High-speed fluid dynamics in magnetic reconnection in a low-beta plasma

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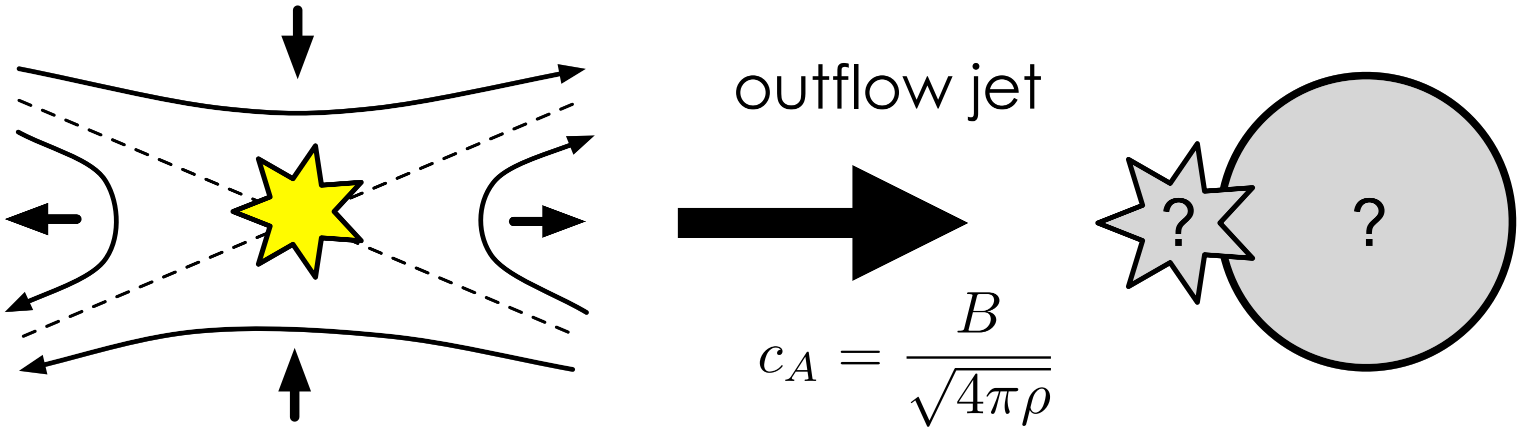
Motivation

- Magnetic reconnection expels a fast outflow jet at the upstream Alfvén speed
- How does the jet interact with an external medium?



$$c_A = \frac{B}{\sqrt{4\pi\rho}}$$

- Key parameter

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

Typical velocity

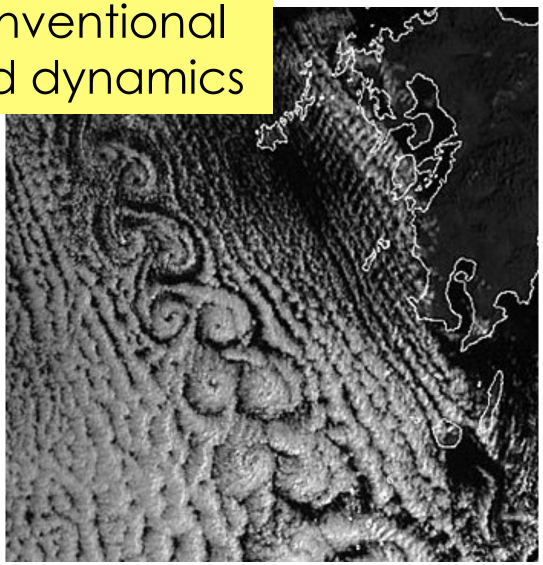
$$\frac{1}{\beta} \sim \left(\frac{c_A}{c_s}\right)^2 \sim \left(\frac{V}{c_s}\right)^2 \sim \mathcal{M}^2$$

