Ion Heating and Energy Partition at the Heliospheric Termination Shock

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Abstract

We use the one dimensional Los Alamos hybrid simulation code to examine heating and energy dissipation via ion reflection and transmission at the perpendicular heliospheric termination shock in the presence of pickup ions. The simulations are 1D in space but 3D in field and velocity components, and are carried out for a range of values of the pickup ion relative density. The simulations show that, because they are relatively cold upstream, the solar wind ions have a relatively large temperature gain across the shock. But, as the relative pickup ion density is increased, the pickup ions gain the larger share of the downstream pressure, consistent with Voyager 2 observations at the termination shock. An analytic model for energy partition among the transmitted solar wind ions, the reflected solar wind ions, and the pickup ions is developed for the perpendicular termination shock. Results of this model are consistent with both hybrid simulations and the Voyager 2 observations.

Outline

- Motivation
  1. Voyager 2 observed that only 20% of the energy goes to solar wind ions [Richardson et al. 2008].
  2. However the Liewer et al. [1993] simulation showed that most of the energy goes to solar wind ions.
  3. Lipatov and Zank (1999)'s1-D simulation concluded that pickup ions are reflected and accelerated.
  4. Li et al. [2008] found that the downstream flow is not subsonic, relative to the magnetosonic speed.
- Hybrid simulation
- Analytical model
- Conclusions
- On-going/future work

Voyager Observations

Table 1. Voyager 1 (V1) and Voyager 2 (V2) Termination Shock Encounters

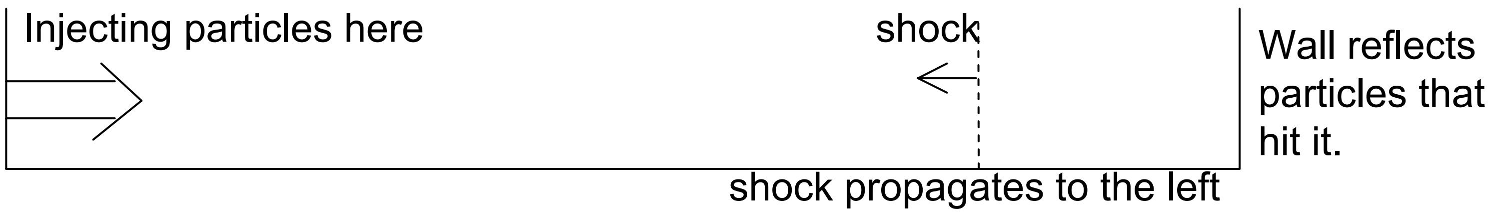
encounters	$r(AU)$	r_s	u_u (km/s)	u_d (km/s)	θ_{Bn}	τ	T_d (k)
V1	94	$2.6^{+0.4}_{-0.2}$	200	100	-	-	-
$V2(TS-2)$	84	2.38 ± 0.14	325	150	$82.8° \pm 3.9°$	10	10^5
$V2(TS-3)$	84	1.58 ± 0.71	250	150	$74.3° \pm 11.2°$	10	10^5

- Shock strength (compression ratio) $r_s=u_u/u_d \sim 2$, it is a weak shock.
- Temperature jump $\tau = T_d/T_u >>$ adiabatic heating.
- Angle between shock normal and downstream magnetic field $\theta_{Bn} \sim 78°$, it is nearly a perpendicular shock.

Los Alamos Hybrid Simulation

- Developed by Dan Winske and collaborators in the early 80'
- Treat ions as particles and electrons as adiabatic massless fluid
- Ideal for computing ion responses to plasma phenomena at ion length and time scales

1-D Setup



- 1-D in space but 3-D in velocity and field components
- Output in downstream rest frame

