SM13B-4163

Low-beta MHD reconnection as a showcase of high-speed fluid dynamics

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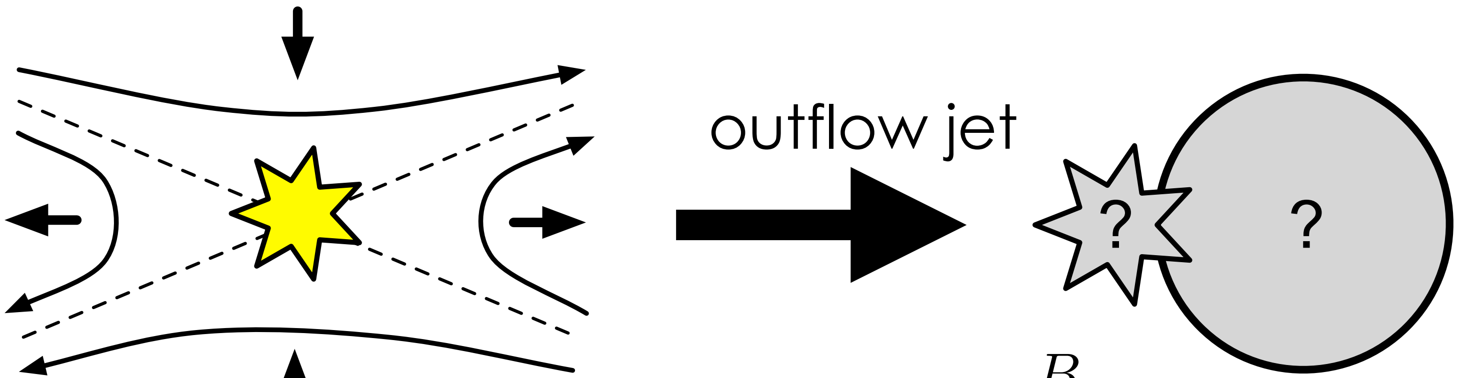
Motivation

- Magnetic reconnection expels a fast outflow jet
- How does the jet interact with an external medium in a large-scale system?

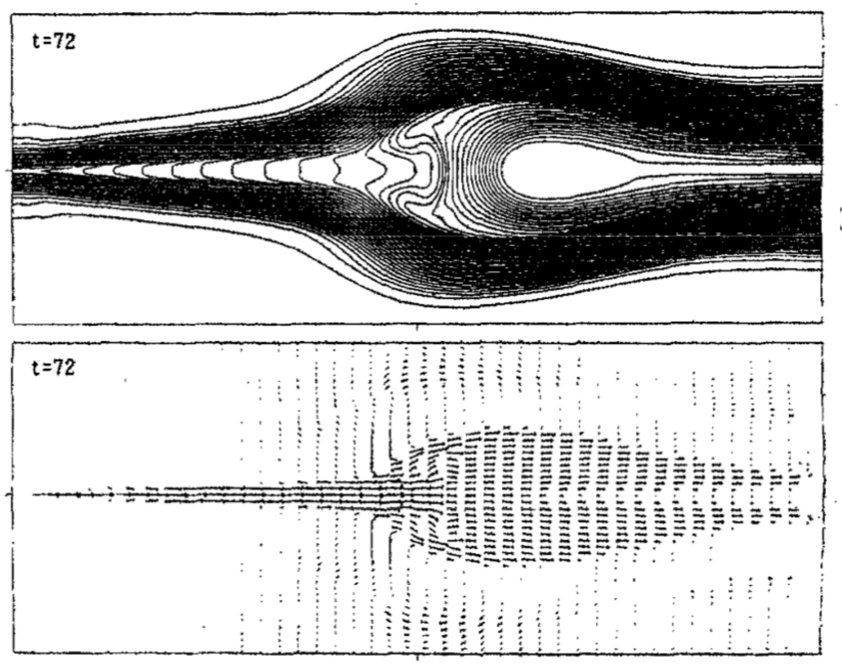


$$c_A = \frac{B}{\sqrt{4\pi m n}}$$

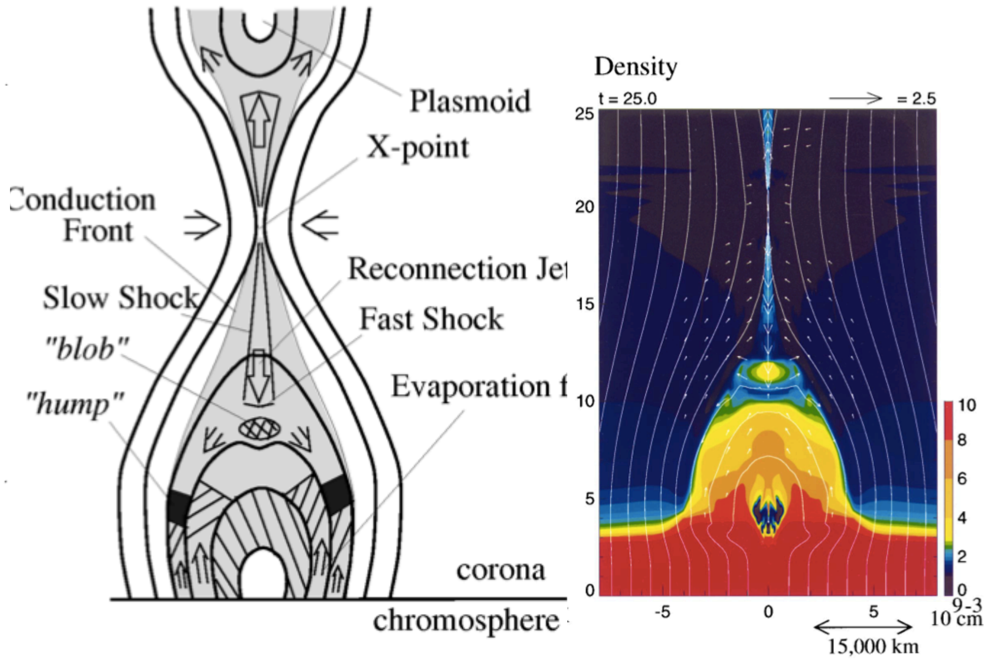
- MHD approximation is useful to explore large-scale evolution of plasma systems

Previous works

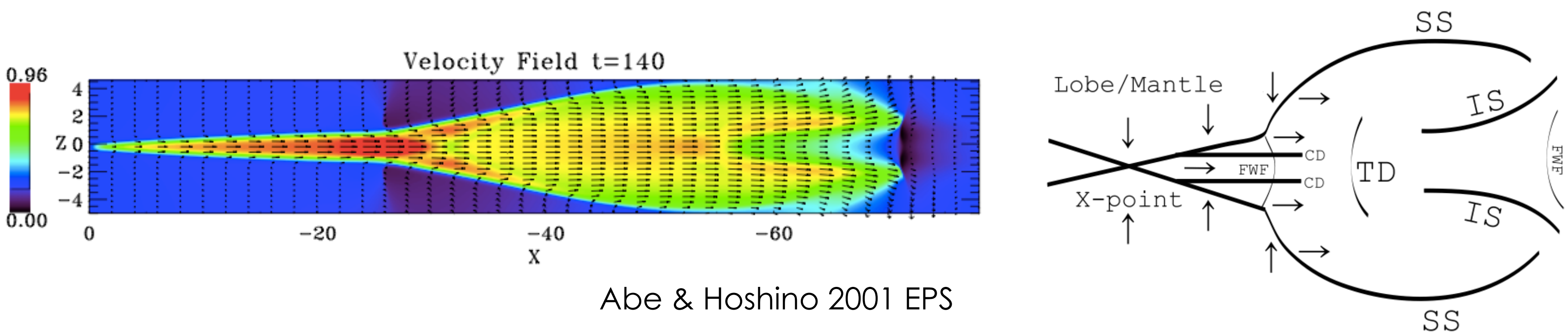
- Many works over several decades



Ugai 1995 PoP



Yokoyama & Shibata 1998 ApJ



Abe & Hoshino 2001 EPS

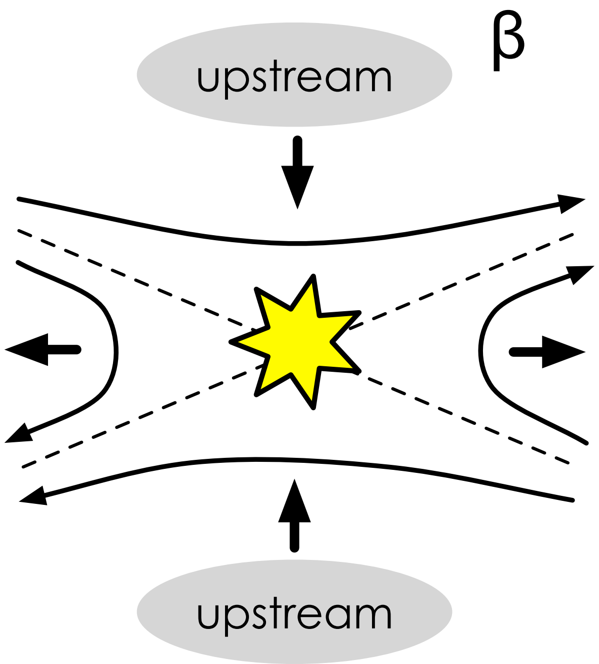
Plasma beta

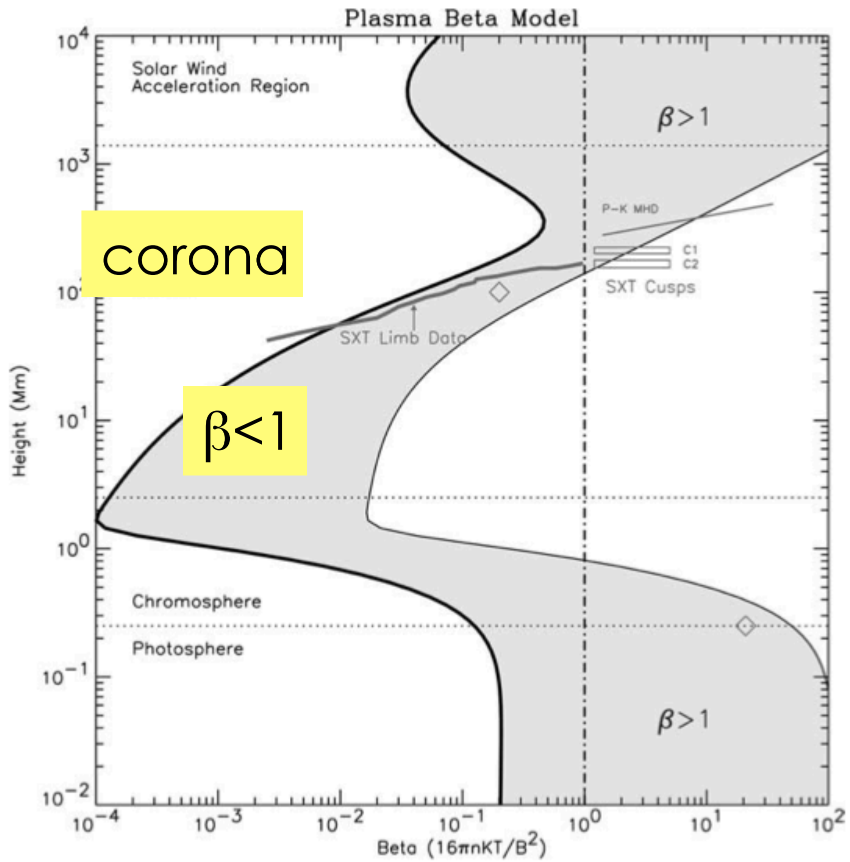
$$\beta \equiv \frac{p_{\rm gas}}{p_{\rm mag}} = \frac{8\pi p}{B^2}$$

$$\beta = \frac{2}{\Gamma}\left(\frac{c_s}{c_A}\right)^2 \rightarrow \left(\frac{c_s}{V}\right)^2$$

Sound speed

Typical velocity





Gary 2001 Sol. Phys.

