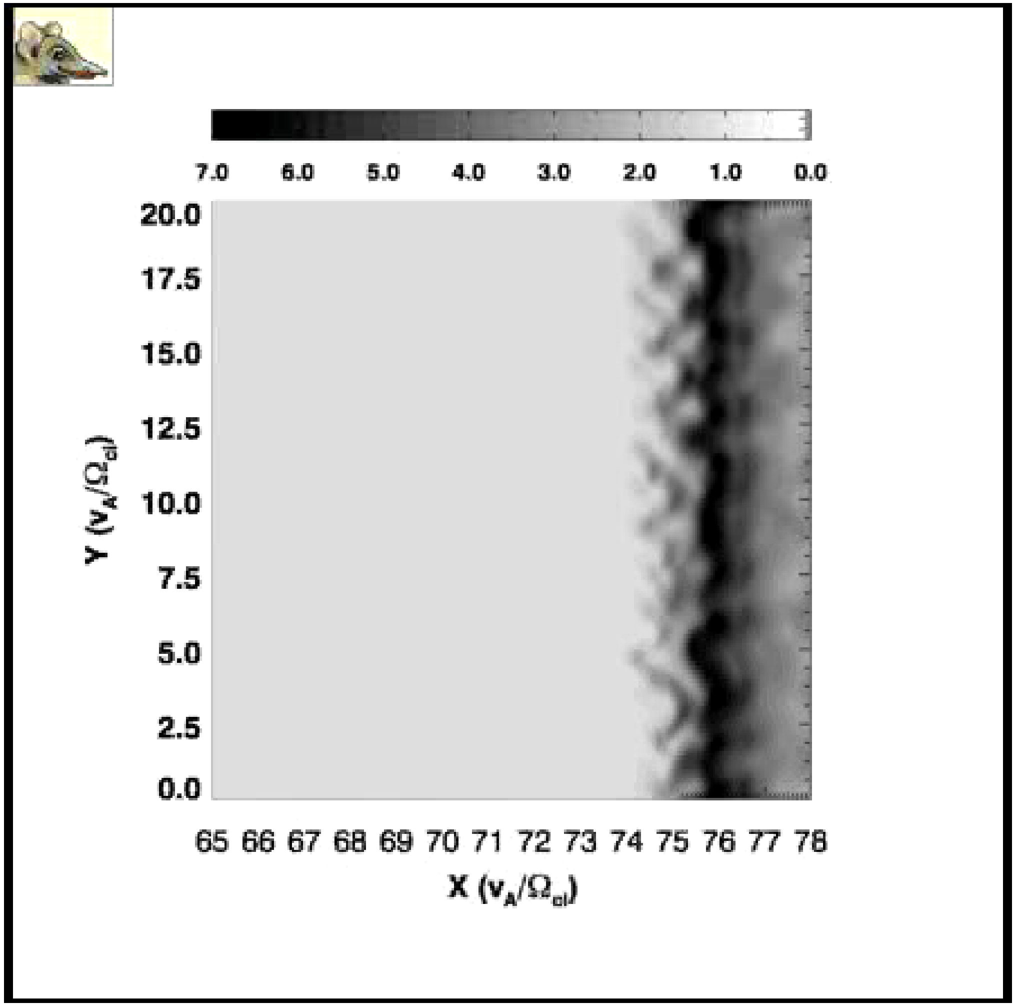
$\theta_{bn} = 90\,\&\,85^o$

Our results: θ_{bn} = 90 & 85.

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

- But note almost periodic ripples / spatial inhomogeneities → near threshold for self-reformation.