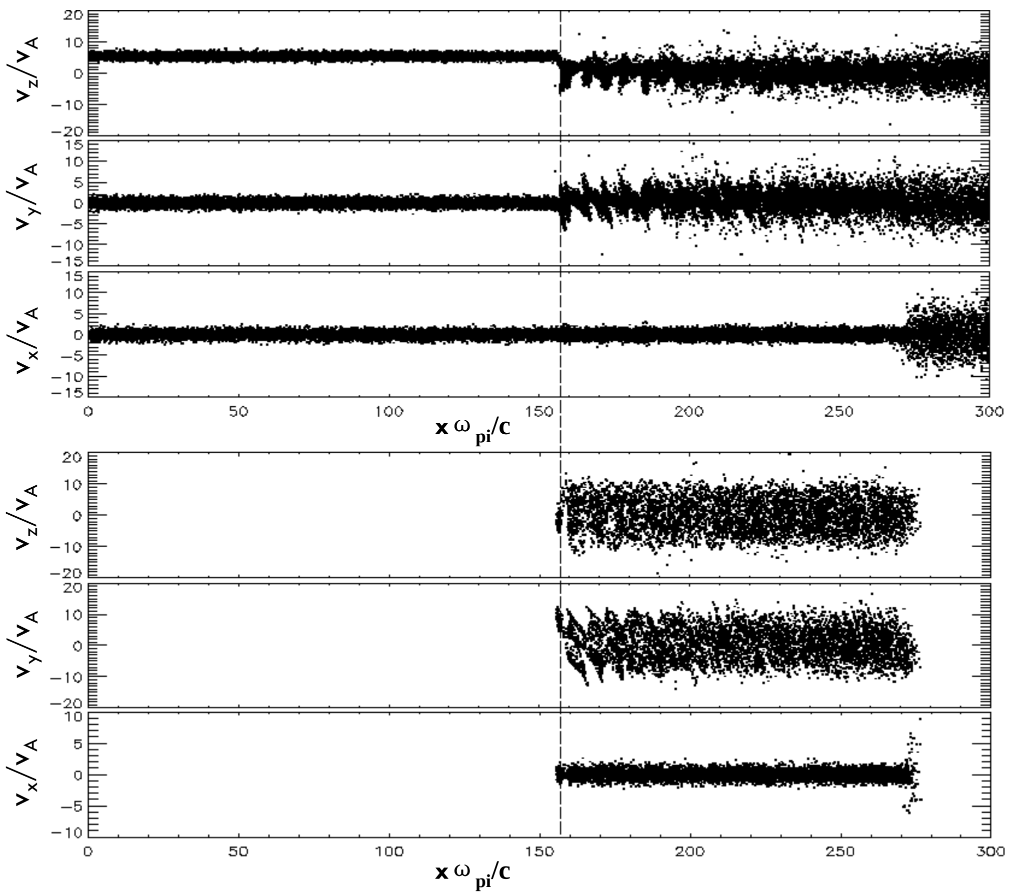
Simulation Cases

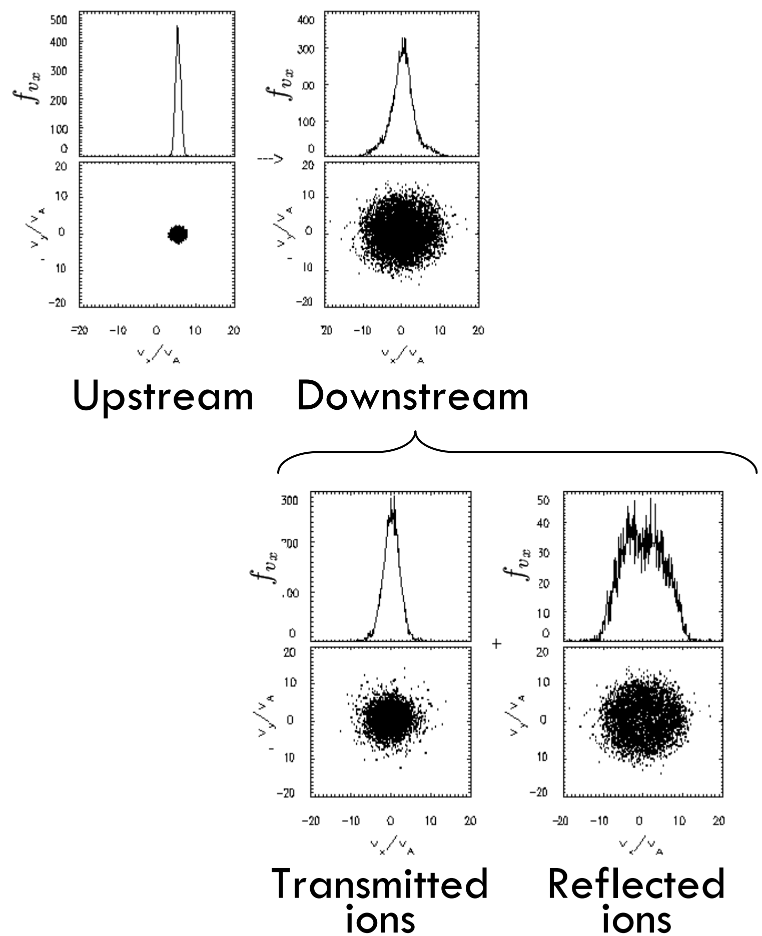
Six Cases at M_A=8, θ_{Bn}=89.9°, β_{sw}=0.5

1. $n_{PUI}/n_u=0$
2. $n_{PUI}/n_u=10\%$
3. $n_{PUI}/n_u=20\%$
4. $n_{PUI}/n_u=30\%$
5. $n_{PUI}/n_u=40\%$
6. $n_{PUI}/n_u=50\%$

It is assumed that the solar wind ion are Maxwellian distributed and the PUIs are shell distributed with a shell velocity of the upstream velocity because of the pick up processes.

Ion Reflection as seen from Phase Space in Case 1 (0% PUI)





Temperature Jump and Energy Partition as seen from all the Simulated Cases

Table 2. Results Calculated from the Hybrid Simulation ($M_A = 8,\ \beta_{sw} = 0.5$)

n_u^{PUI}/n_u	$u_d(v_A)$	$r_s = \frac{n_d}{n_u}$	$\tau_{adiabat}$	τ_{sw}	τ_{PUI}	η_{sw}	η_{PUI}
0%	2.5	2.91	2.04	16.85	-	100%	-
10%	2.8	2.76	1.97	10.46	3.23	49.9%	50.1%
20%	3.2	2.49	1.85	7.72	2.81	30.5%	69.5%
30%	3.5	2.26	1.72	6.86	2.32	26.1%	73.9%
40%	3.9	2.07	1.62	6.80	2.08	24.1%	75.9%
50%	4.0	1.93	1.55	6.32	1.95	20.7%	79.3%

Here energy partition $\eta_{species} = \frac{P_d^{species} - P_u^{species}}{P_d - P_u}$, temperature jump $\tau_{species} = \frac{T_d^{species}}{T_u^{species}}$.

$$T = \frac{m}{3k}(< v_x^2 - < v_x >^2 > + < v_y^2 - < v_y >^2 > + < v_z^2 - < v_z >^2 >).$$

Analytical Model

- ## Assumptions:

1. Reflected solar wind ions gain gyro/thermal velocities that approximate the upstream bulk velocity – specular reflection ($v_d^{sw}=u_u$).
2. PUIs are approximated as all transmitted without reflection.
3. Transmitted ions are heated adiabatically ($v_d^{trans}=v_u r_S^{(\gamma-1)/2}$).