- Likely parameter to control coronal reconnection
- A parameter for compressible fluid effects

MHD code

- Resistive MHD equations in a conservative form

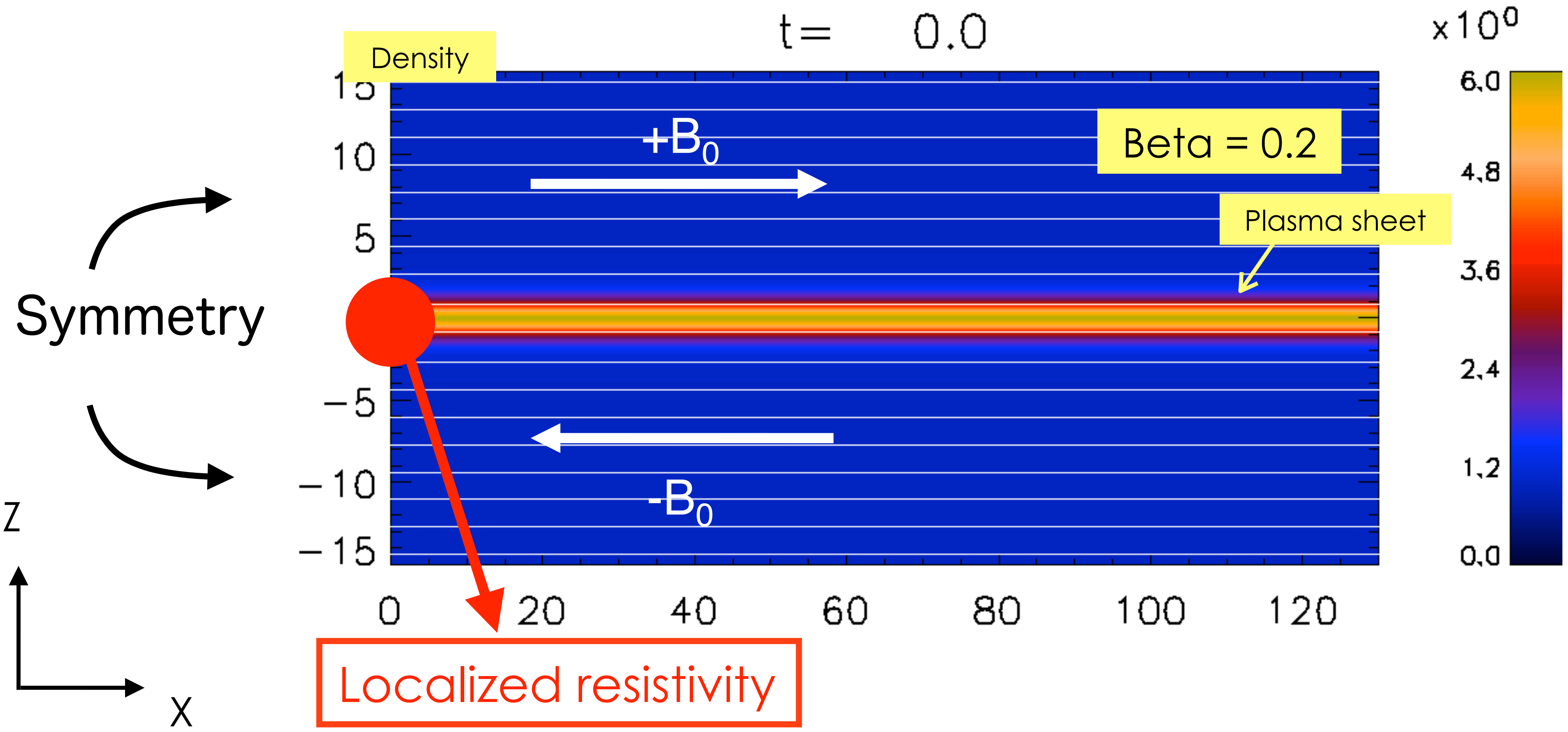
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$
$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} + p_T \boldsymbol{I} - \boldsymbol{B}\boldsymbol{B}) = 0,$$
$$\frac{\partial e}{\partial t} + \nabla \cdot \Big((e + p_T)\boldsymbol{v} - (\boldsymbol{v} \cdot \boldsymbol{B})\boldsymbol{B} + \eta \boldsymbol{j} \times \boldsymbol{B} \Big) = 0,$$
$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v}) + \nabla \times (\eta \boldsymbol{j}) = 0,$$

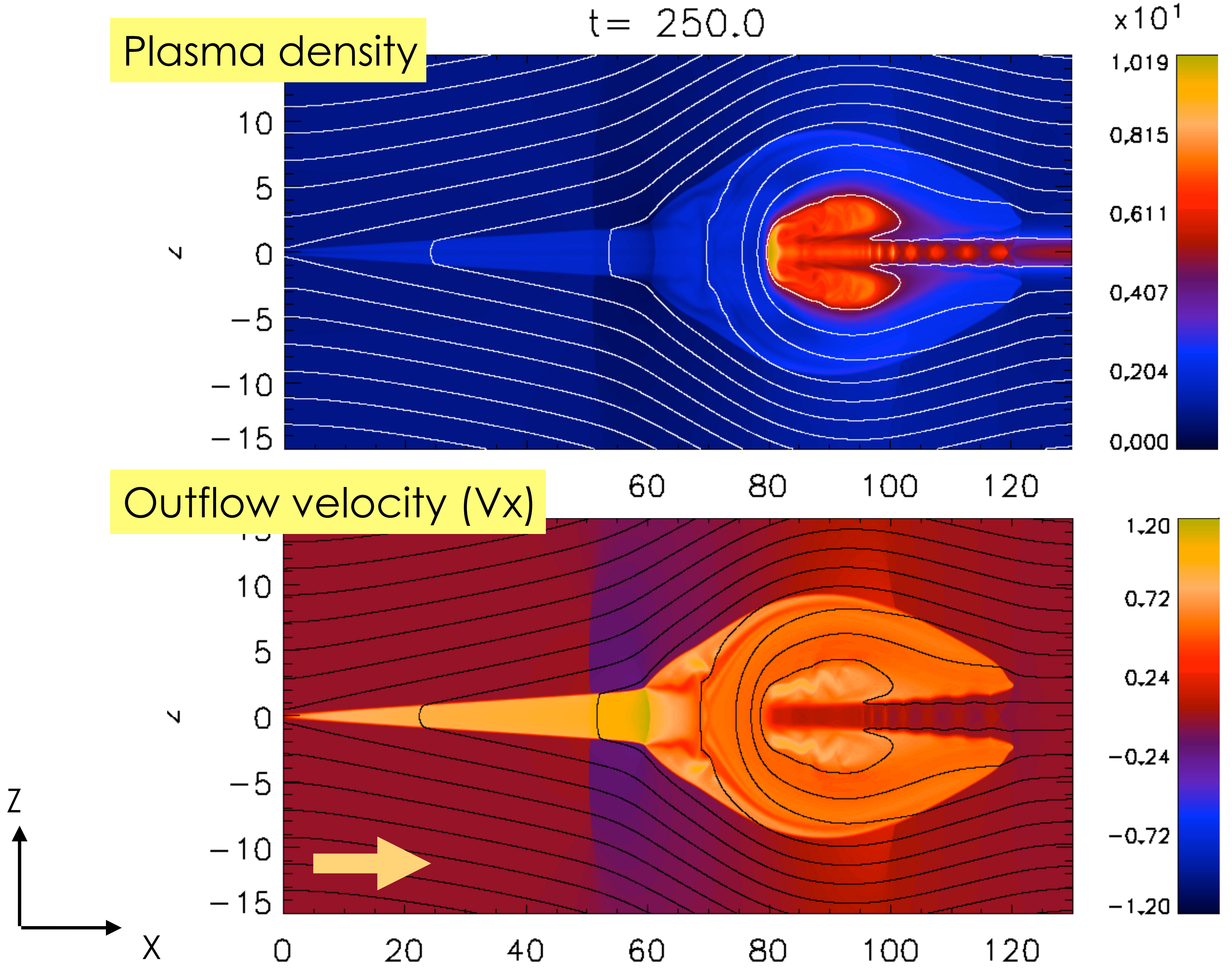
$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{j}$$

- Second order HLL/HLLD Riemann solver
    - HLL solver for 2011 paper is attached to arXiv:1101.2255
    - We'd be happy to offer our HLLD solver for collaboration