4.2. Clear evidence for 2D reformation



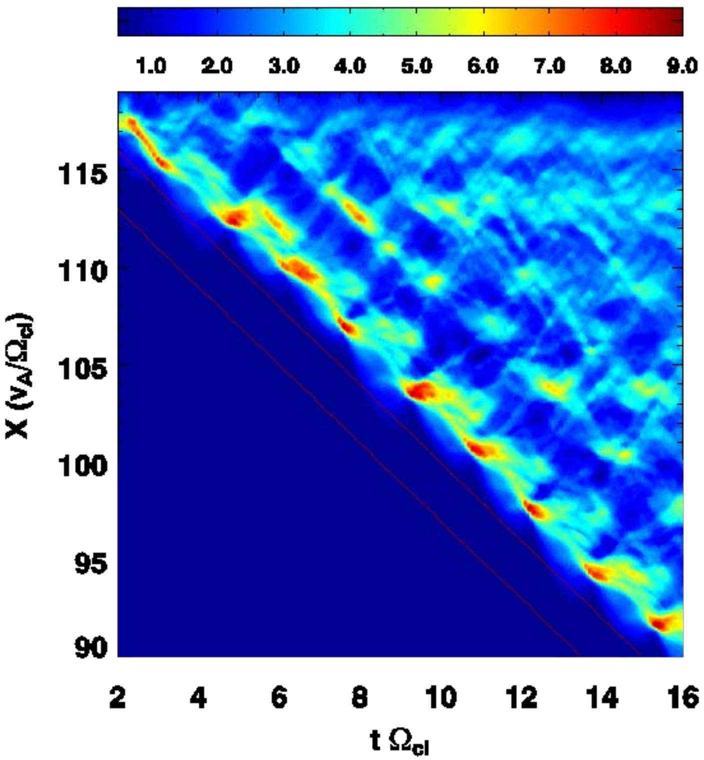
$$M_A = 6.2$$

$$\beta_i = 0.15$$

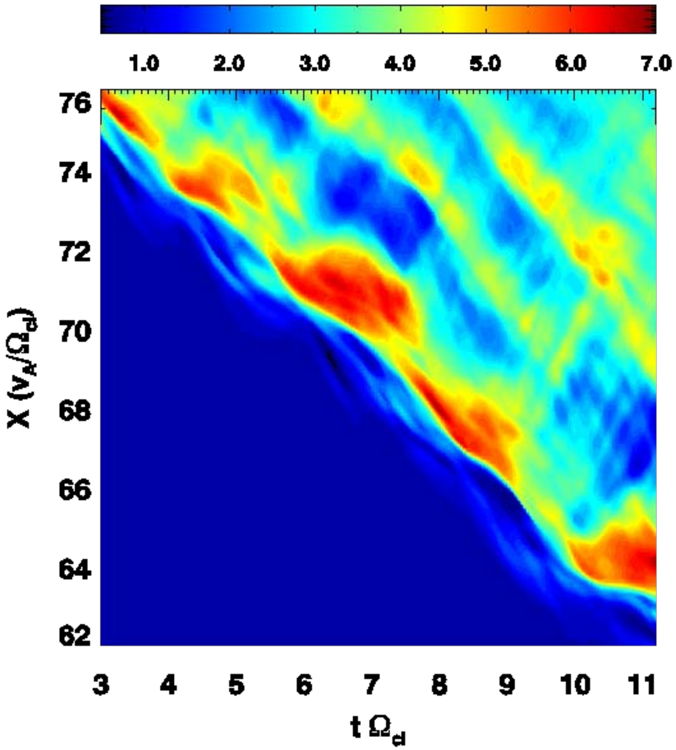
$$\beta_e = 0.2$$

$$\theta_{bn} = 85^o$$

4.3 1D & 2D reforming shocks