- ## Solvers:

1. Rankine-Hugoniot relations for upstream thermal pressure from two species (solar wind and PUI) for perpendicular shock to get r_S.
2. Solve momentum balance at shock to get energy partition in downstream.

$$\rho_u u_u^2 + P_u + \frac{B_u^2}{2\mu_0} = \rho_d u_d^2 + P_d + \frac{B_d^2}{2\mu_0}$$

where $P_u = P_u^{sw} + P_u^{PUI}$,

$$P_d = P_d^{sw-trans} + P_d^{sw-ref} + P_d^{PUI} = r_S^{\gamma}(1-\varepsilon_{ref})(P_u - \varphi\rho_u u_u^2/3) + r_S\varepsilon_{ref}\rho_u u_u^2/3 + r_S^{\gamma}\varphi\rho_u u_u^2/3,$$

and ε_{ref} is the solar wind reflection efficiency defined as $n_{sw\text{-}ref}/n_{sw}$.

Analytical Solutions

- Define PUI density ratio $\varphi = \frac{n_{PUI}}{n_u}$, Magnetosonic Mach number $M_{MS} = \frac{u}{\sqrt{v_A^2 + v_{cs}^2}} = \frac{M_A M_{cs}}{\sqrt{M_A^2 + M_{cs}^2}}$

  then $\delta = \frac{P_u}{\rho_u u_u^2} = \frac{P_u^{sw} + P_u^{PUI}}{\rho_u u_u^2} = \frac{1}{3}[\varphi + (1-\varphi)\frac{\gamma\beta_{sw}}{2M_A^2}],\ \ M_{cs}^2 = \frac{1}{\gamma\delta}.$
- Shock strength r_S can be solved from $(r_S - 1)[r_S^2 \frac{2-\gamma}{M_A^2} + r_S(\frac{\gamma}{M_A^2} + 2\gamma\delta + \gamma - 1) - (\gamma - 1)] = 0$
- For any given φ, γ , M_A, β_{sw}, we can solve for

reflection efficiency

$$\varepsilon_{ref} = \frac{1 - \frac{1}{r_S} + \frac{1 - r_S^2}{2M_A^2} + (1 - r_S)\delta}{\frac{r_S(1-\varphi)}{3} + \frac{r_S^\gamma \varphi}{3} - r_S^\gamma \delta},$$

energy partition

$$\eta_{sw-trans} = \frac{(1-\varepsilon_{ref})(r_S^\gamma - 1)(\delta - \varphi/3)}{r_S^\gamma \varphi/3 + r_S^\gamma(\delta - \varphi/3)(1-\varepsilon_{ref}) + \varepsilon_{ref} r_S(1-\varphi)/3 - \delta},$$

$$\eta_{sw-ref} = \frac{\varepsilon_{ref} r_S^\gamma (1-\varphi)/3 - \varepsilon_{ref}(\delta - \varphi/3)}{r_S^\gamma \varphi/3 + r_S^\gamma(\delta - \varphi/3)(1-\varepsilon_{ref}) + \varepsilon_{ref} r_S(1-\varphi)/3 - \delta},$$

$$\eta_{PUI} = \frac{\varphi(r_S^\gamma - \varphi)/3}{r_S^\gamma \varphi/3 + r_S^\gamma(\delta - \varphi/3)(1-\varepsilon_{ref}) + \varepsilon_{ref} r_S(1-\varphi)/3 - \delta},$$