Sound speed

Typical Mach number

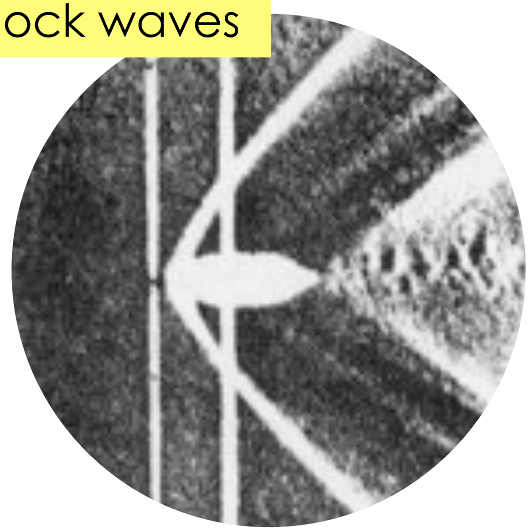
Branches of fluid dynamics

Conventional fluid dynamics



tenki.jp 2015

Shock waves



Mach 1887

1

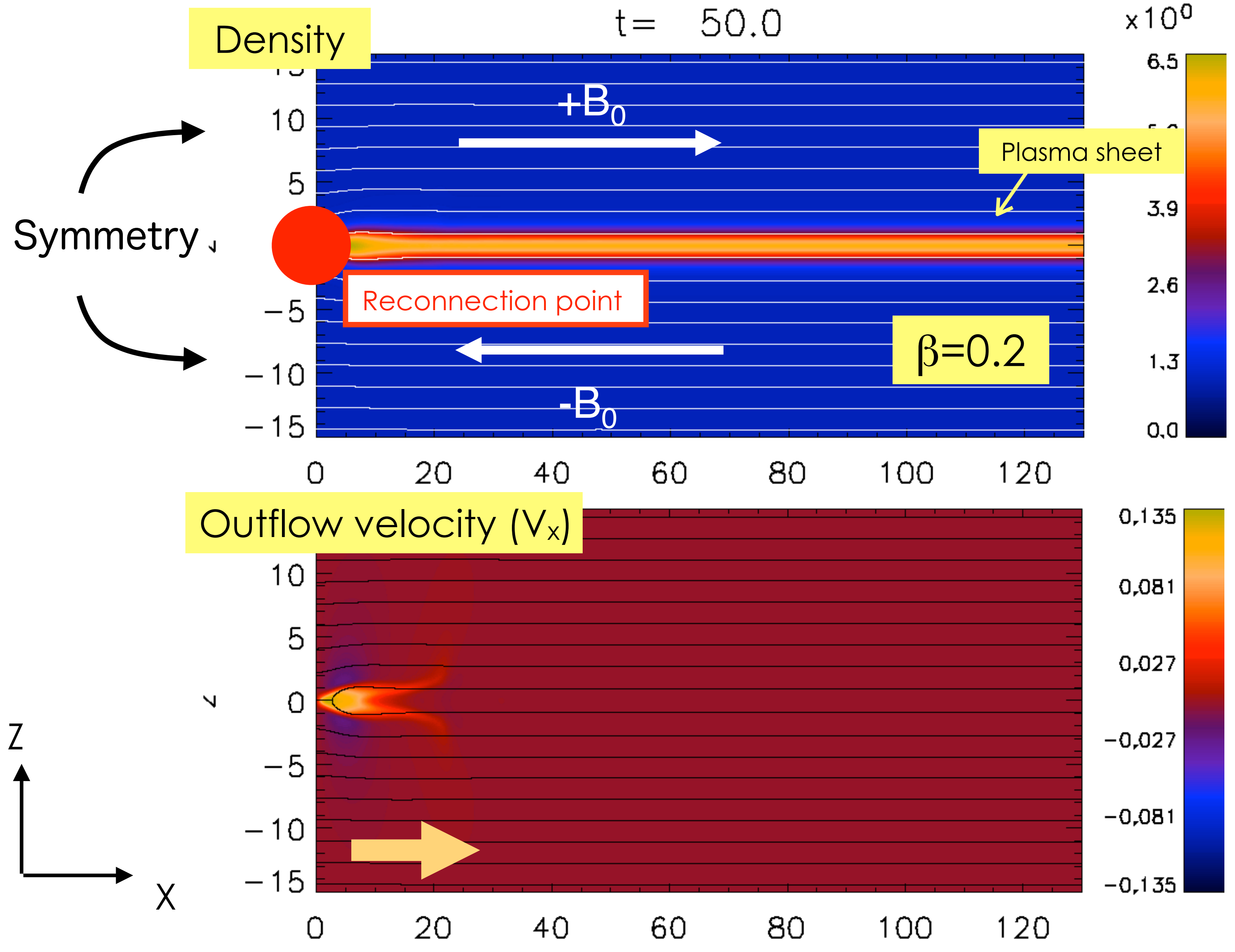
$$\mathcal{M} = \frac{V}{c_s}$$

Subsonic — Transonic — Supersonic

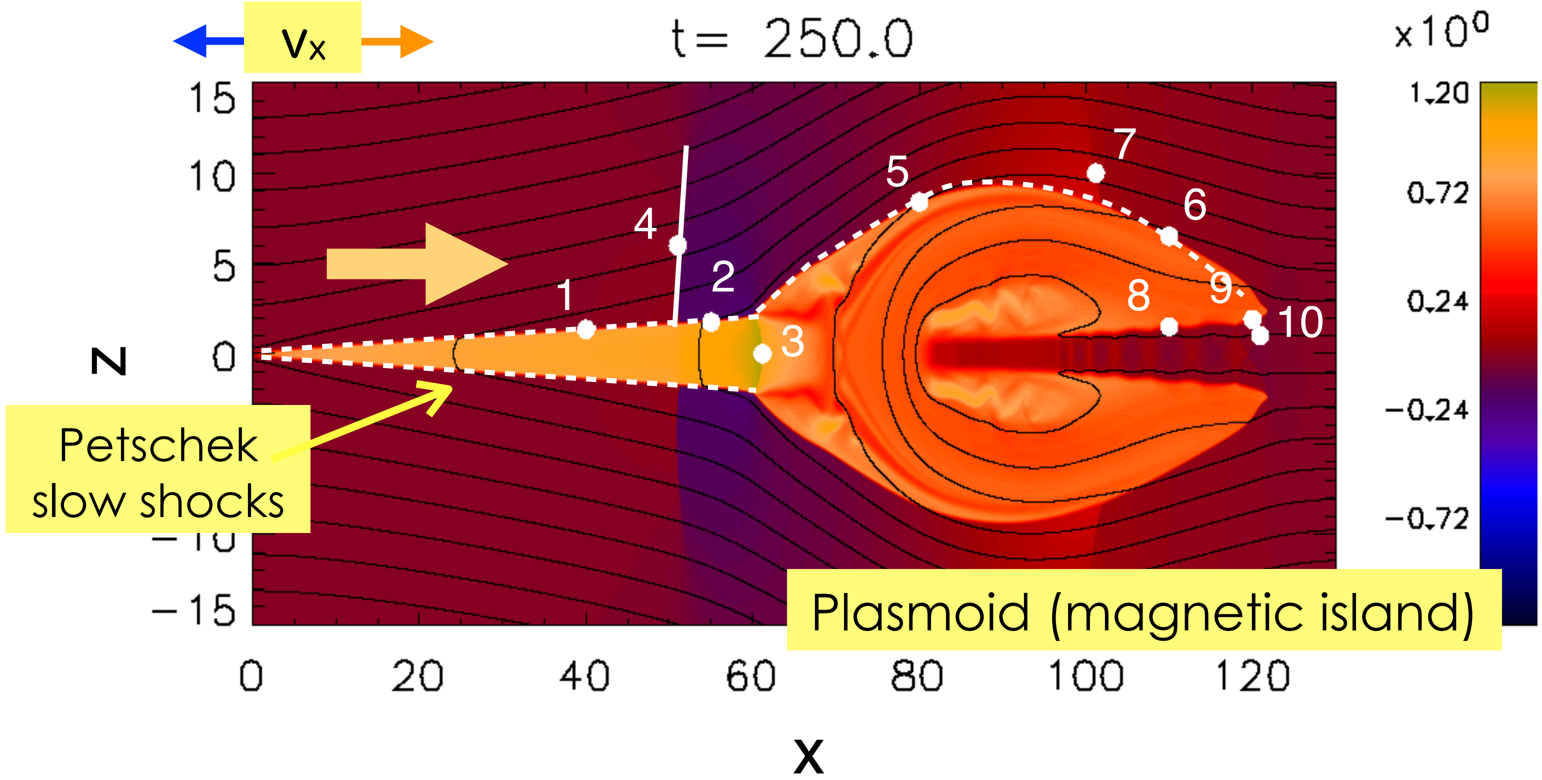