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

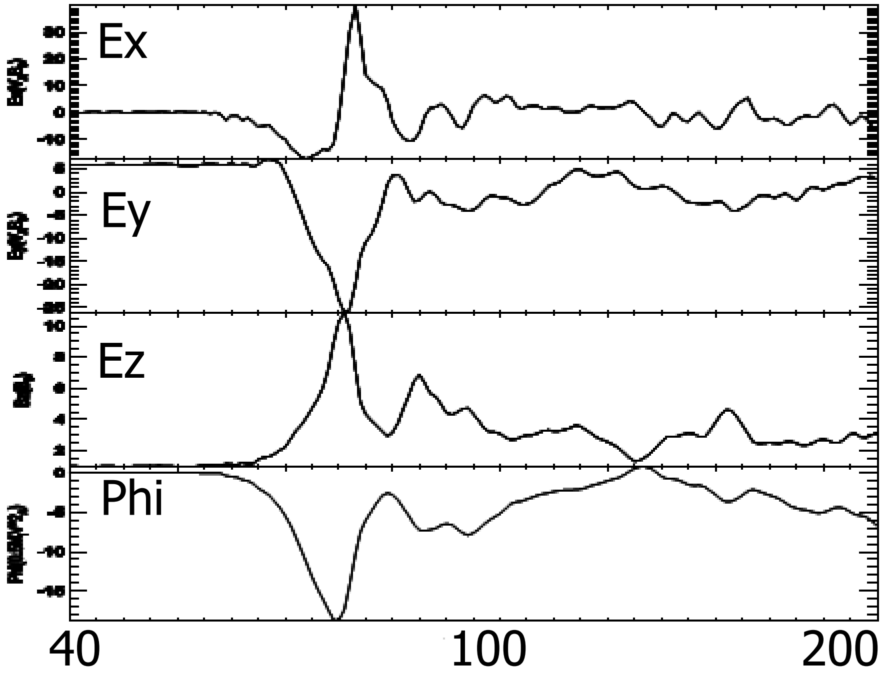


2D hybrid: reforming shock with period about 2.1 Ω_{ci}^{-1} (upstream)

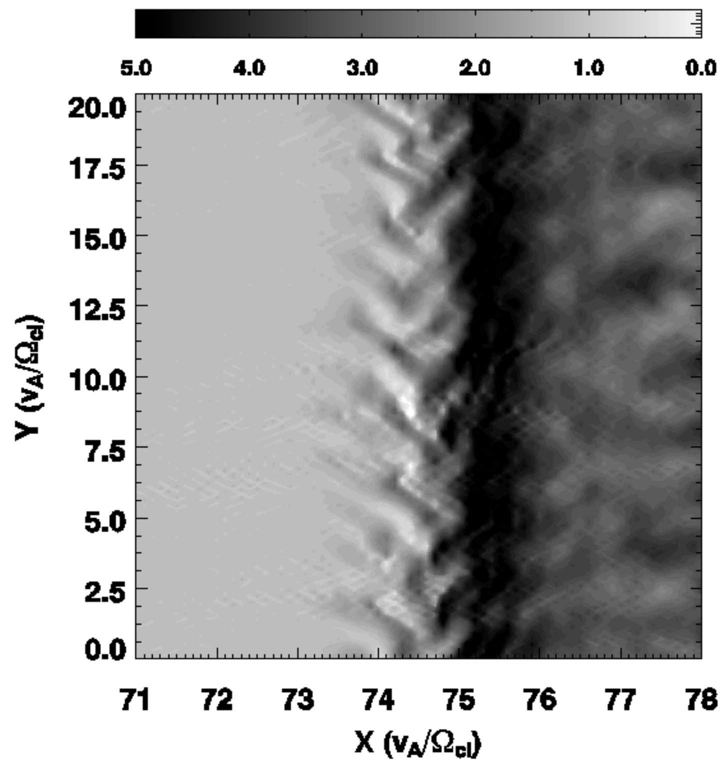
$$M_A = 6.2$$
$$\beta_i = 0.15$$
$$\beta_e = 0.2$$
$$\theta_{bn} = 85^o$$