Initial configuration

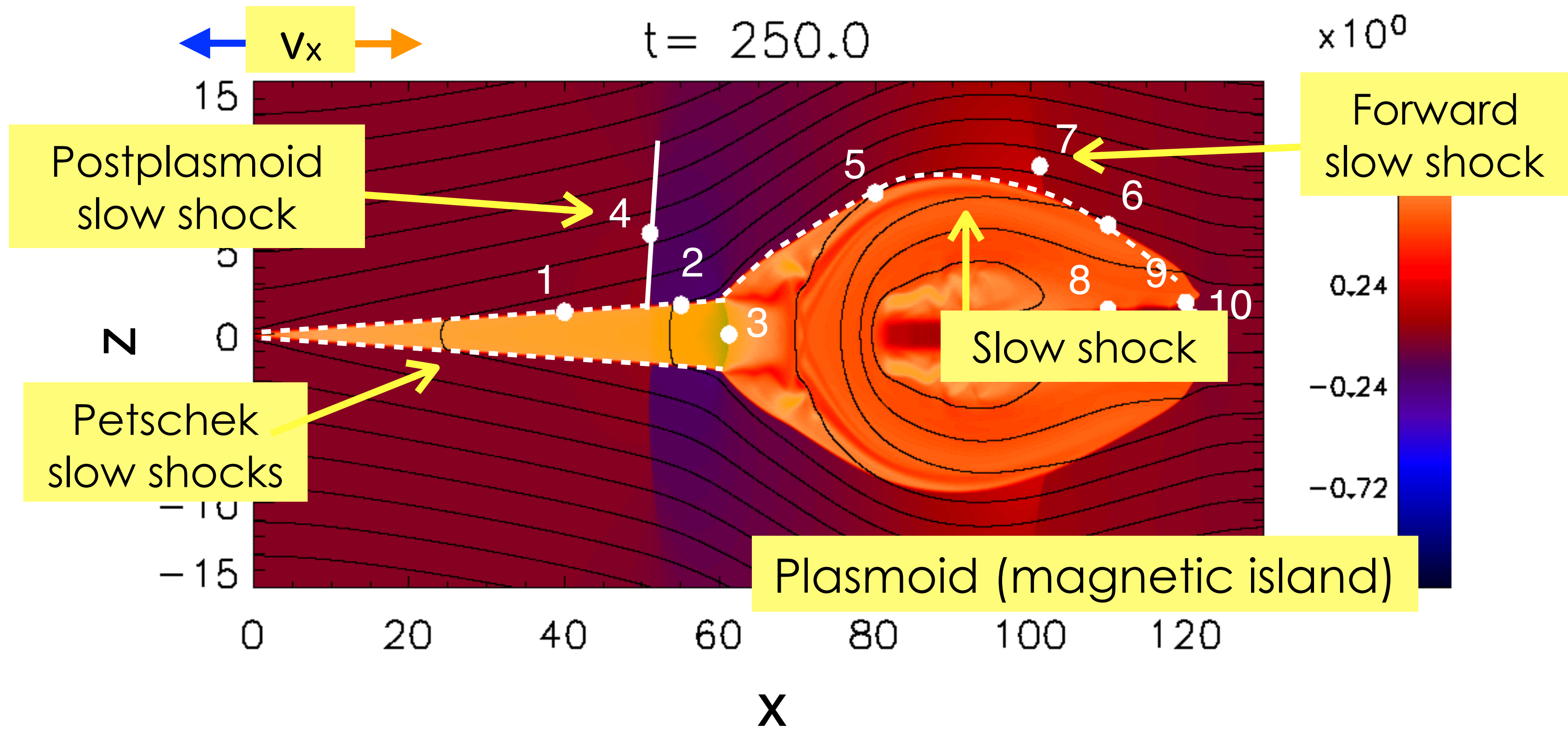
- A Harris-sheet with anti-parallel fields
- Domain: [0, 200] x [0, 150] (6000 x 4500 cells)
- Low beta in the upstream: $\beta = 2p/B^2 = 0.2$





t= 250.0
Plasma density
x10^1
1.019
0.815
0.611
0.407
0.204
0.000
Outflow velocity (Vx)
1.20
0.72
0.24
−0.24
−0.72
−1.20
z
10
5
0
−5
−10
−15
0
20
40
60
80
100
120
Z
X

Various shocks!



- Extensive analysis on shock conditions (Minimum variance analysis; MVA-B)

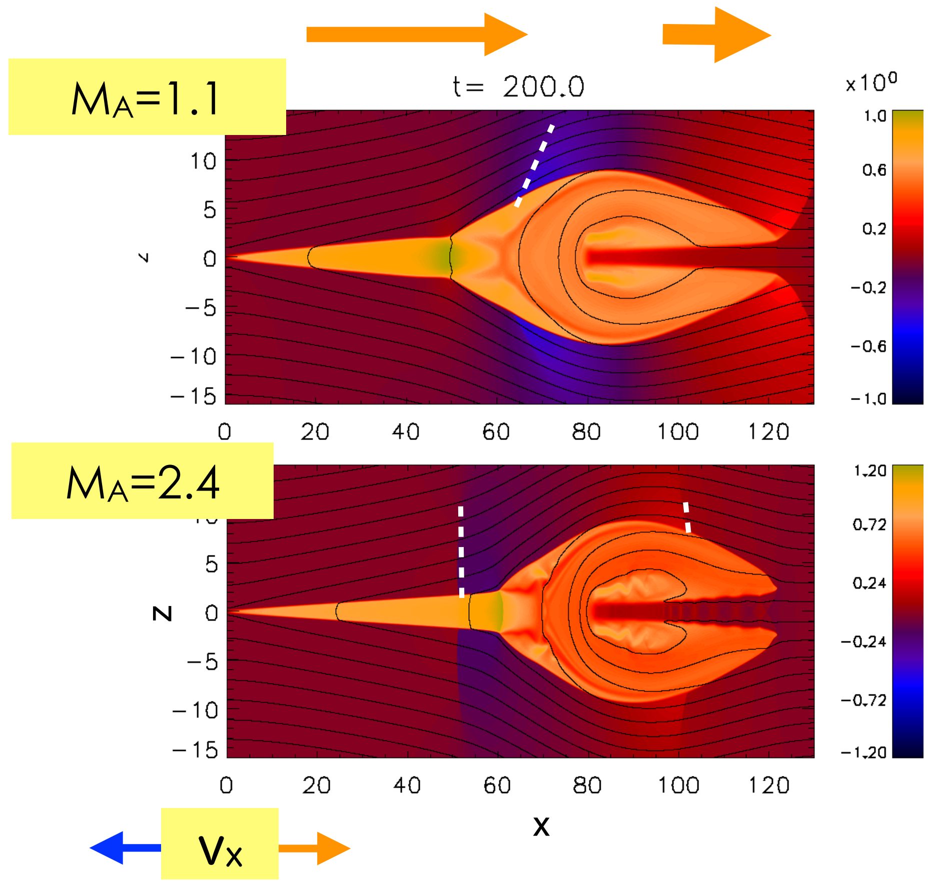
TABLE I. Rankine–Hugoniot analysis. The subscripts 1 and 2 denote the upstream and downstream quantities. The locations (x,z) in the simulation domain [see also Fig. 1(b)], the shock normal vector $\hat{n}$, the shock velocity v_{sh}, the angle between $\hat{n}$ and the upstream magnetic field B_1, the upstream plasma beta, flow Mach numbers to fast, intermediate (Alfvén), and slow-mode speeds, and the temperature ratio. The asterisk sign (*) indicates unreliable results (see Sec. III F). The letter (S) indicates a slow shock, (F) is a fast shock, and (U) is unclassified.

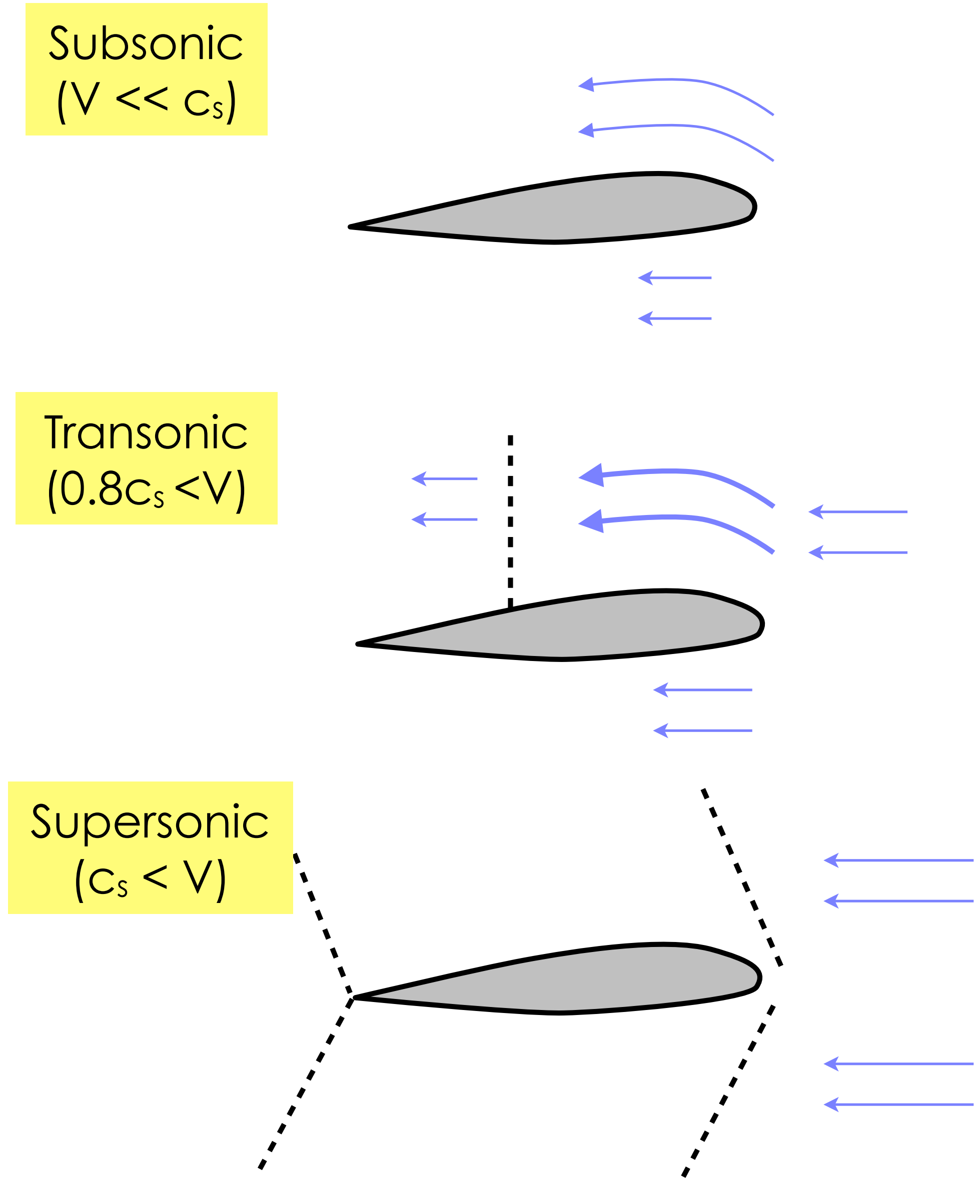
No.	Location	(n_x, n_z)	v_{sh}	$\|\theta_{BN}\|$	β_1	$\mathcal{M}_{f1}$	$\mathcal{M}_{i1}$	$\mathcal{M}_{s1}$	$\mathcal{M}_{f2}$	$\mathcal{M}_{i2}$	$\mathcal{M}_{s2}$	T_2/T_1	
1	(40.0, 1.35)	(−0.03, 1.00)	0.0	86.3	0.22	0.06	0.98	2.49	0.04	0.69	0.69	2.72	(S) Petschek shock
2	(55.0, 1.75)	(−0.04, 1.00)	−0.013	86.3	0.098	0.06	0.88	3.22	0.04	0.58	0.58	4.58	(S) Petschek shock
3	(61.2, 0)	(−1.00, 0.00)	−0.40	90	303	1.41			0.77			1.38	(F) Reverse shock
4	(51.0, 6.0)	(1.00, −0.04)	0.31	9.4	0.12	0.41	0.42	1.34	0.33	0.34	0.78	1.33	(S) Postplasmoid vertical shock
5	(80.0, 8.4)	(−0.18, 0.98)	−0.06	86.5	0.16	0.05	0.85	2.47	0.03	0.56	0.65	2.54	(S) Outer shell
6	(110.0, 6.5)	(0.24, 0.97)	0.19	84.9	0.21	0.06	0.76	1.99	0.05	0.53	0.64	2.06	(S) Outer shell
7	(101.2, 10.0)	(0.94, 0.33)	0.54	25.2	0.23	0.43	0.49	1.15	0.39	0.44	0.87	1.15	(S) Forward vertical shock
8	(110.0, 1.5)	(−0.06, −1.00)	0.10	87.8	1.1	0.12	4.5*	6.5*	0.12	3.9*	4.0*	1.55	(U) Intermediate shock?
9	(120.0, 1.9)	(0.13, −0.99)	0.13	87.1	0.49	0.09	2.0*	3.8*	0.08	1.7*	1.9*	1.86	(U) Slow shock?
10	(120.9, 1.0)	(0.64, −0.77)	0.50	46.8	2.63	1.22	3.00	3.40	0.88	2.66	3.06	1.18	(F) Oblique shock