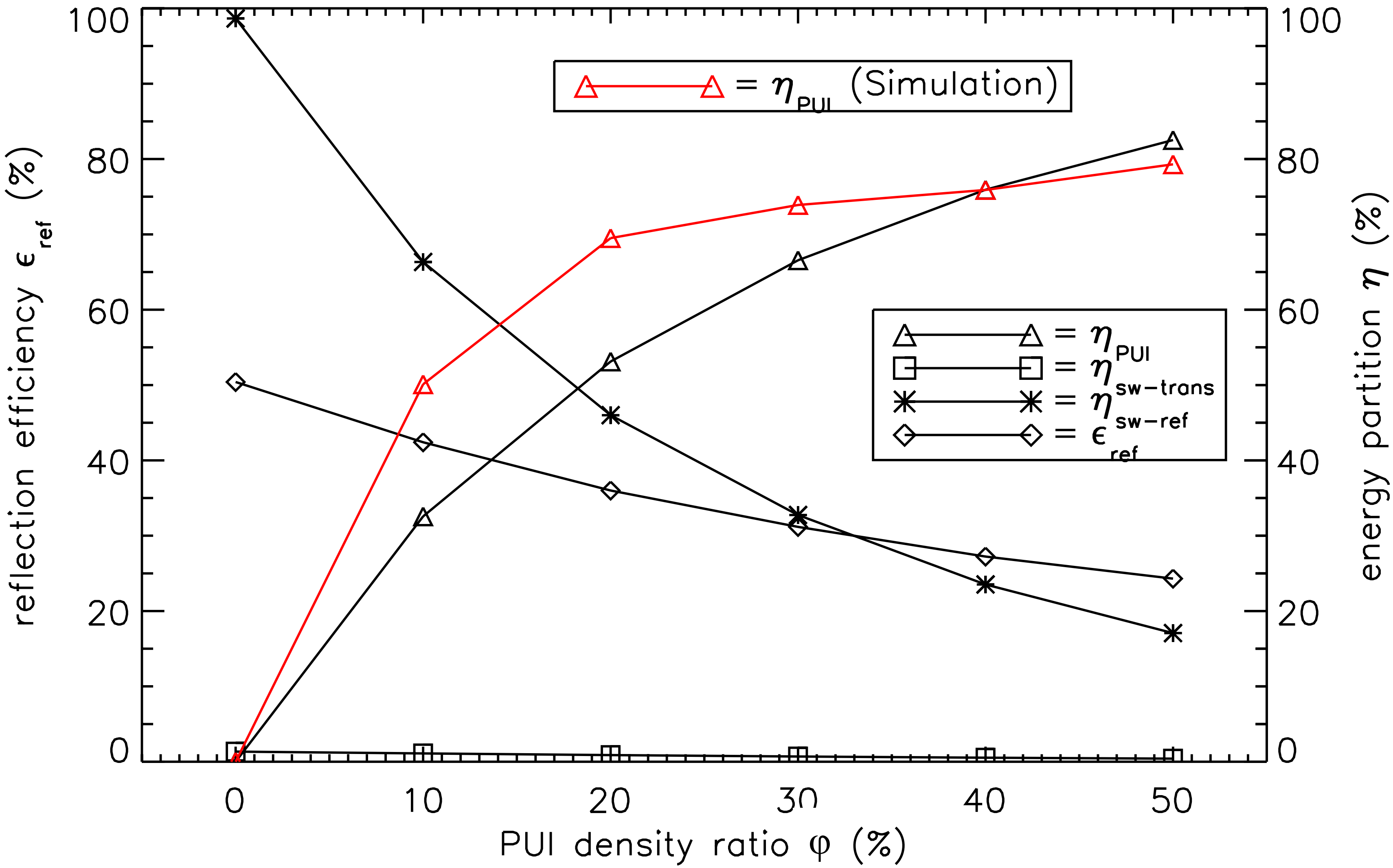
pressure jump

$$\varpi = \frac{P_d}{P_u} = r_S^\gamma(1-\varepsilon_{ref})(1 - \frac{\varphi}{3\delta}) + \frac{r_S \varepsilon_{ref}}{3\delta} + \frac{r_S^\gamma \varphi}{3\delta},$$

and downstream Mach numbers

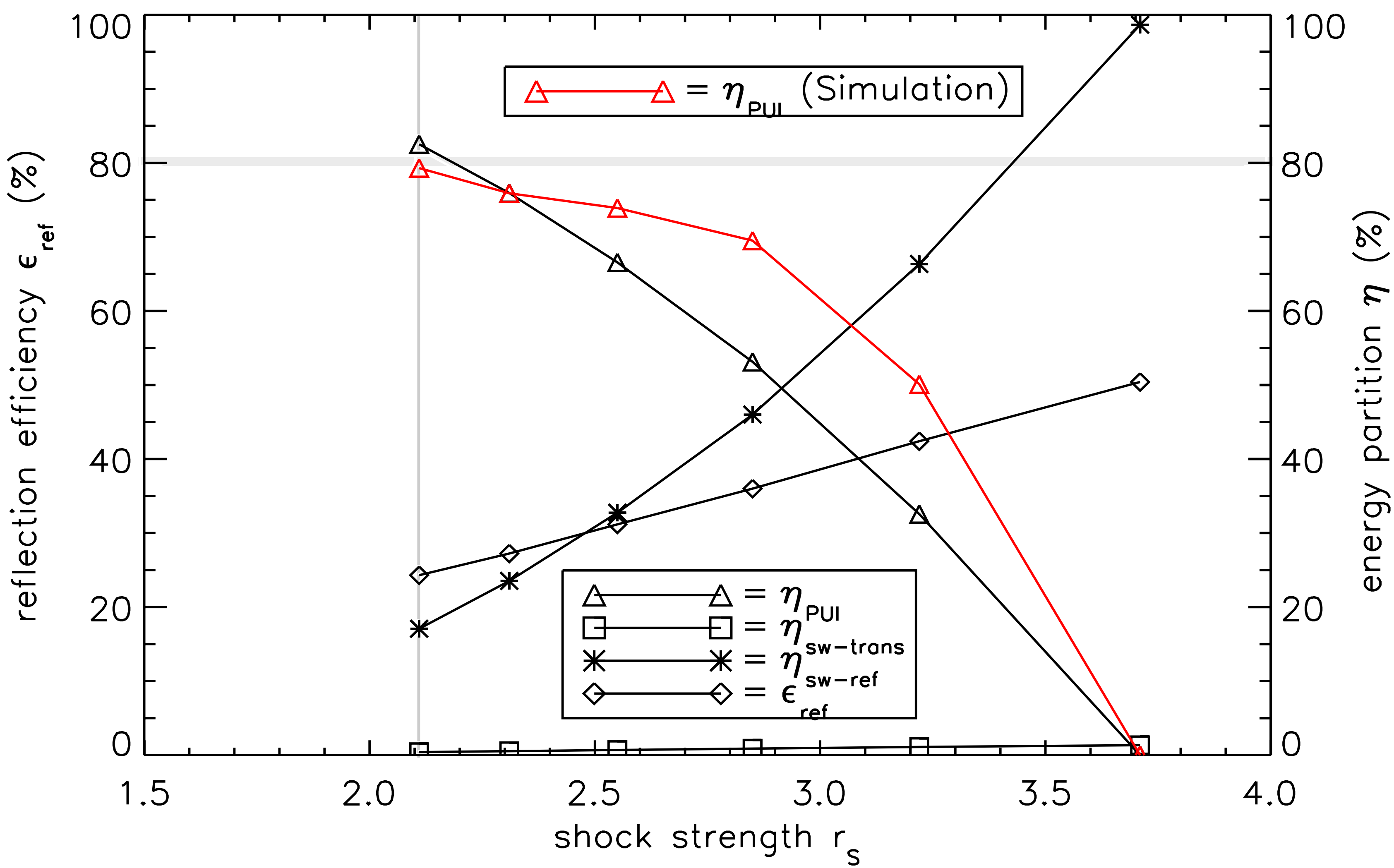
$$M_{A,d} = r_S^{-1.5} M_A,\ \ M_{cs,d} = \frac{Mcs}{\sqrt{r_S \varpi}}.$$