- Incompressible fluids

- Compressible fluid dynamics
- High-speed fluid dynamics
  - Adiabatic effects
  - **Shocks**
  - **Shock-shock interaction**

MHD simulation



Various shocks!



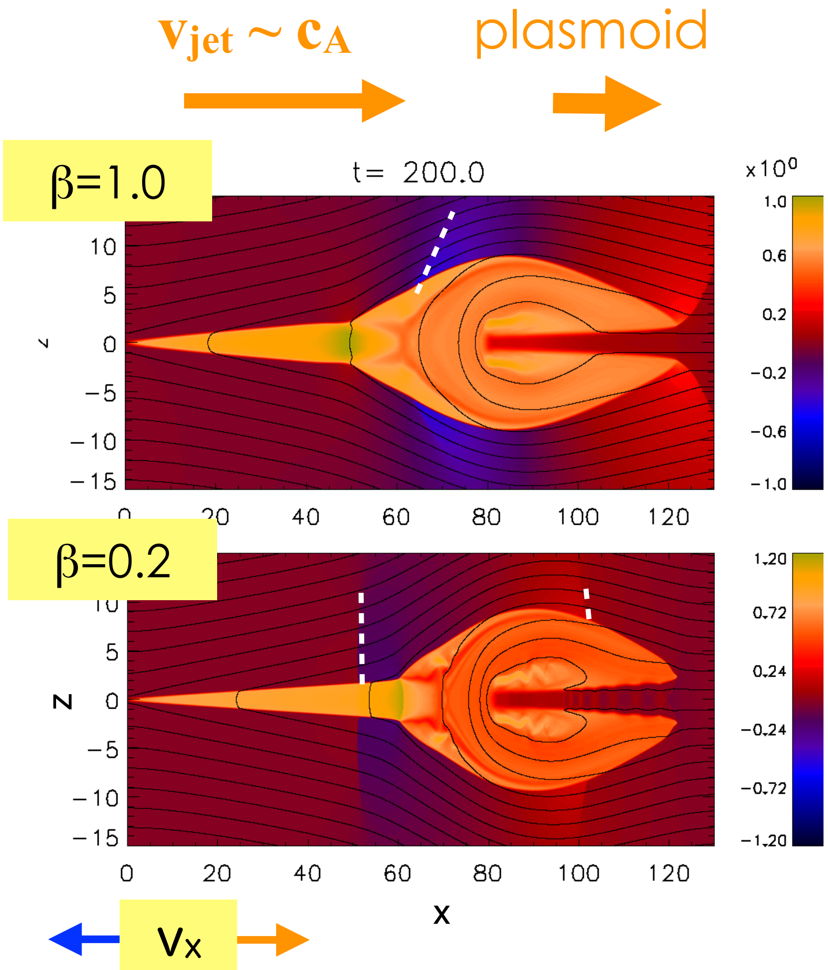
- Extensive analysis on shock conditions (Minimum variance analysis; MVA-B)