Normal shock (Recompression shock)

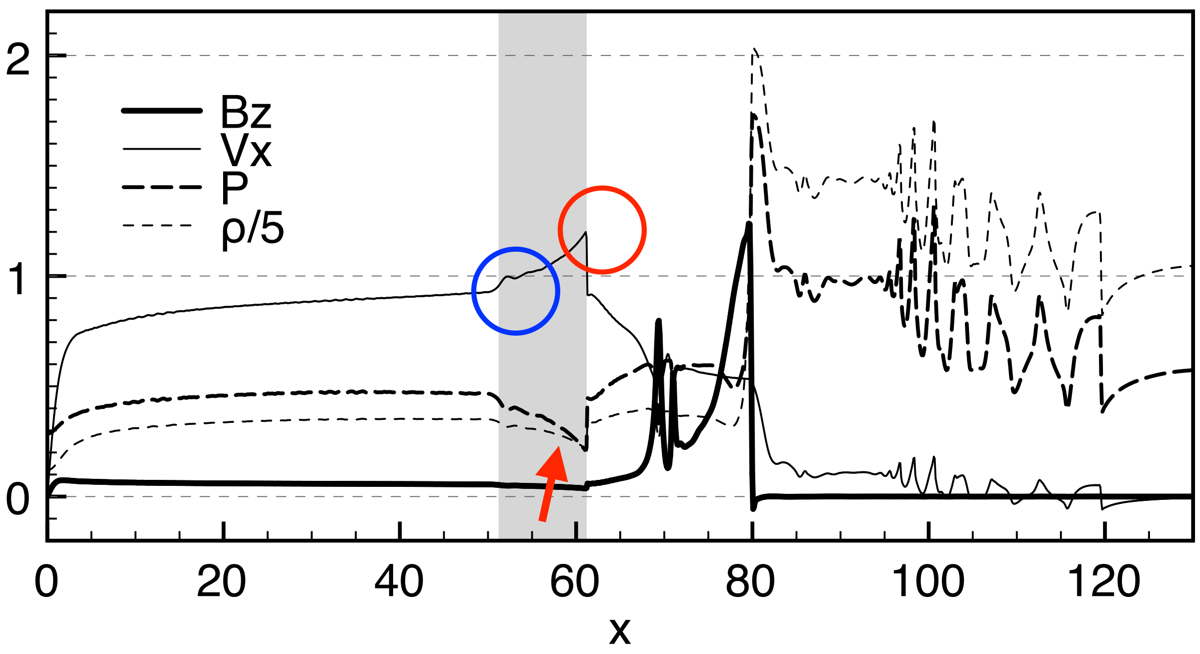
- MHD slow shock
- Analogy to airfoil

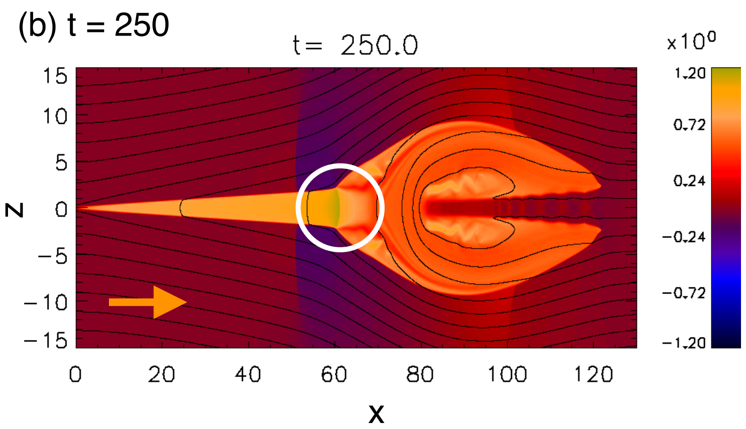
$v_{jet} \approx c_A$ jet leading edge

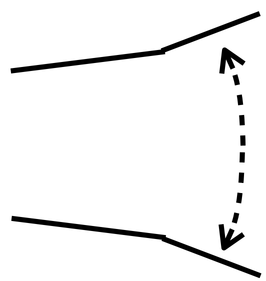




Super-Alfvénic flow



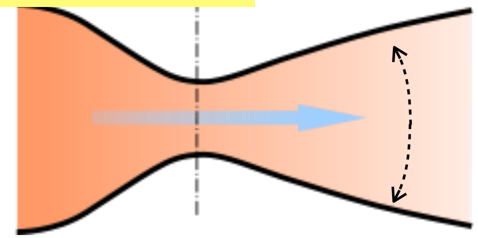




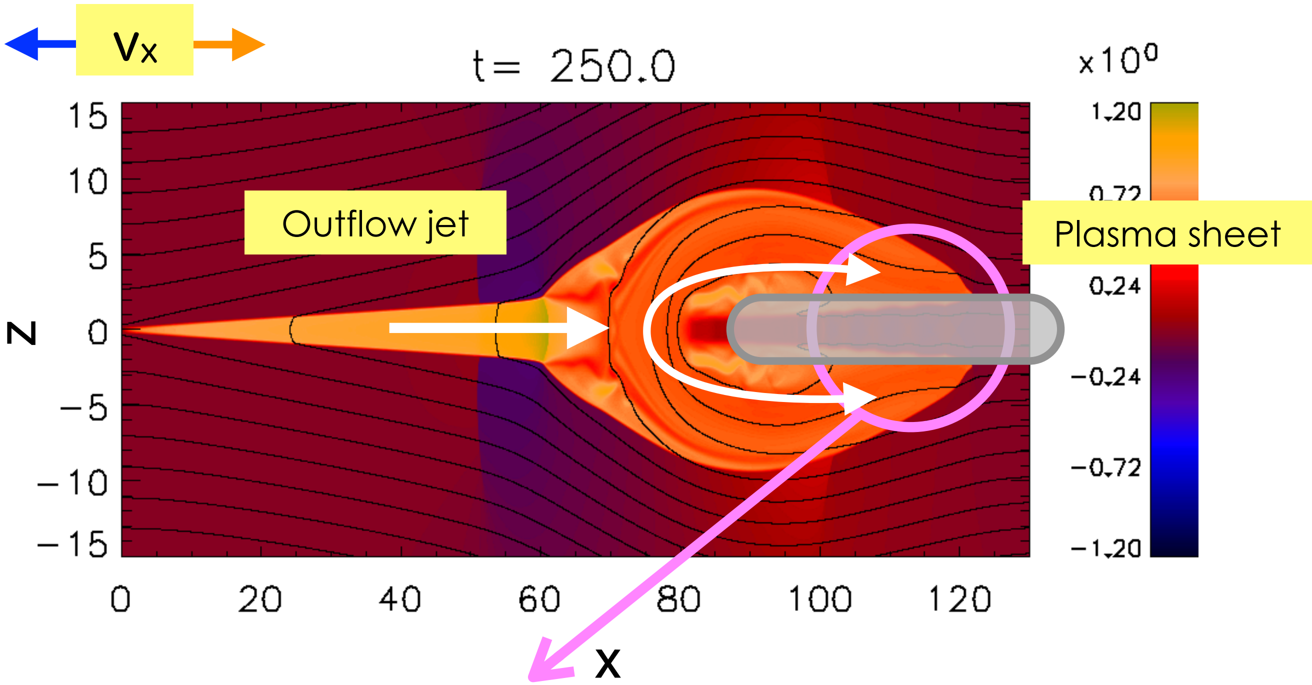
- Two reasons
  - RH condition for the rarefied upstream region
  - Adiabatic acceleration in the deconfinement region (Shimizu & Ugai 2000, 2003)
  - Supersonic regime