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 Ω_{ci}^{-1}



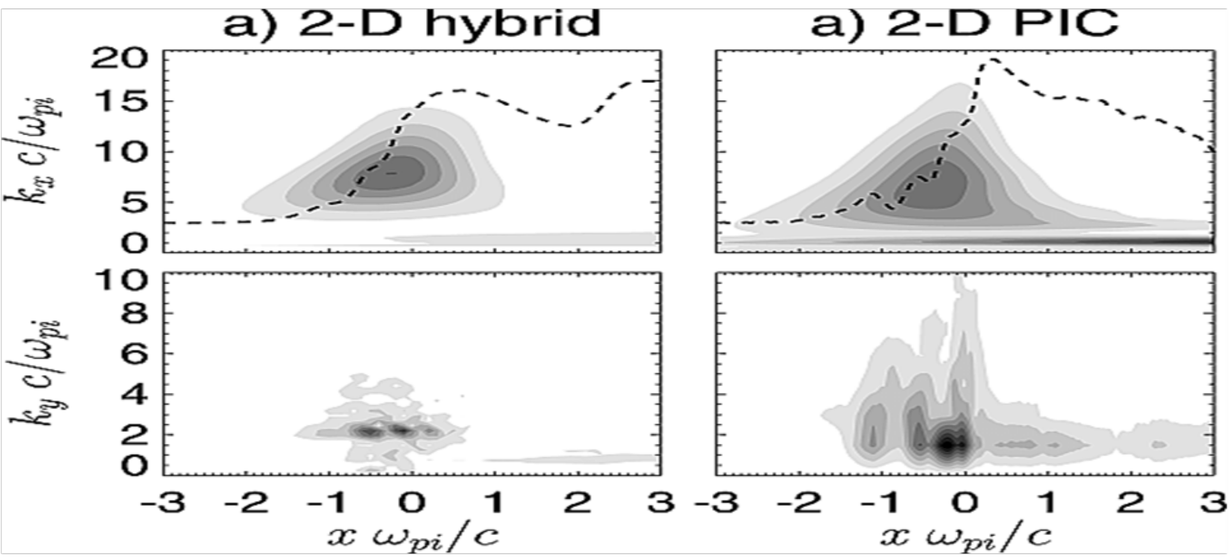
2D snapshots after 3.0 Ω_{ci}^{-1}

No waves in the foot region

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

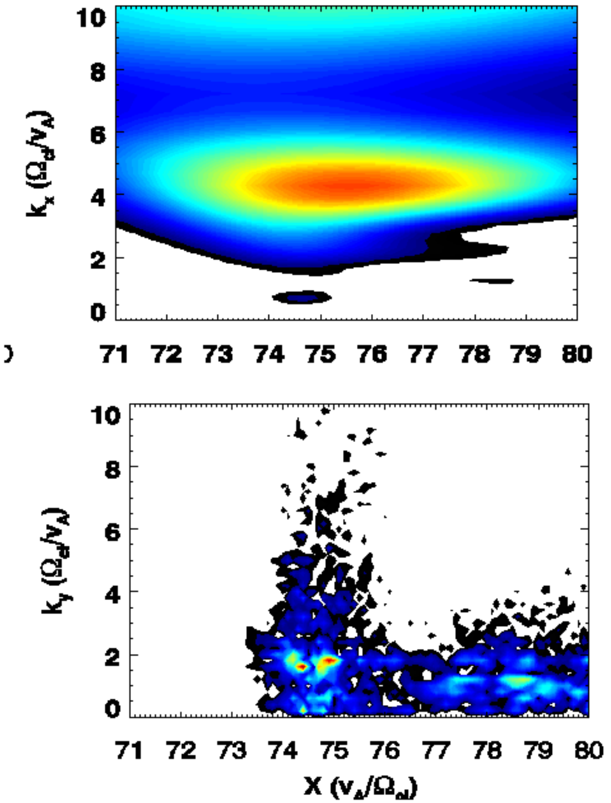
Frequencies in simulation frame

Wave spectra



[Hellinger et al., GRL, 2007]