Analytical Result: Energy Partition and Solar Wind Reflection Efficiency as a Function of PUI Density Ratio



Analytical Result: Energy Partition and Solar Wind Reflection Efficiency as a Function of shock strength

Voyager observed value is shaded horizontally. The corresponding shock strength is marked by a verticle grey line.



Analytical Result: Super-Alfvenic, Sub-Sonic and Sub-Magnetosonic Downstream Flow

PUI	M_A	M_{sonic}	M_{Msonic}	$M_{A,d}$	$M_{sonic,d}$	$M_{Msonic,d}$
0%	8	16.63	7.21	1.12	0.51	0.46
10%	8	4.12	3.67	1.38	0.52	0.48
20%	8	2.96	2.78	1.66	0.54	0.51
30%	8	2.43	2.33	1.96	0.56	0.54
40%	8	2.11	2.04	2.28	0.59	0.57
50%	8	1.89	1.84	2.61	0.61	0.60

Conclusions

- On heating: Solar wind ions have a larger temperature gain across the shock because they are relatively cold upstream and therefore more of them are subject to reflection (consistent with Liewer et al. 1995).
- On energy partition: PUI accounts for most of the dissipation in terms of net energy gain (consistent with Richardson et al. 2008)
- On downstream flow: super-Alfvenic, sub-sonic, sub-Magnetosonic (consistent with Li et al. 2008).
- The termination shock has more of a gas kinetic shock character than an Alfvenic shock character, because upstream plasma beta (β_{PUI}+ β_{sw}) is so large.

To be submitted soon, stay tuned!

More work to be done

- 1-D/2-D comparison
- Physics of reflection should be modified
- ß=0.05 for solar wind in simulation and analytical model; γ=1.9 for PUIs in analytical model(on going)

2	PUI	u_d	r_s	tau_sw	tau_PUI	eta_sw	eta_PUI
3	0.00%	1.8	3.55	247.3	n/a	100.00%	n/a
4	10.00%	2.3	3.21	84.2	3.21	33.60%	66.40%
5	12.00%	2.4	3.07	72	3	28.70%	71.30%
6	13.00%	2.5	2.95	57.2	2.89	25.80%	74.25
7	14.00%	2.5	2.83	42.7	3.03	19.50%	80.50%
8	15.00%	1.6	2.8	31.8	3.21	13.40%	86.60%
9	20.00%	3	2.54	17.6	2.54	10.50%	89.50%
10	30.00%	3.6	2.17	8.27	2	11.10%	87.90%
11	40.00%	4.2	2.09	14.65	1.85	9.90%	90.10%
12	50.00%	4.5	1.99	9.76	1.67	2.10%	97.90%
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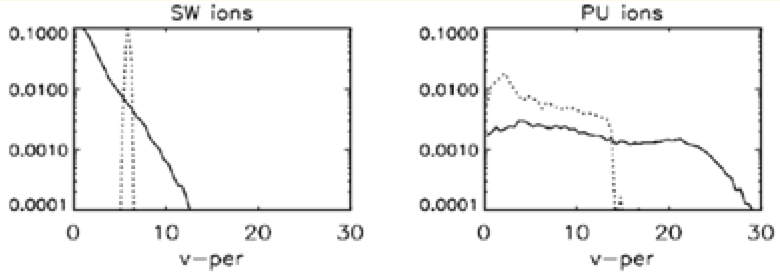
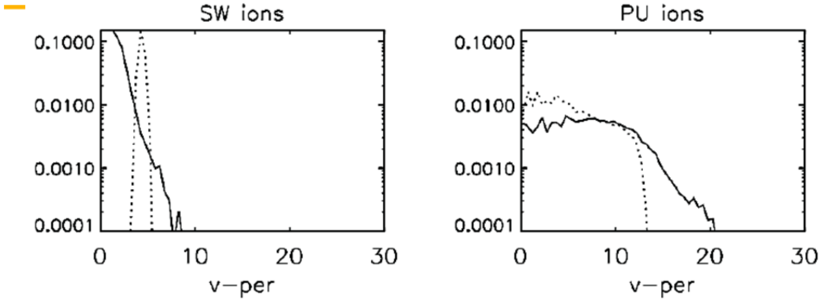
Spectra (Gary et al., Voyagers in the Heliosheath, Kauai, Hawaii 10 January 2009)