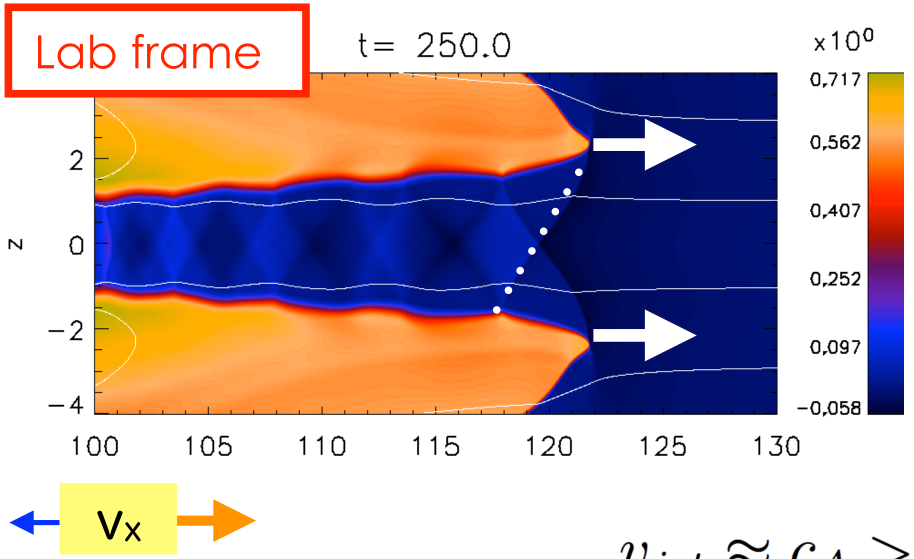
$$v_{jet} \approx c_A > c_s$$

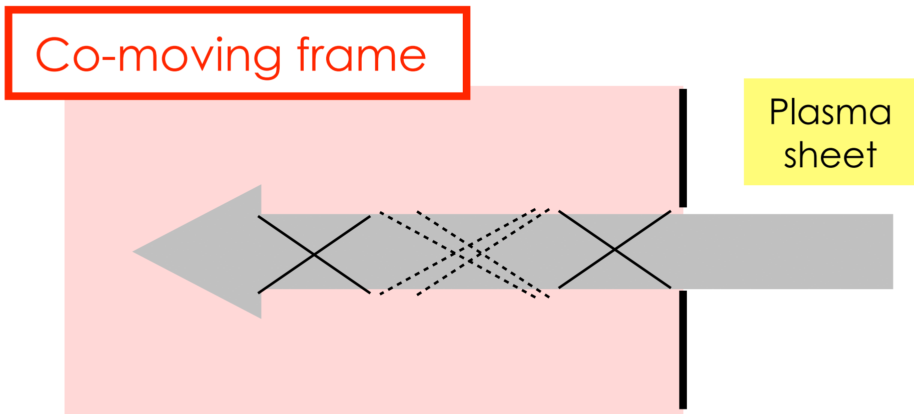
Laval nozzle



Shock diamond



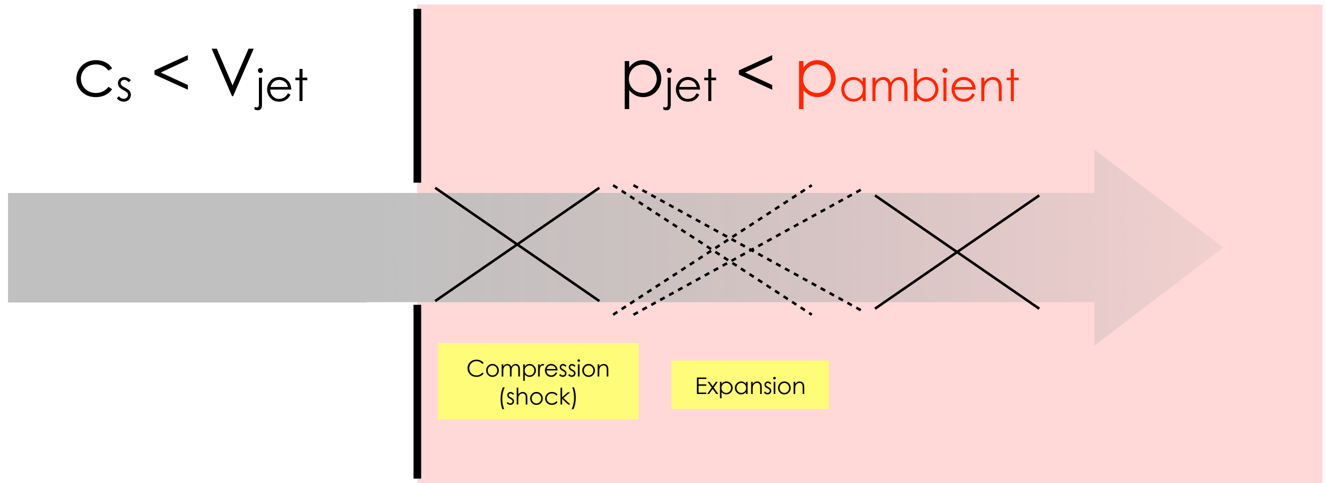




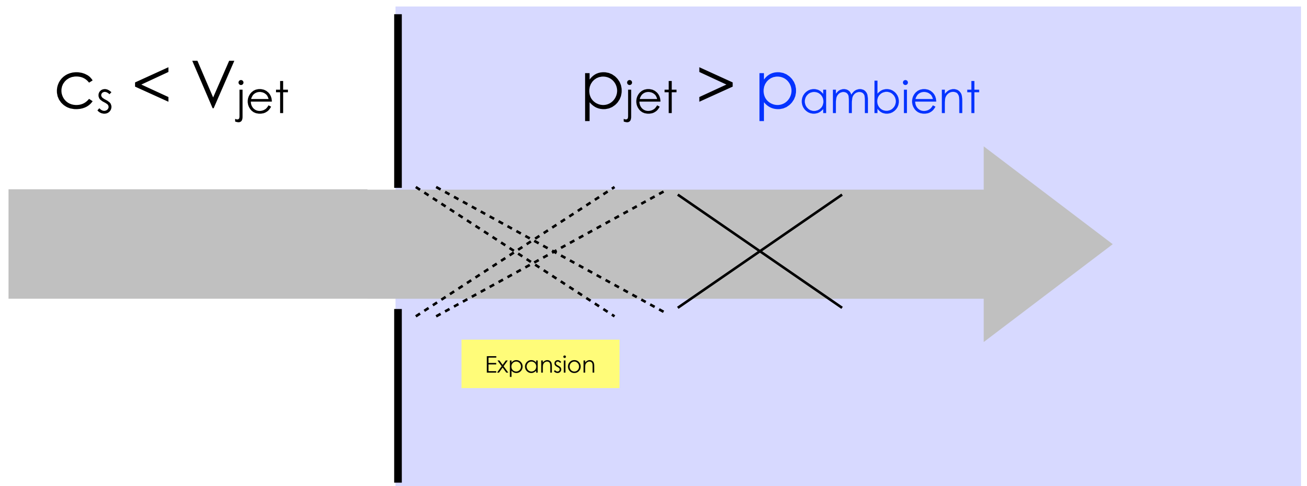
$$v_{jet} \approx c_A > c_s \iff \beta < 1$$

Shock diamond

- (a) Over-expanded flow (過膨張)



- (b) Under-expanded flow (不足膨張)



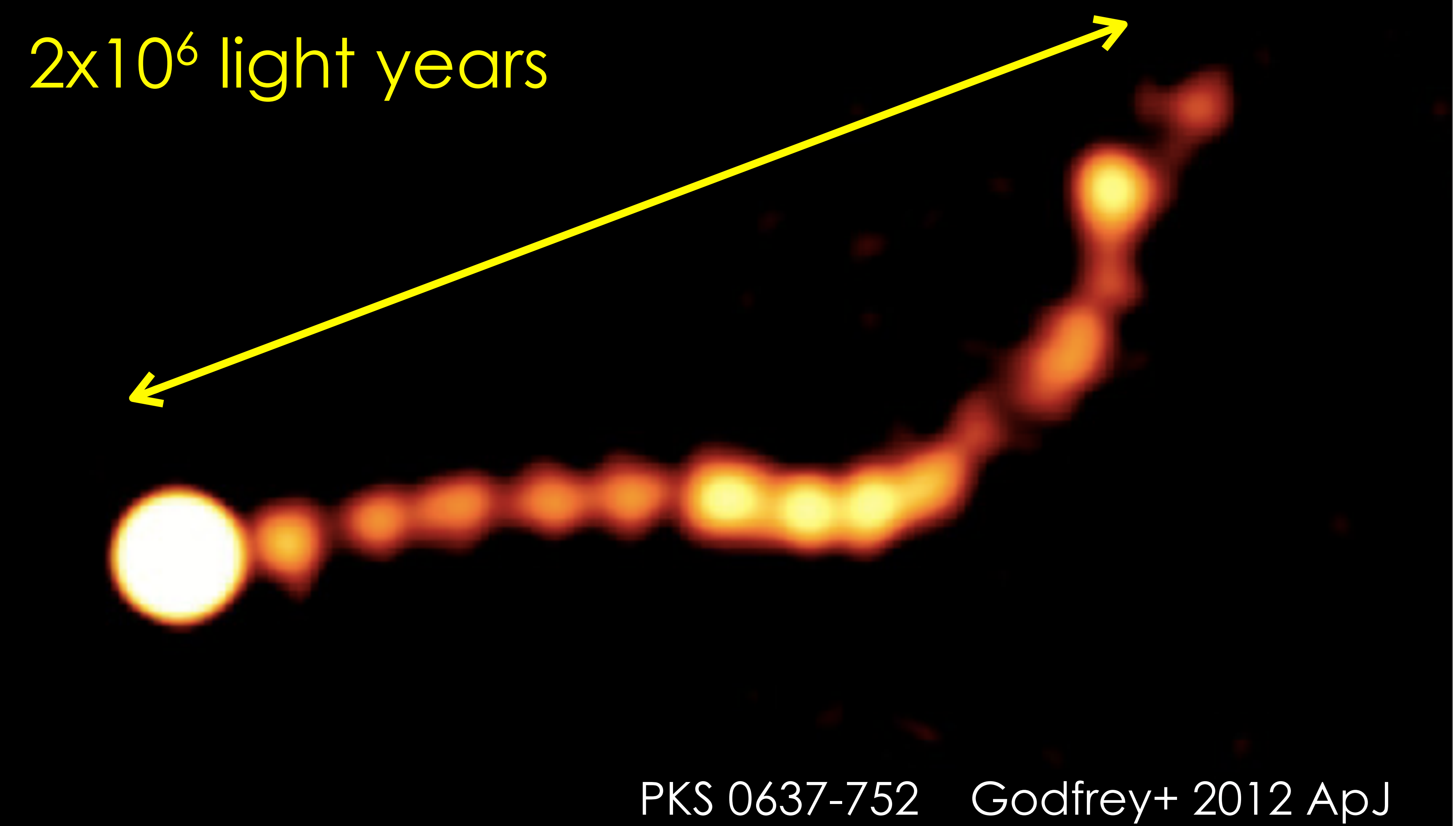
Shock diamonds in aeronautics

BBC online http://www.bbc.com/future/story/20130701-flying-the-worlds-fastest-plane

Shock diamonds in video game

Microsoft Flight Simulator X https://www.youtube.com/watch?v=S8QGaiE4yWc

Shock diamonds in astrophysics



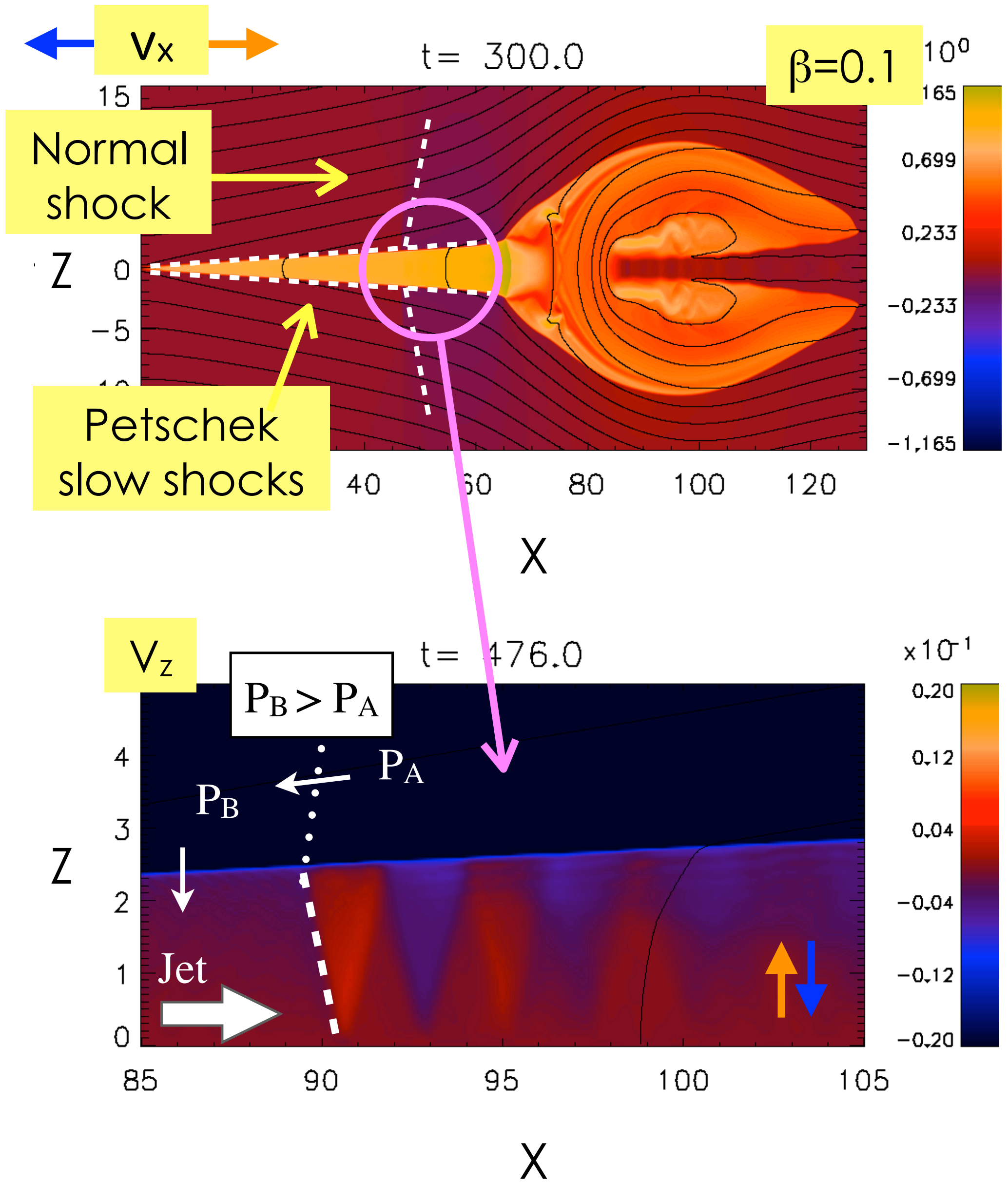
Hidden shock-diamonds

- Crossing point between Petschek shocks and recompression shocks

- Sufficient condition:

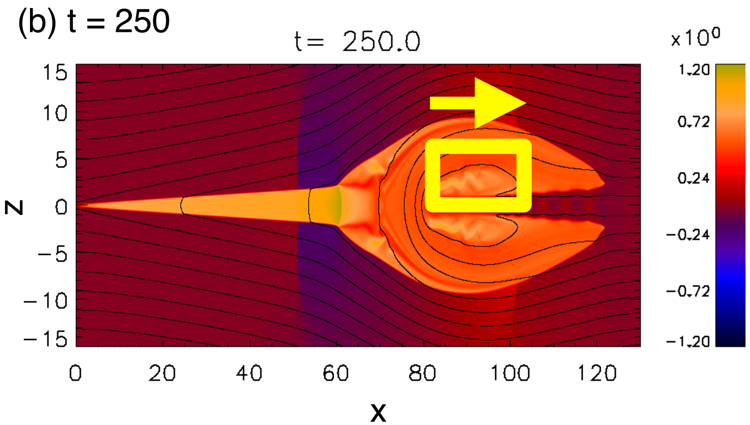
$$c_{s,\mathrm{outflow}} < [c_{A,in} - c_{\mathrm{shock}}] < [c_{A,in} - c_{s,in}]$$

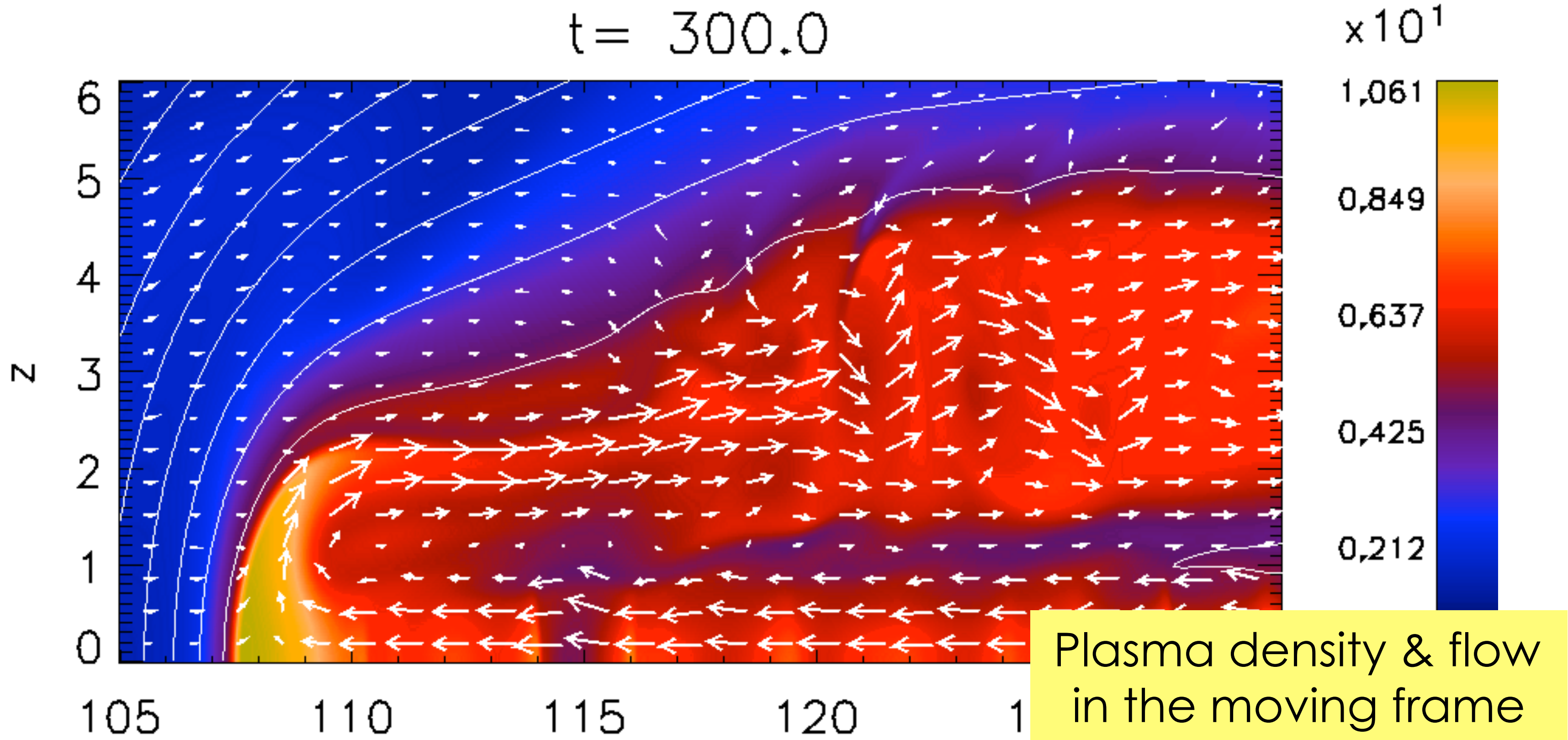
$$\Rightarrow \beta < 0.135$$



Kelvin-Helmholtz instability inside the plasmoid

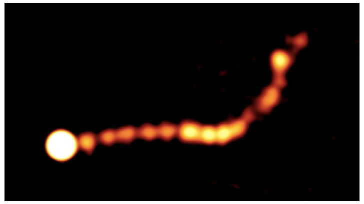
- Plasmas are hit and reflected by the reconnection jet front
- KH instability due to the reflected flow