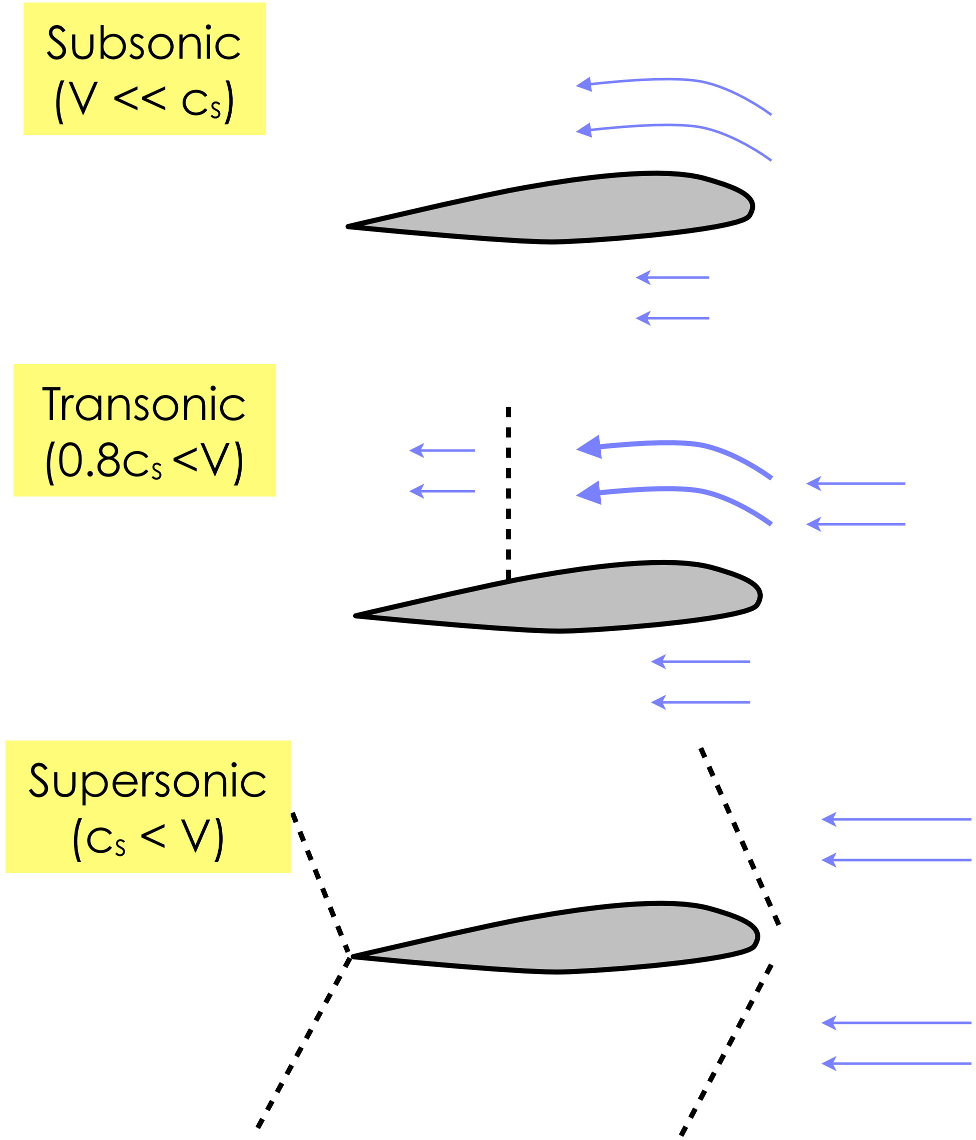
TABLE I. Rankine–Hugoniot analysis. The subscripts 1 and 2 denote the upstream and downstream quantities. The locations (x,z) in the simulation domain [see also Fig. 1(b)], the shock normal vector $\hat{n}$, the shock velocity v_{sh}, the angle between $\hat{n}$ and the upstream magnetic field $\boldsymbol{B}_1$, 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}	$\lvert\theta_{BN}\rvert$	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: Analogy to airfoil

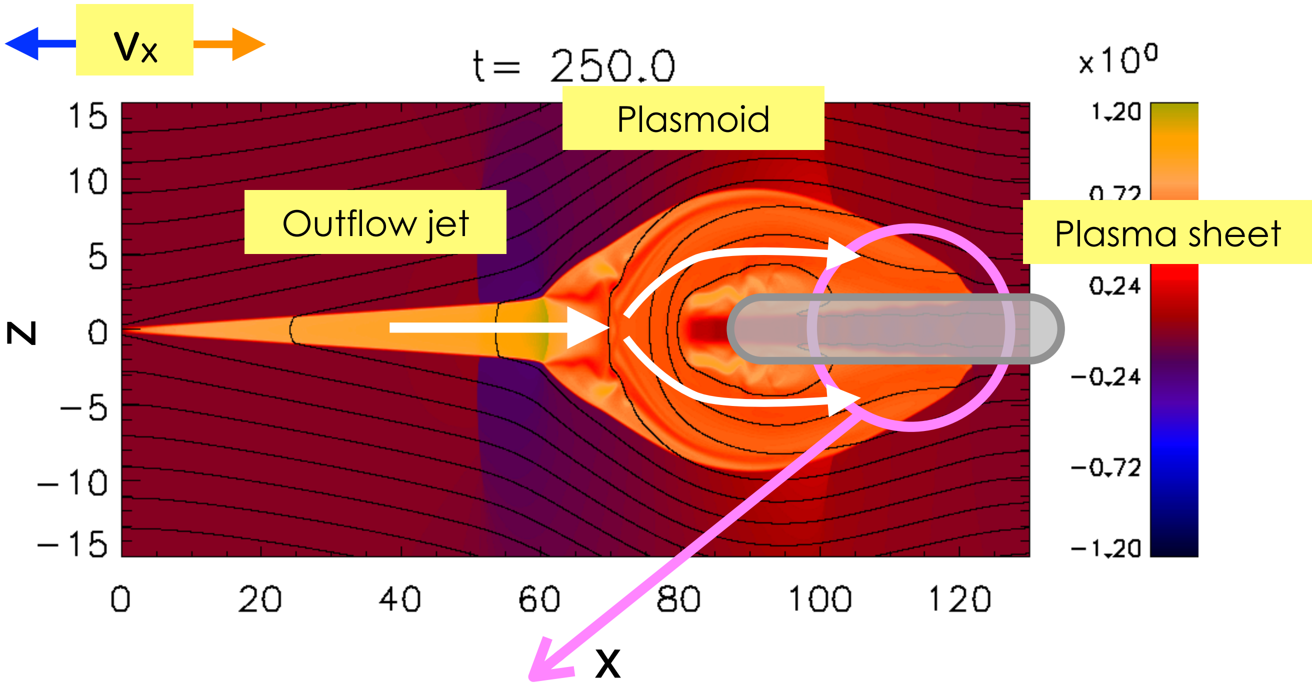
- MHD slow shock
- Recovery/recompression shock