Case 1, 0% PU Ions: Downstream Ions Show Strong Heating due to Reflection



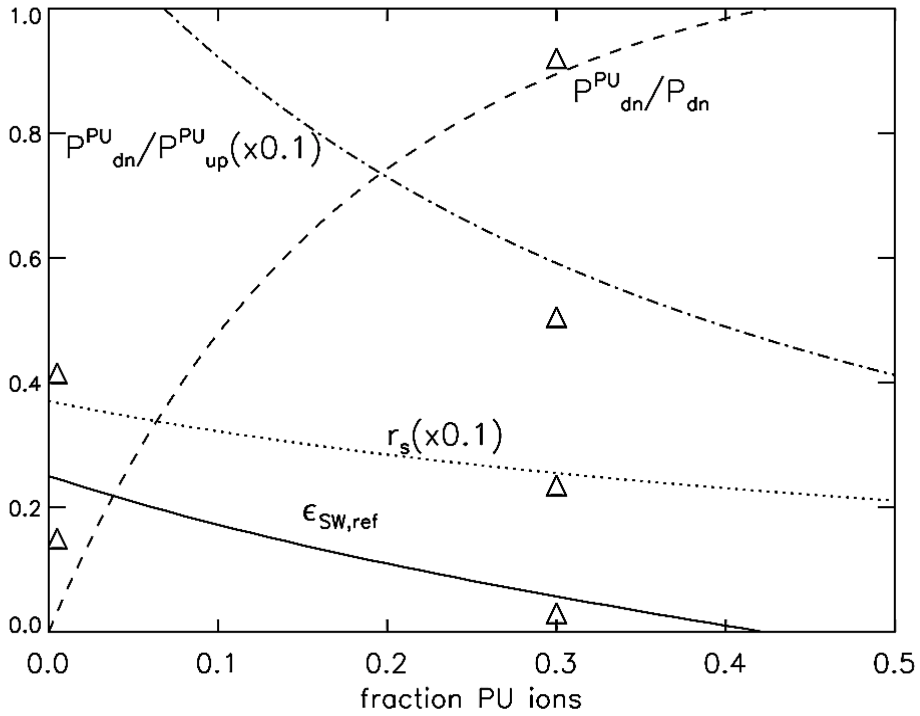
- Upstream: dashed lines. Downstream: solid lines.
- Solar wind ions downstream:
  - Thermally heated "core" and
  - Nonthermal "tail" of ions reflected and subsequently accelerated.
- Pickup ions:
  - Substantial acceleration

Case 2, 30% PU ions: Much Less SW Ion Heating, Less PU Heating Also

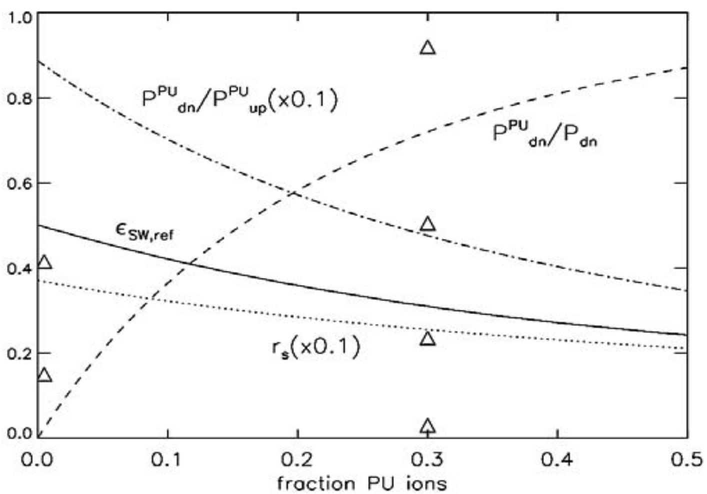


- Upstream: dashed lines. Downstream: solid lines.
- Solar wind ions downstream:
  - Thermally heated "core" and
  - Nonthermal "tail" of ions reflected and subsequently accelerated.
- Pickup ions:
  - Modest acceleration

Refined Analytical Result (Gary et al., Voyagers in the Heliosheath, Kauai, Hawaii,10 January 2009)



- Reflection $\Rightarrow$ PU ions heated non-adiabatically (γ_{PU} = 1.9)
- Stronger PU heating $\Rightarrow$ Much less SW ion reflection needed as compared with the formula from the Wu et al paper at 2008 AGU (below)