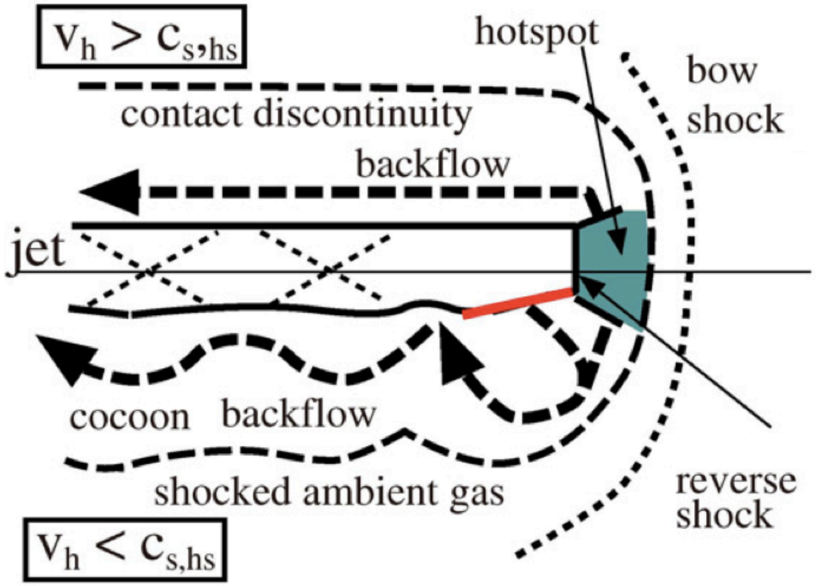




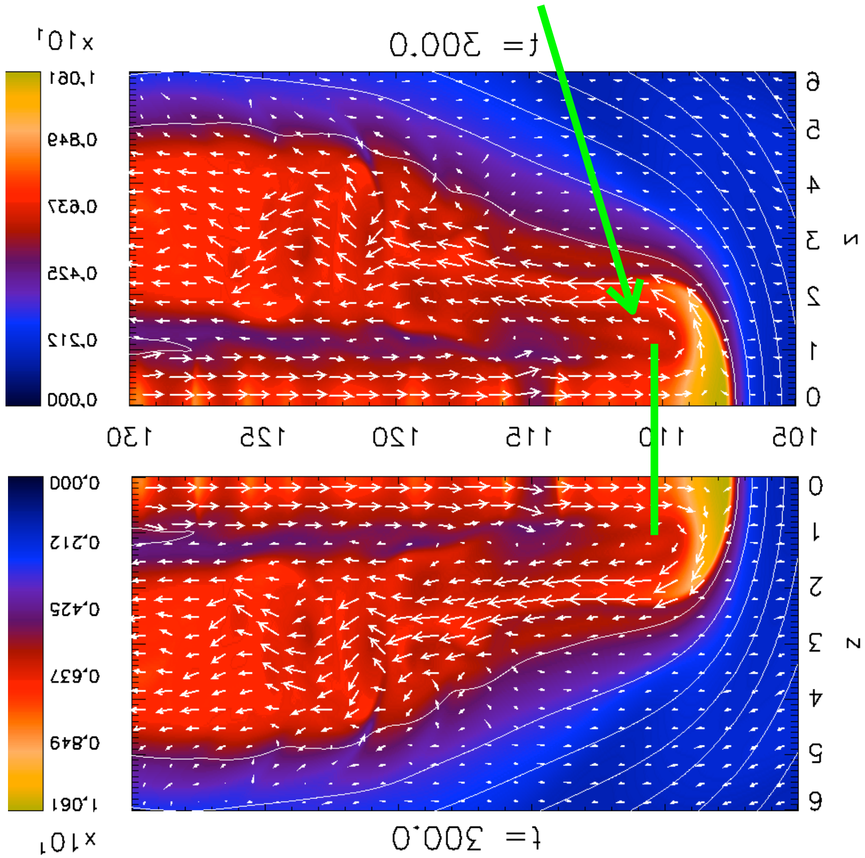
Comparison with astrophysical jet model

- Supersonic jets (Norman+ 1982)
- Very similar except reverse shock





No reverse shock

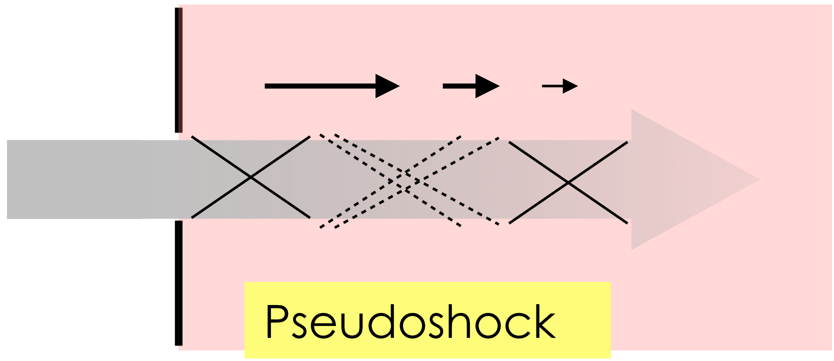


Mizuta+ 2010 ApJ

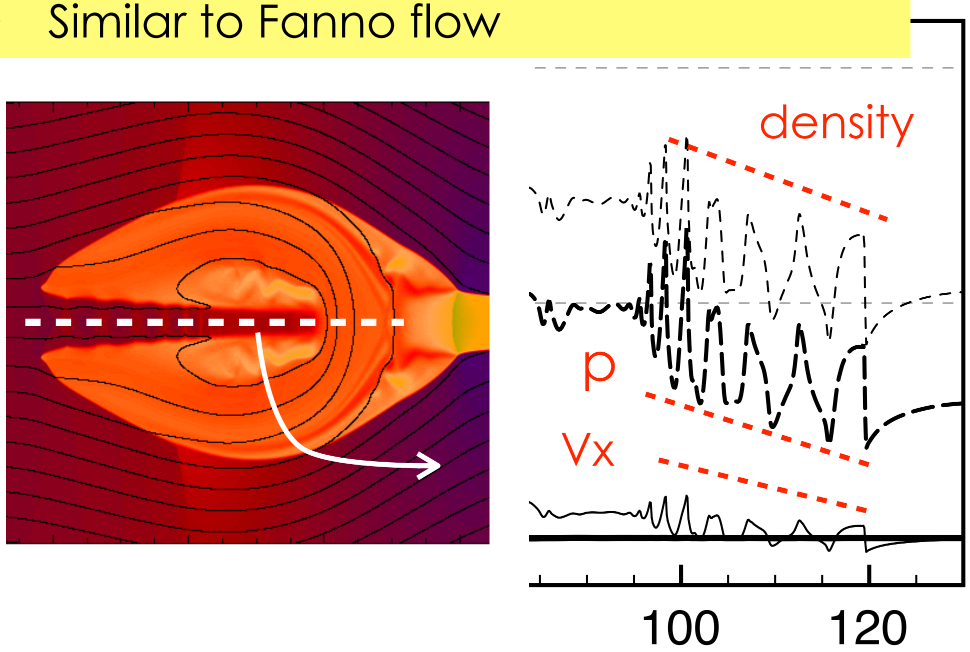
Pseudo-shock (oblique diffuser)

- (a) Over-expanded flow

$p_{jet} < p_{ambient}$

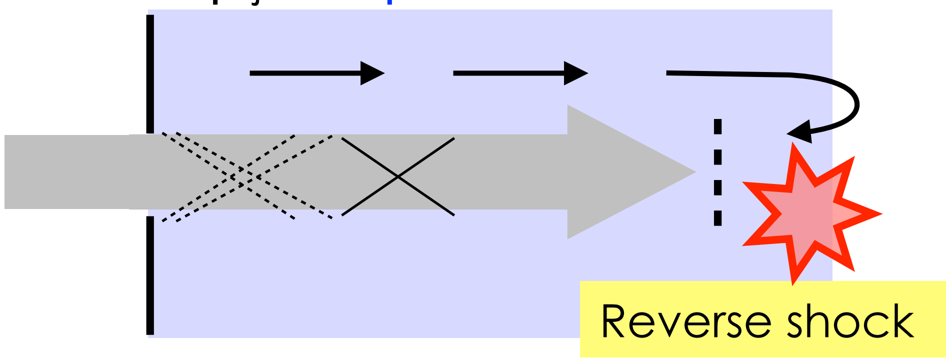


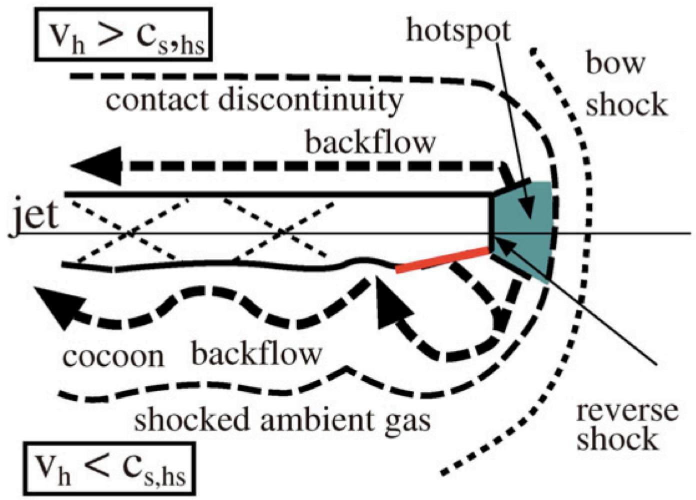
- Shock-train decelerates the flow
- Similar to Fanno flow



- (b) Under-expanded flow

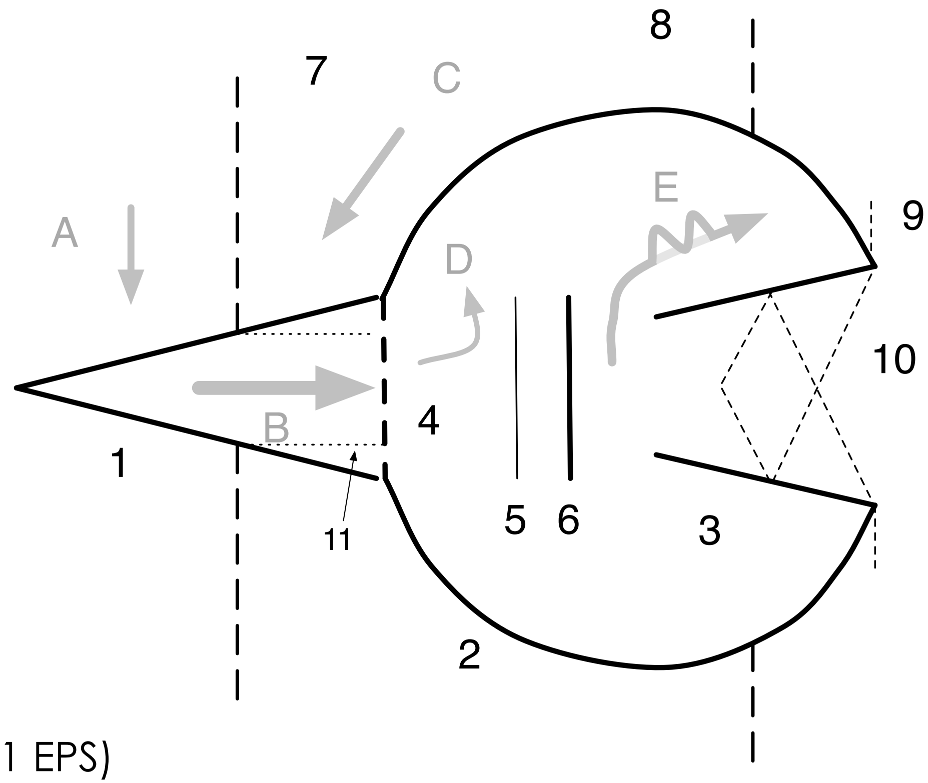
$p_{jet} > p_{ambient}$





A complete catalog of plasmoid structure (2011)

A. reconnection inflow
B. outflow jet
C. post-plasmoid backward flow
D. internal flow
E. flapping jet (KH instability)

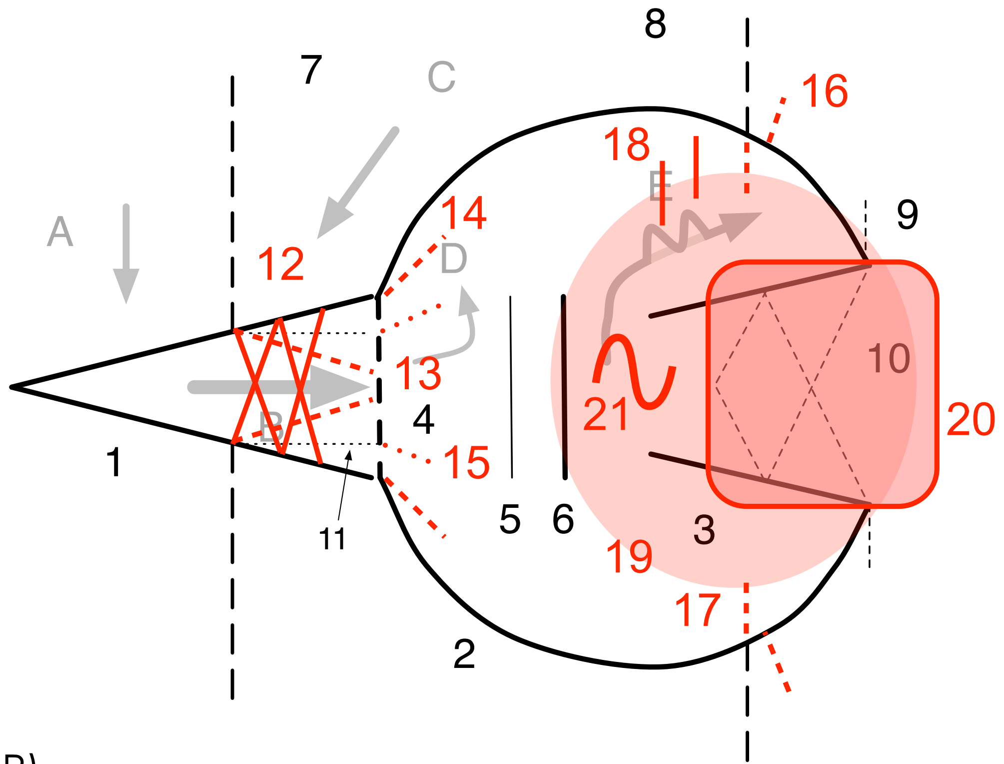


1. Petschek slow shock (Petschek 1964)
2. outer shell = slow shock (Ugai 1995 PoP)
3. intermediate shock (Abe & Hoshino 2001 EPS)
4. fast shock (Forbes & Priest 1983 SoP)
5. loop-top front (Ugai 1987 GRL)
6. tangential discontinuity
7. post-plasmoid vertical slow shock (Zenitani+ 2010 ApJ)
8. outer vertical slow shock (Zenitani & Miyoshi 2011 PoP)
9. fast-mode wave front (Saito et al. 1995 JGR)
10. shock-reflection (diamond chain) (Zenitani+ 2010 ApJ)
11. contact discontinuity (Zenitani & Miyoshi 2011 PoP)

Zenitani & Miyoshi 2011 PoP

A complete catalog of plasmoid structure (2015)