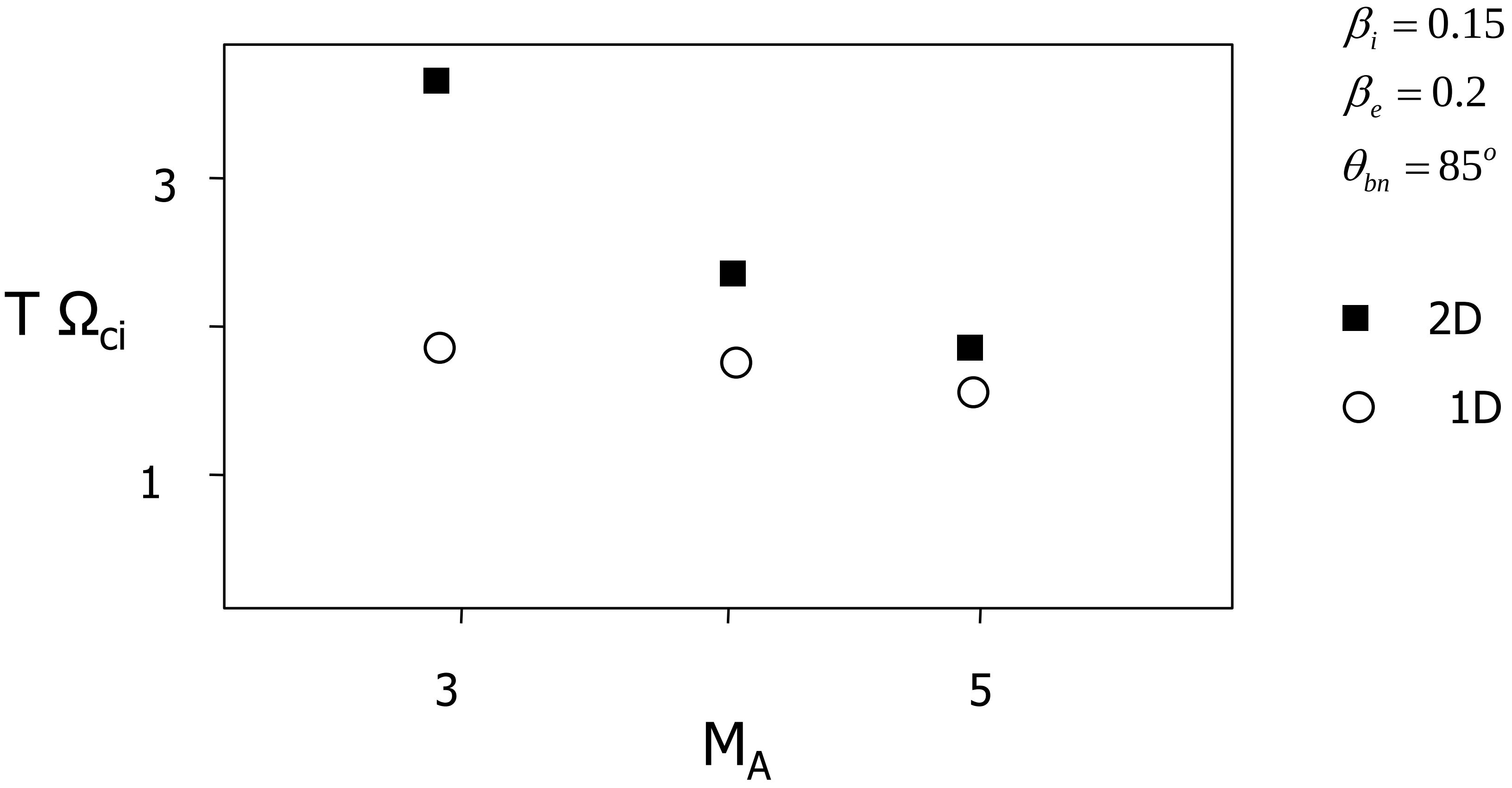
Our results



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

Whistlers with $\omega \approx 5\ \Omega_{ci}$ in simulation frame & $\lambda \approx 0.2 V_A/\ \Omega_{ci}$