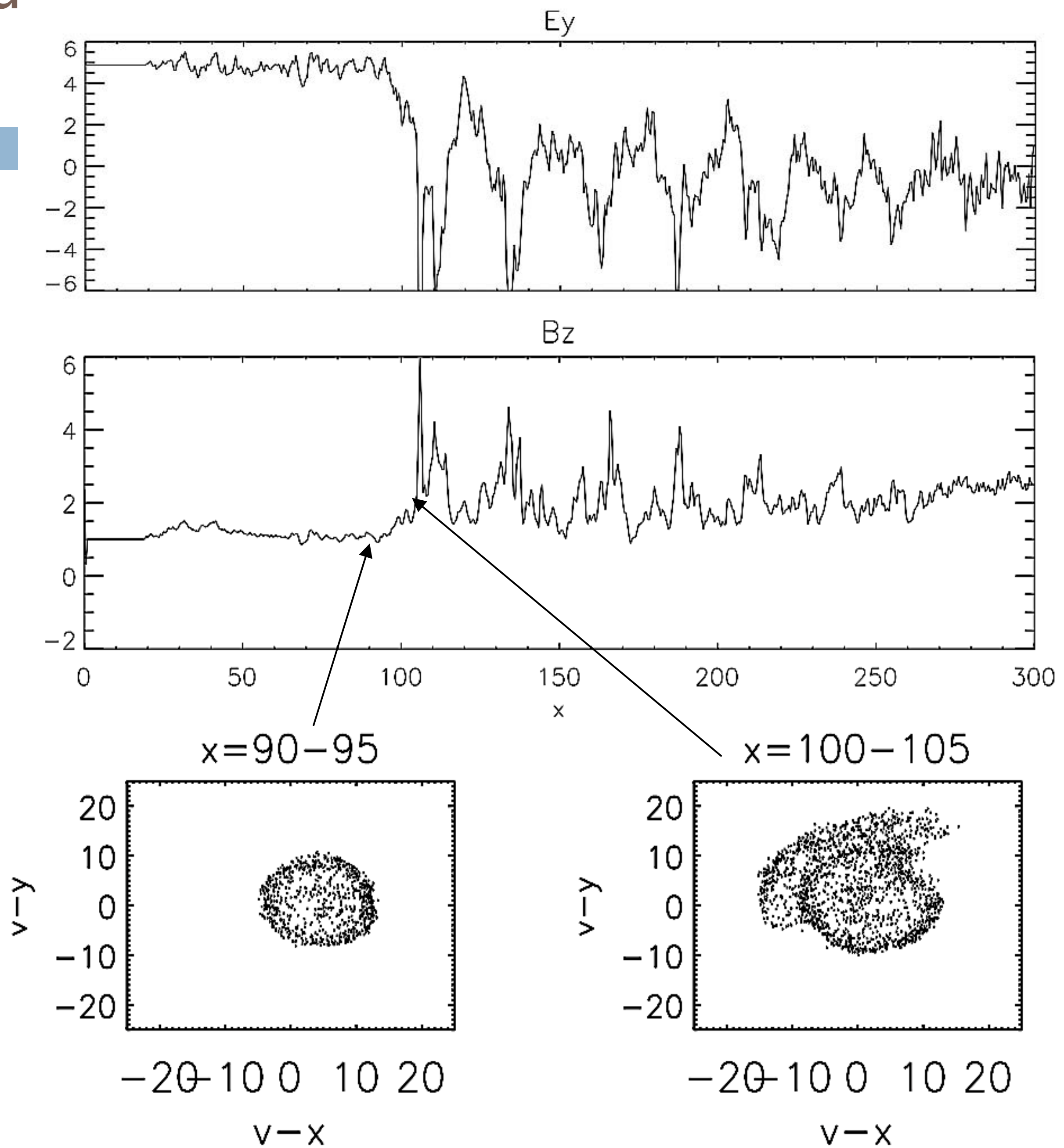


On-going (Provided by Dan Winske)