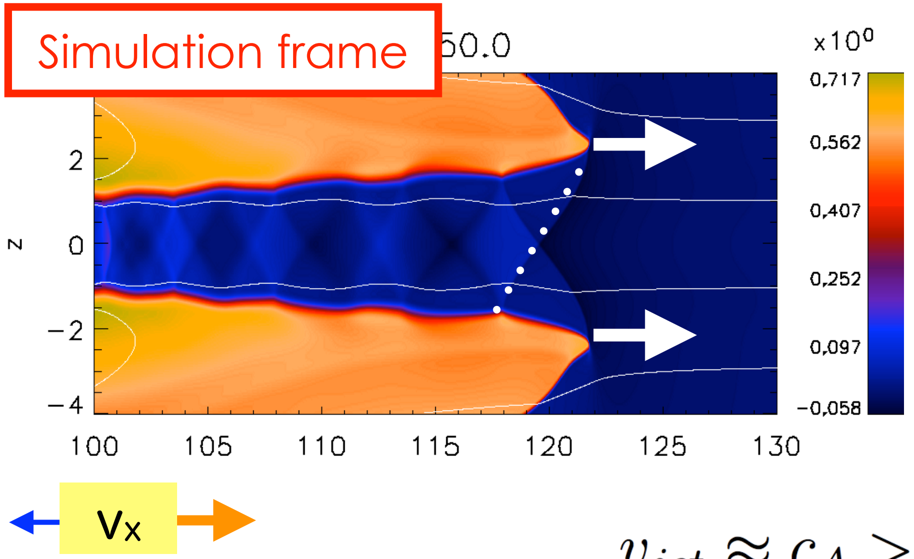


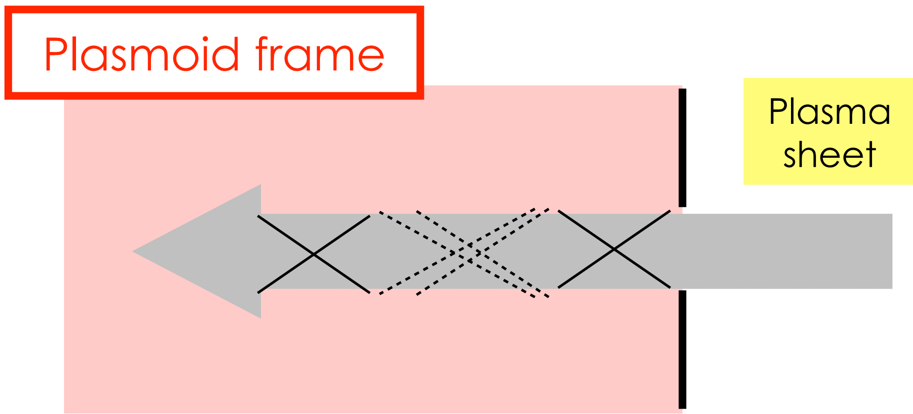


See also https://www.youtube.com/watch?v=8OIqfCTAZQo

Shock diamond

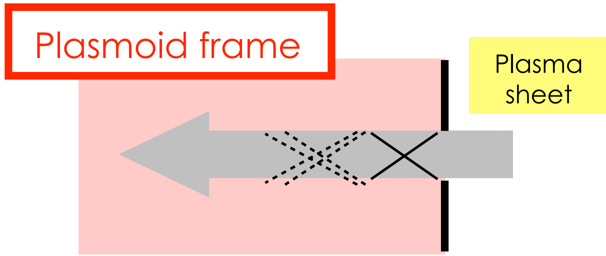




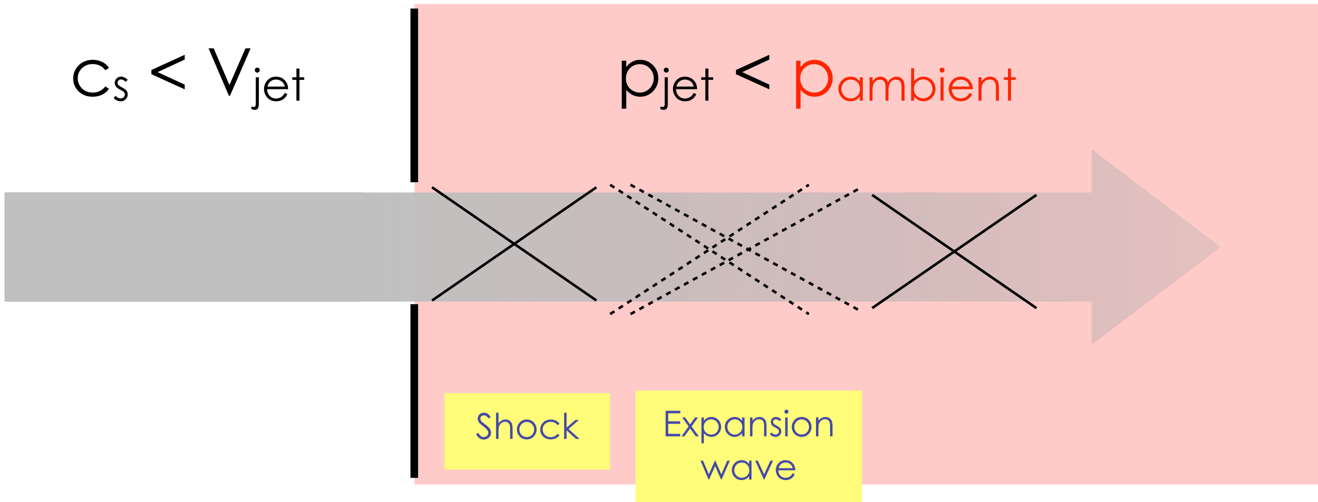


$$v_{jet} \approx c_A > c_s \iff \beta < 1$$

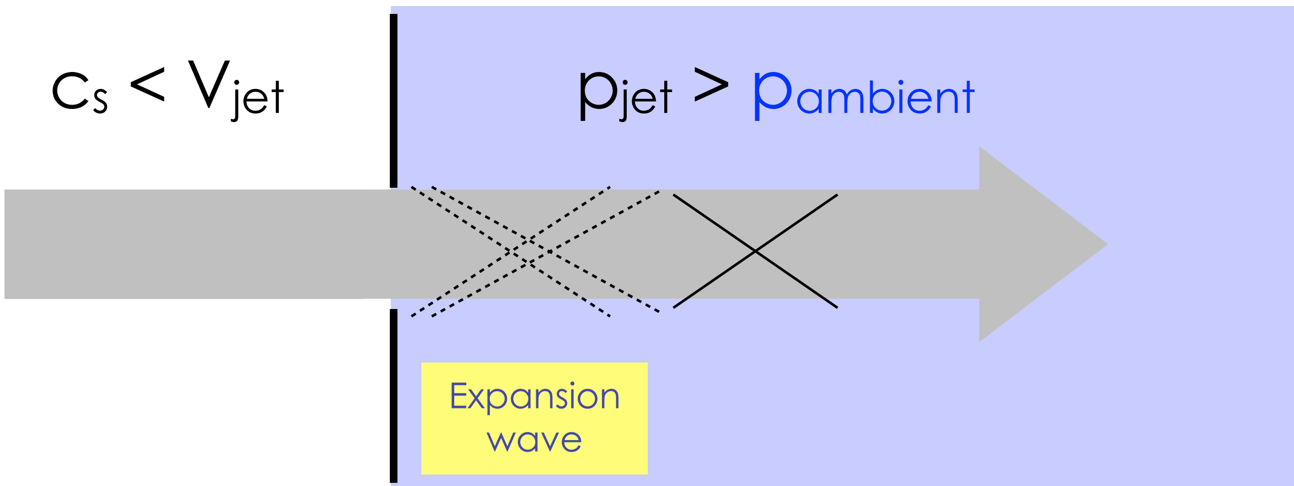
Supersonic nozzle problem



- (a) Over-expanded flow



- (b) Under-expanded flow



Shapiro 1953

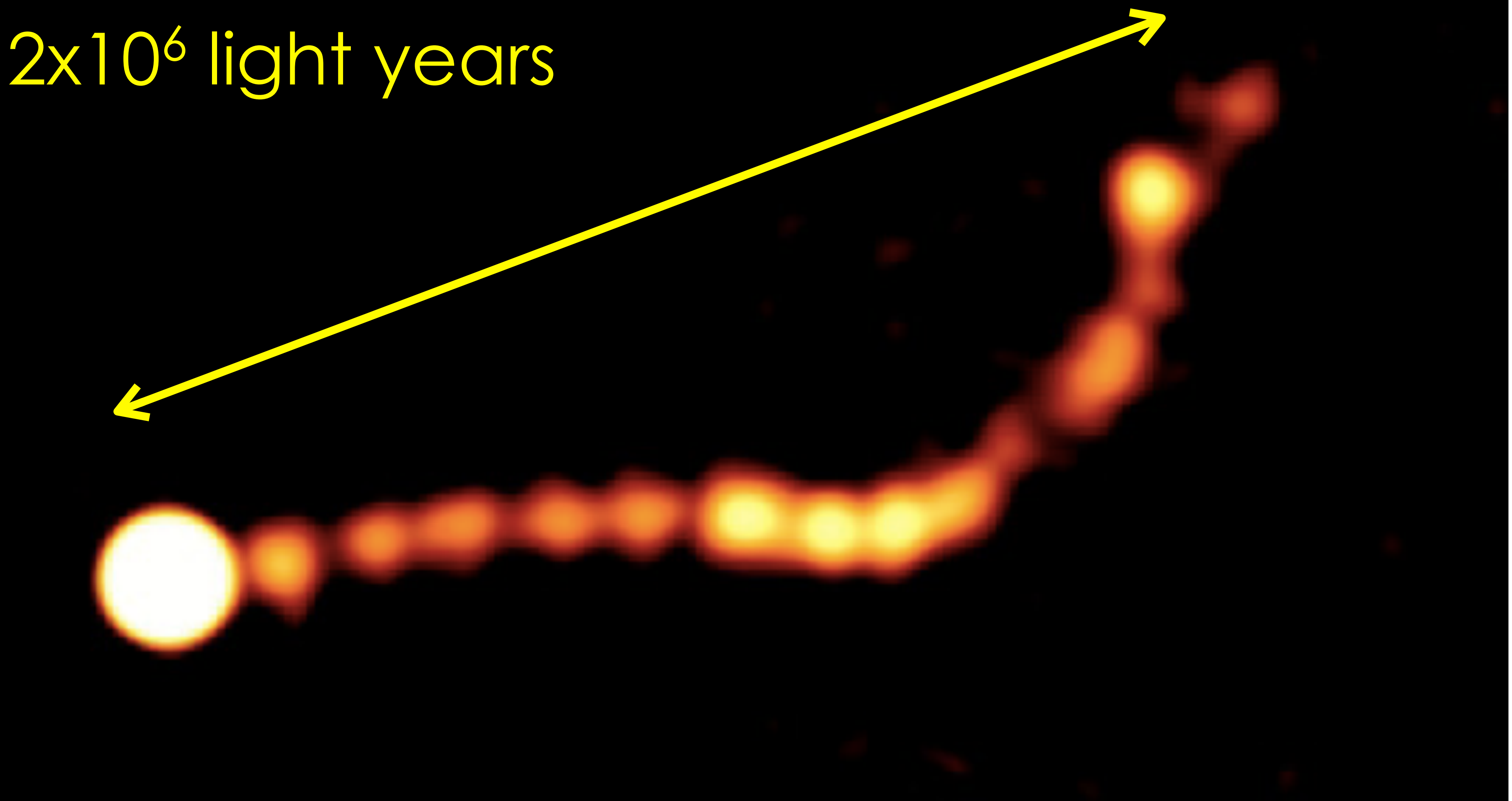
Shock diamonds in aeronautics

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

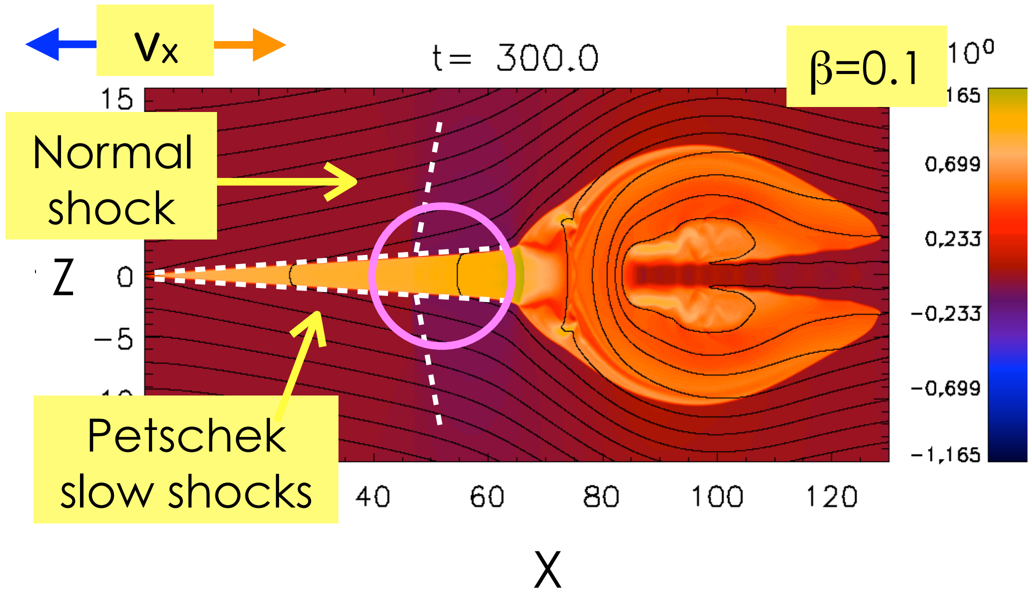


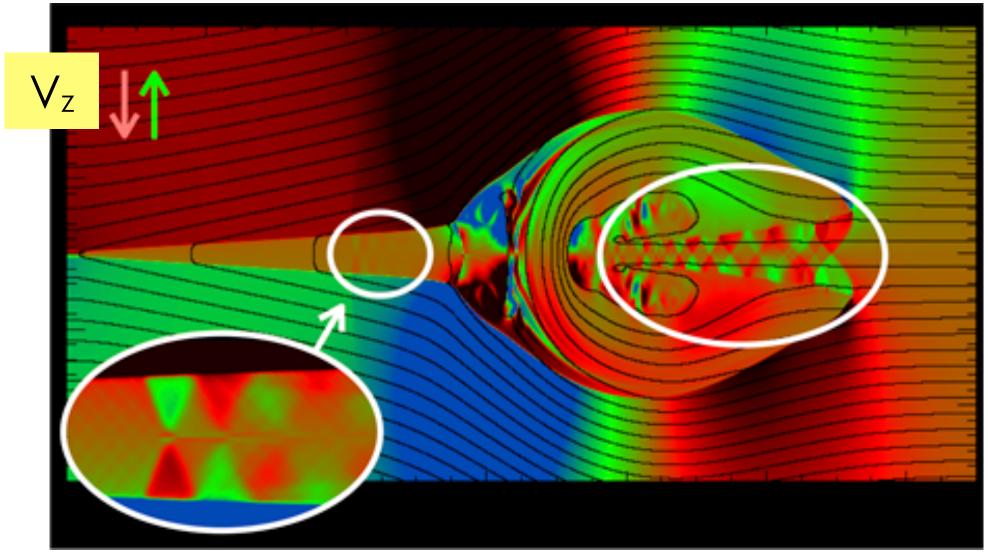
PKS 0637-752 Godfrey+ 2012 ApJ

Hidden shock-diamonds

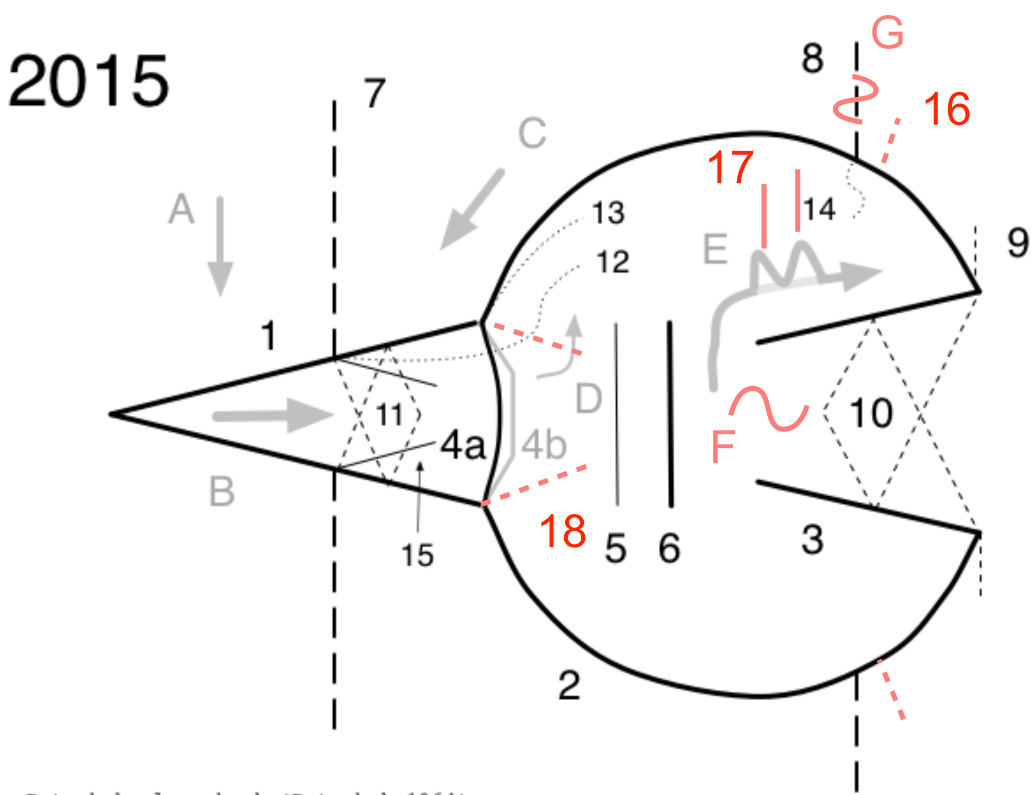