4.5 Slower reformation in 2D

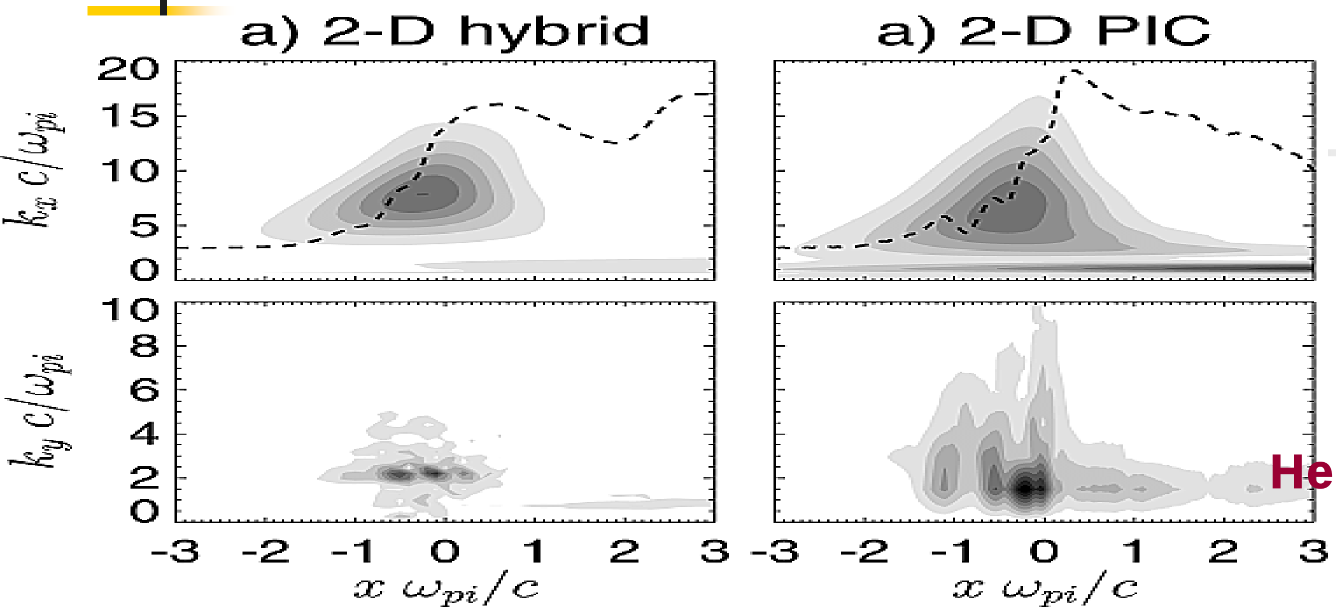


5. Summary and implications for STEREO

- Resolved controversy: in general, shocks undergo self-reformation in 2D for high enough M_A and θ_{bn} .
- Hellinger et al. case verified to be time-steady but near threshold (M_A , θ_{bn} , β) 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.

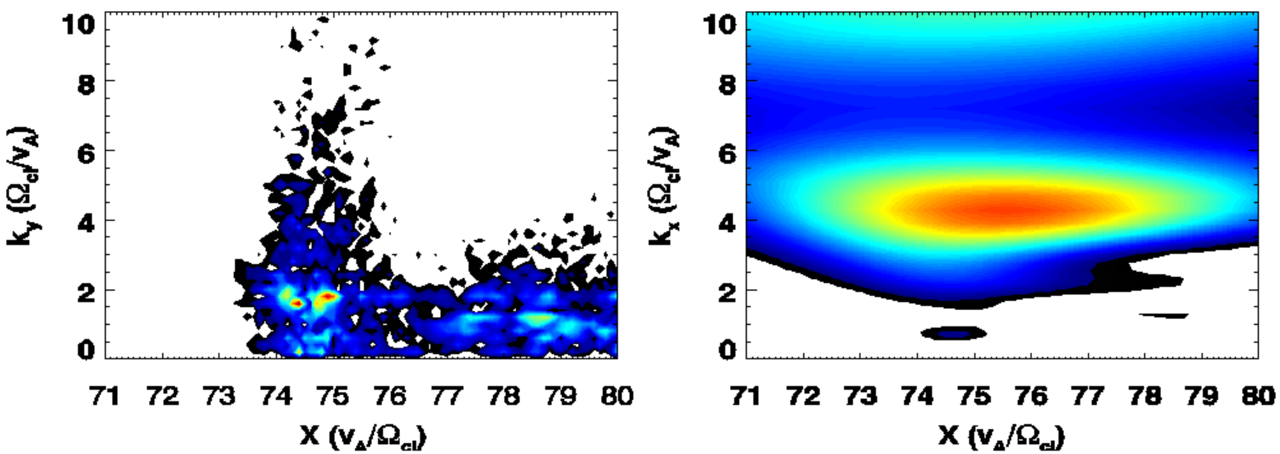
4.5 Wave spectra



FFT transform in y-direction

Wavelet transfrom in x-direction
+ y-direction average

Hellinger et al., GRL, 2007



Similar wave spectrum but different shock Parameters and shock reformation processes

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.