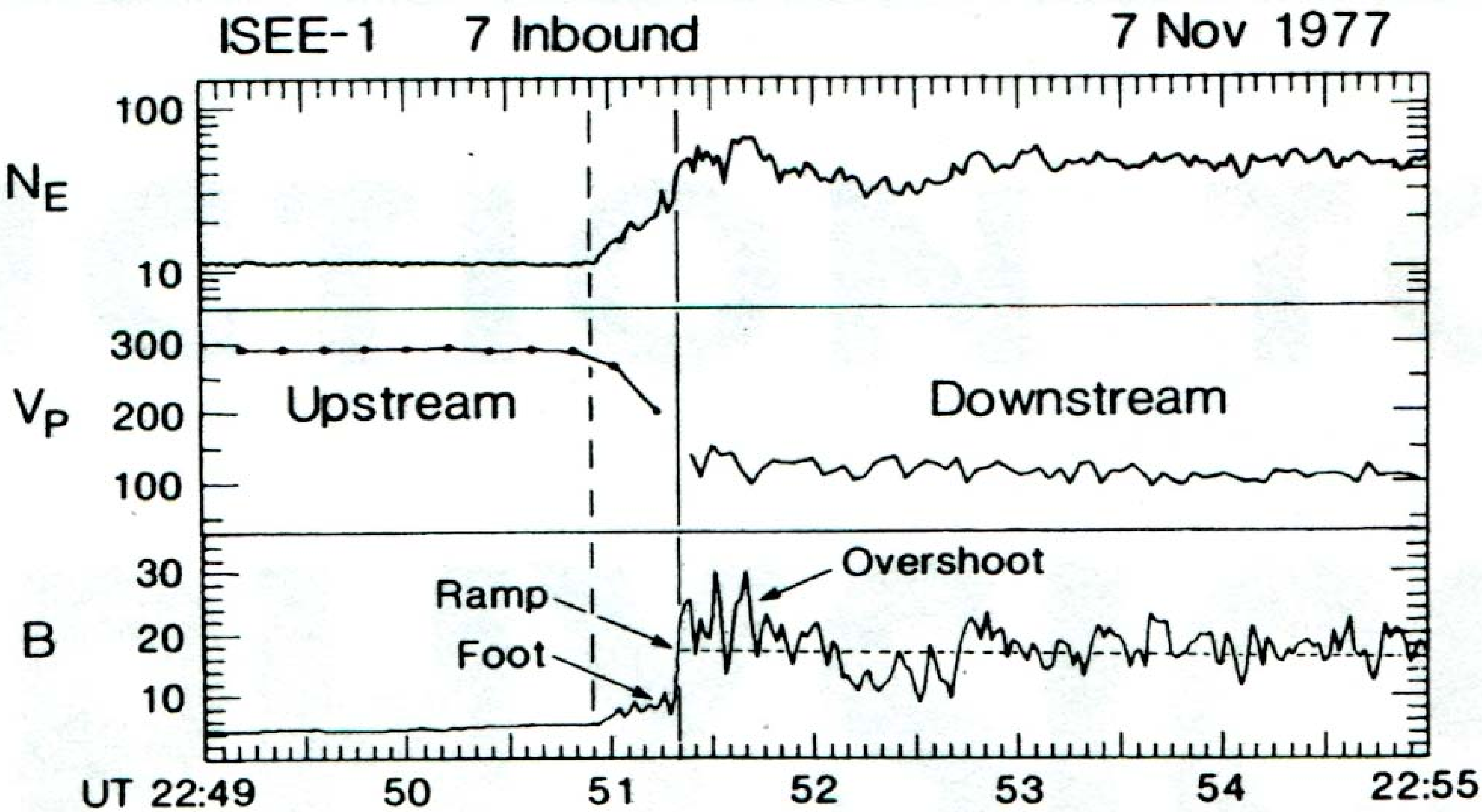
- Ring-distribution PUIs

  1. Thin slices of phase space at the shock show some PU ions specularly reflected and then gain additional energy from E_y upstream

1. 2. Reflection process complicated by change in E_y at the shock front ($E_y < 0$ at $x = 105$)



For more discussions: Basic shock structure



Adapted by D. Burgess from Sckopke et al., 1983

For more discussions: Supercritical shock ion reflection process

For supercritical shock, dissipation by electron heating (adiabatic) is insufficient to stop shock steepening, and ion reflection results.

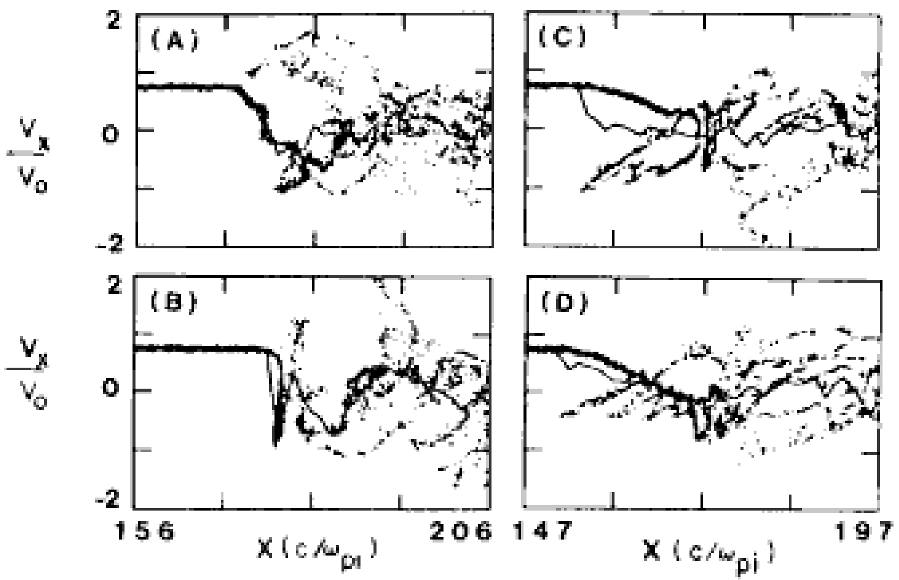


FIG. 2. V_x- x phase space at four times during a reflection cycle.

A fraction of energetic incoming ions (those with large positive v_x is reflected by a potential barrier and magnetic ramp at the shock front.

These reflected ions (v_x<0) will not continue to undergo free streaming like the transmitted ions, but will gyrate around back into the shock, form an extended foot region, slow/brake the incoming ion and widen the ramp, gain energy from the **E**X**B** electric field, and are swept downstream.

Cycle (last $1\omega_{pi}^{-1}$) complete and ramp steepen again.

- As mach number increased, the reflection process increases.
- After thermalization with the directly transmitted ions, a heated downstream population results.

References: Gosling, Goodrich, Quest, Winske, Giacalone