A. reconnection inflow
B. outflow jet
C. post-plasmoid backward flow
D. internal flow
E. flapping jet (KH instability)



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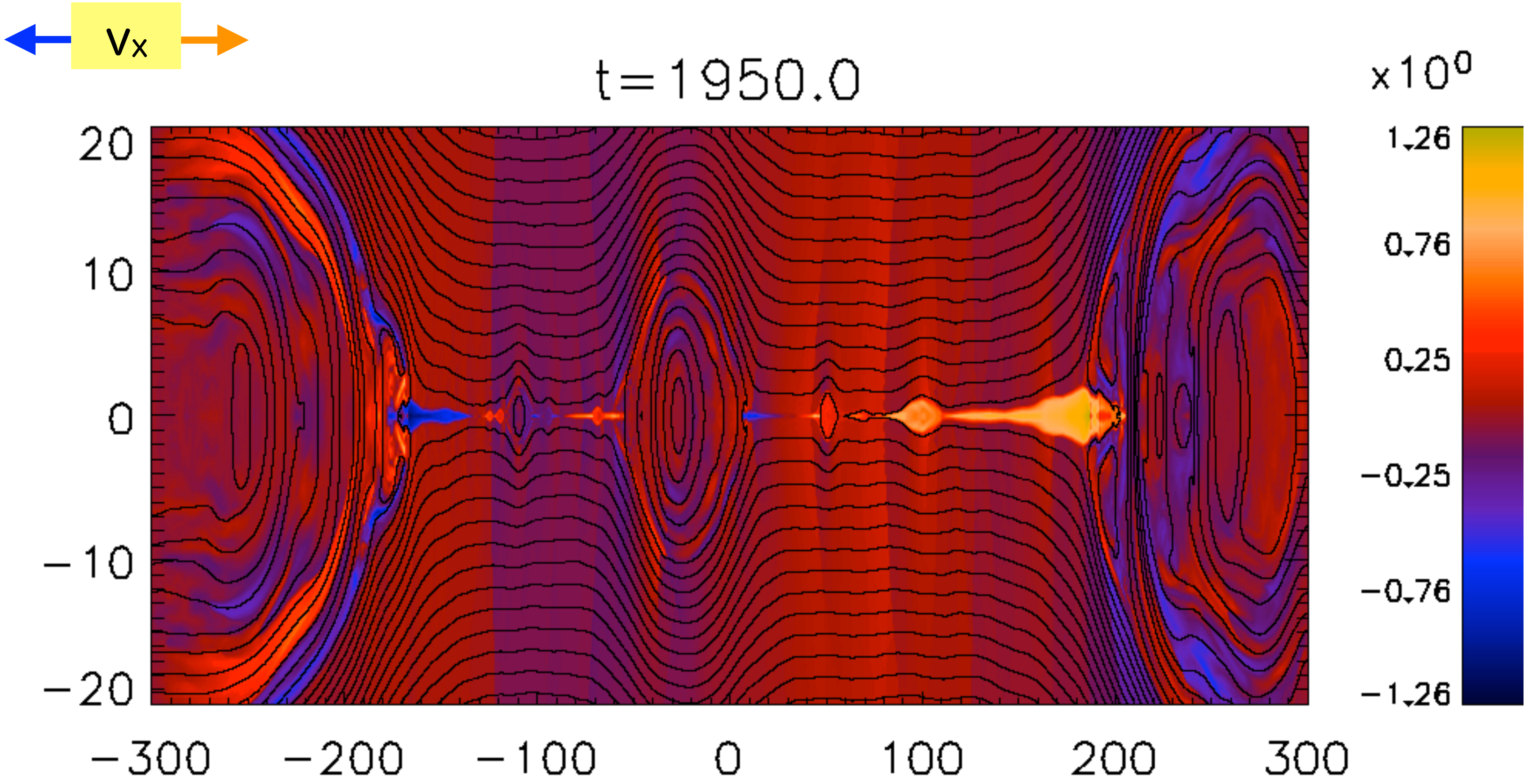
8. outer vertical slow shock (Zenitani & Miyoshi 2011 PoP)
9. fast-mode wave front (Saito et al. 1995 JGR)
10. overexpanded shock-diamond (Zenitani+ 2010 ApJ)
11. contact discontinuity (Zenitani & Miyoshi 2011 PoP)
12. underexpanded shock-diamond
13. Slow-mode expansion fan?
14. contact discontinuity
15. contact discontinuity
16. preshock
17. contact discontinuity
18. vortex-driven shock
19. inner shell
20. pseudo shock
21. odd-parity KH instability

Plasmoid-dominated reconnection



- Run with very high Lundquist number : S = 10**5.5
- Increasingly turbulent, due to a spectrum of normal slow shocks
- Wave-drag to the plasmoid motion
- ⇒ Global dynamics can be affected

Summary

- We have investigated the fine structure of the reconnection-plasmoid system
- New structures are better understood as high-speed (compressible) fluid effects in low-β regimes $v_{jet} \approx c_A > c_s \iff \beta < 1$
  - Adiabatic acceleration
  - Recompression shock
  - Shock diamonds
- Relevance to the jet physics
- The catalog project is going on
- There are still basic issues in MHD reconnection physics

References

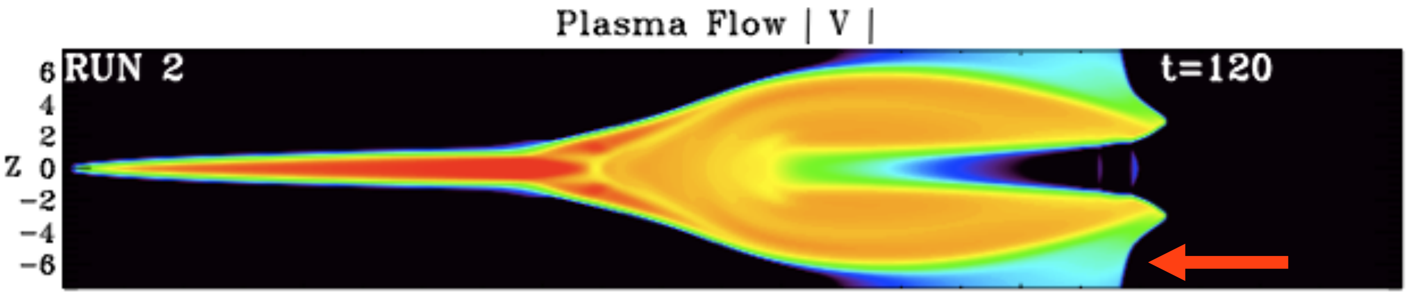
- Zenitani & Miyoshi, *Phys. Plasmas* **18**, 022105 (2011)
  Code available at arXiv:1101.2255
- Zenitani, submitted (2015)

Paper request

Your name	e-mail

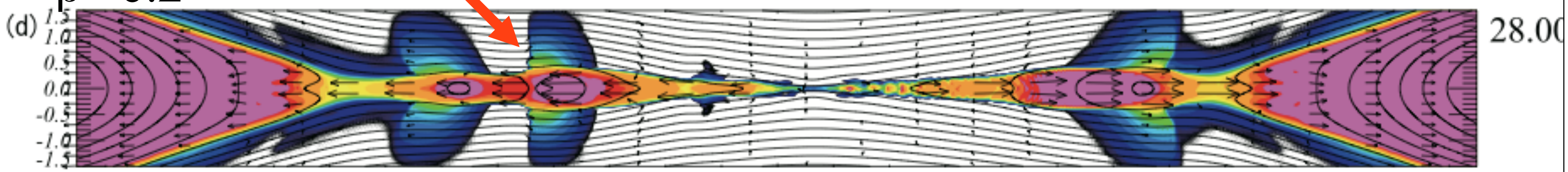
Unknown "shocks" explained

β= 0.25

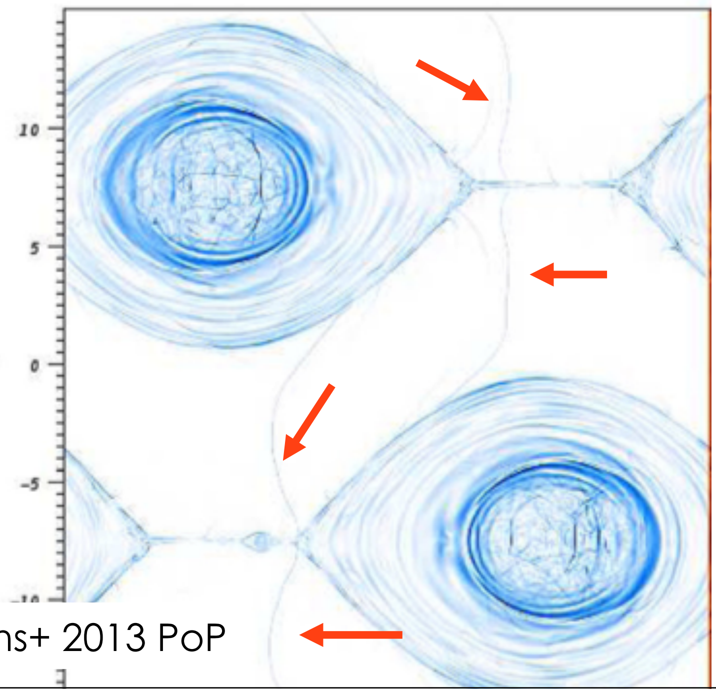


Abe & Hoshino 2001 EPS

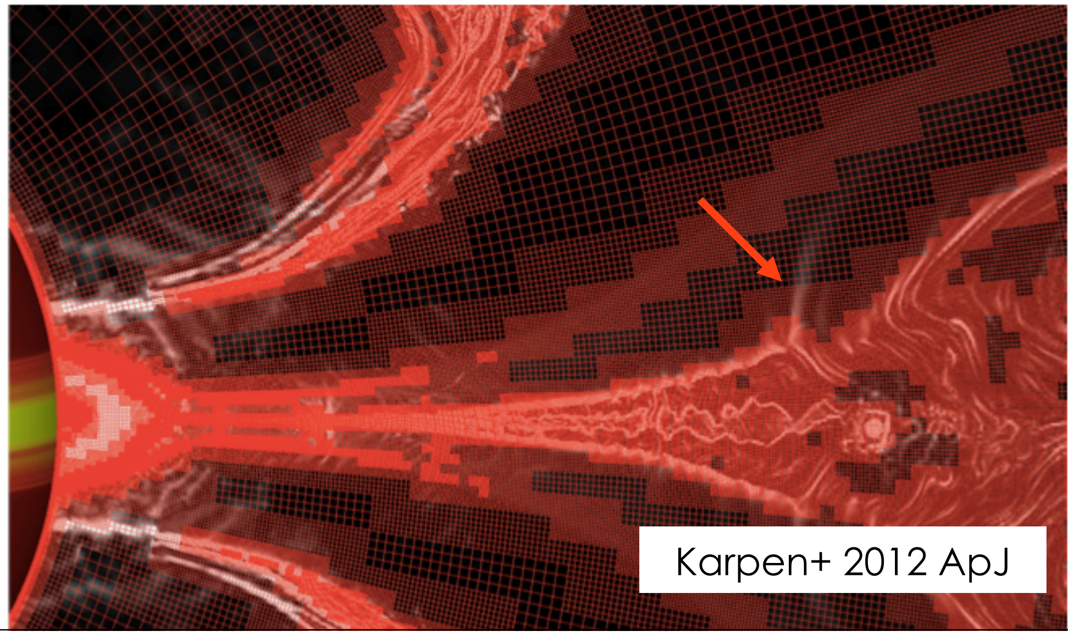
β= 0.2



Tanuma & Shibata 2007 PASJ



Keppens+ 2013 PoP



Karpen+ 2012 ApJ