- Under-expanded shock-diamonds at the shock crossing point

- Triple-point structure is even more complicated (Zenitani 2015 PoP)
  - Contact discontinuity
  - Slow expansion fan





A digital catalog of the plasmoid structure



1. Petschek slow shock (Petschek 1964)
2. outer shell = slow shock (Ugai 1995)
3. intermediate shock (Abe & Hoshino 2001) or slow shock (Saito et al. 1995)
4a fast shock (Forbes & Priest 1983)
4b oblique shock & Mach disk (Takasao et al. 2015)
5. looptop front (Ugai 1987)
6. tangential discontinuity
7. post-plasmoid vertical slow shock (Zenitani et al. 2010)
8. outer vertical slow shock (Zenitani & Miyoshi 2011)
9. fast-mode wave front (Saito et al. 1995)
10.overexpanded shock-diamonds (Zenitani et al. 2010)
11.underexpanded shock-diamonds (Zenitani 2015)
12.contact discontinuity (Zenitani & Miyoshi 2011, 2015)
13.contact discontinuity (Zenitani 2015)
14.contact discontinuity (Zenitani 2015)
15.slow expansion wave front (Zenitani 2015)

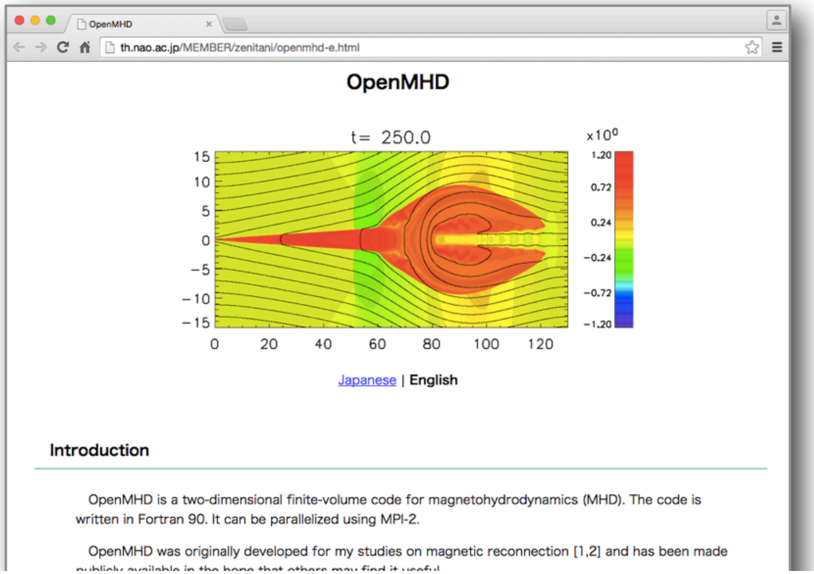
A. reconnection inflow
B. outflow jet
C. post-plasmoid reverse flow
D. internal flow
E. flapping jet (KH instability)

- In high Mach number, low-β regime, reconnection system is dominated by shocks
- This regime has long been unexplored!

$$\frac{1}{\beta} \sim \left(\frac{c_A}{c_s}\right)^2 \sim \left(\frac{V}{c_s}\right)^2 \sim \mathcal{M}^2$$

OpenMHD code

- Simple, Scalable, and Shock-capturing MHD code
  - TVD Runge=Kutta method
  - TVD MUSCL scheme + HLLD solver
  - Hyperbolic divergence cleaning
  - Parallel-IO
- Search "OpenMHD" without a space



http://th.nao.ac.jp/MEMBER/zenitani/openmhd-e.html

Summary

- We have investigated the shock structure of a reconnection-plasmoid system
- In high Mach-number, low-β regime, several new structures are found:
  - Recompression shock
  - Over-expanded shock diamonds at the front
  - Under-expanded shock diamonds inside the jet
- They are outcomes of high-speed (compressible) fluid effects : $\mathcal{M} > 1$
- Code publicly available
- References:
  - Zenitani, *Phys. Plasmas* **22**, 032114 (2015)
  - Zenitani & Miyoshi, *Phys. Plasmas* **18**, 022105 (2011)

Thank you for your attention.
Have a safe return trip!

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