Magnetic reconnection as a showcase of high-speed fluid dynamics

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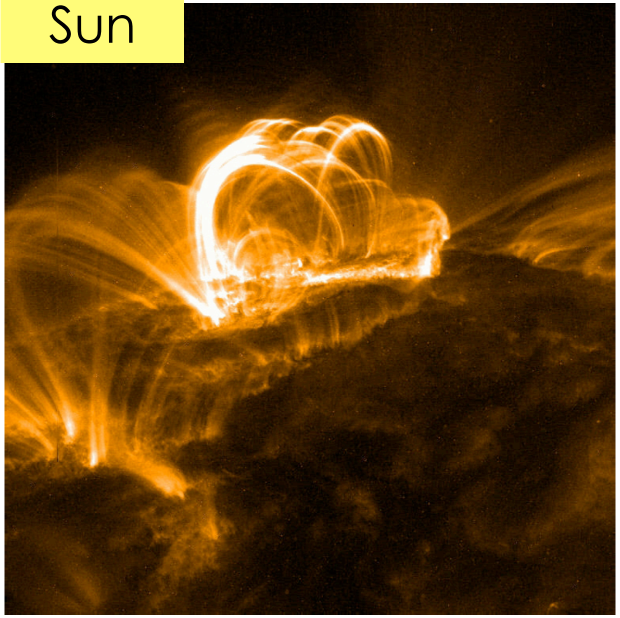
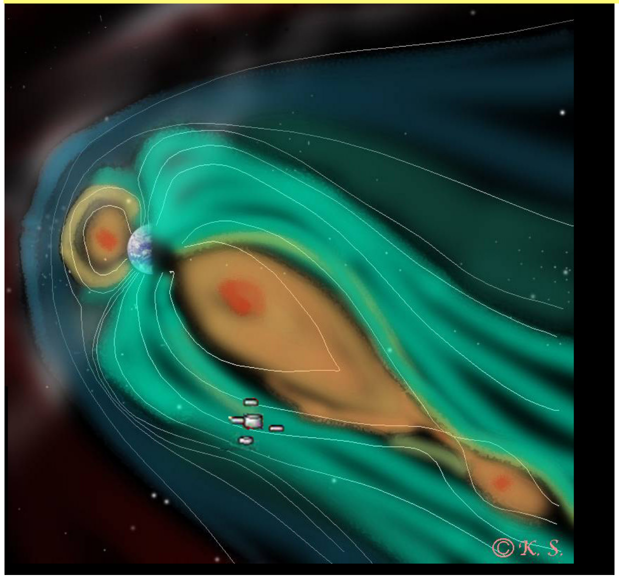
Magnetic reconnection

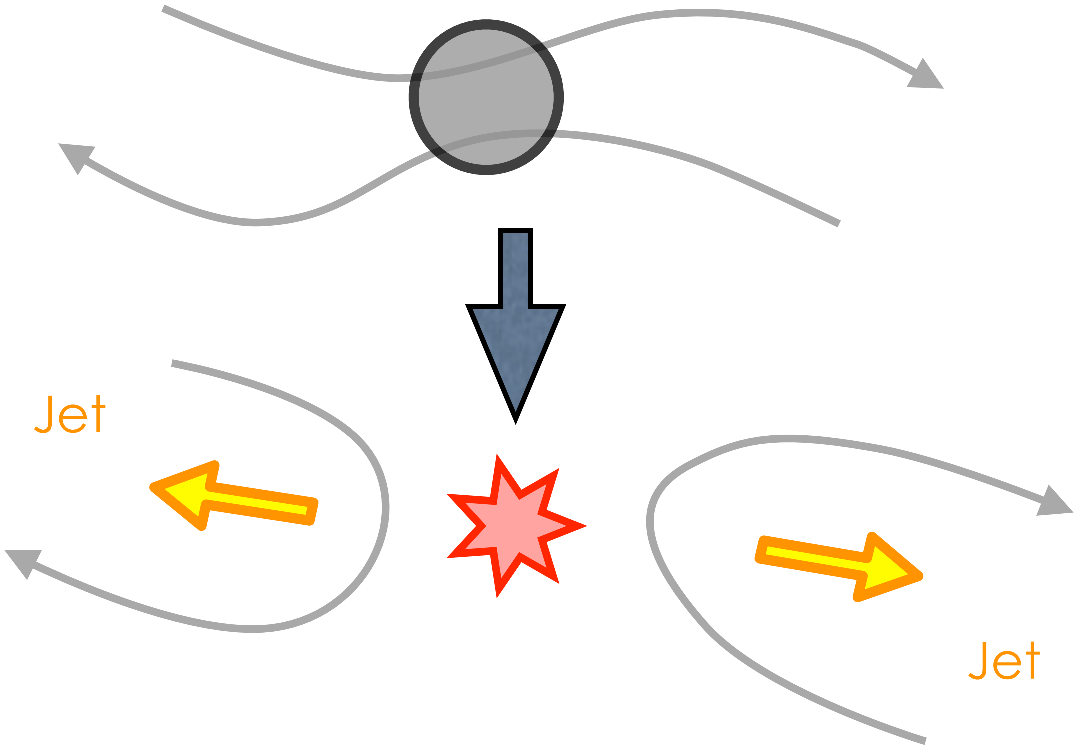
Sun



Earth's Magnetosphere

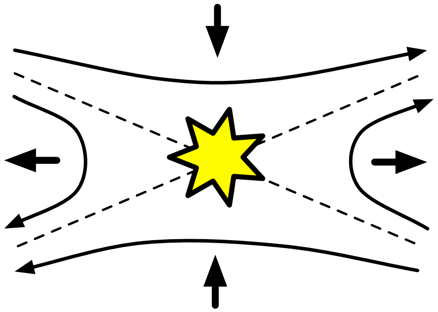


- MHD-scale phenomena
- Re-configuration of magnetic field lines
- Release of magnetic energy to plasma energy

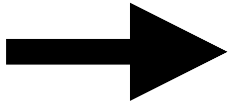


Jet-driven structure in RX

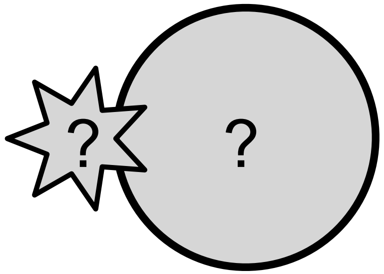
- Magnetic reconnection generates a complex structure by interacting with outer environments.



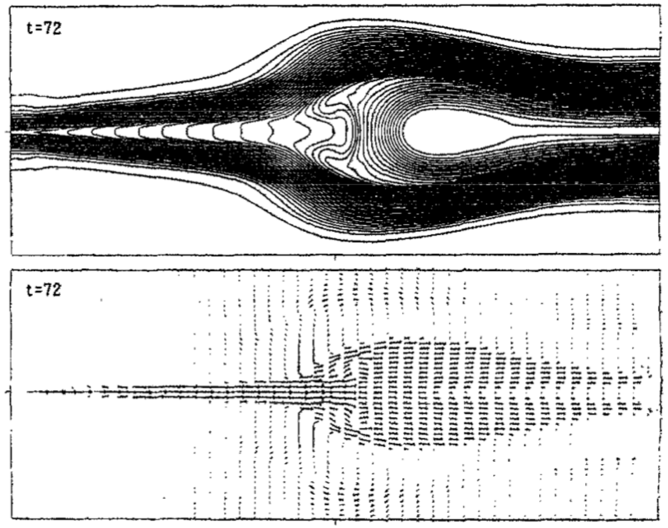
jet

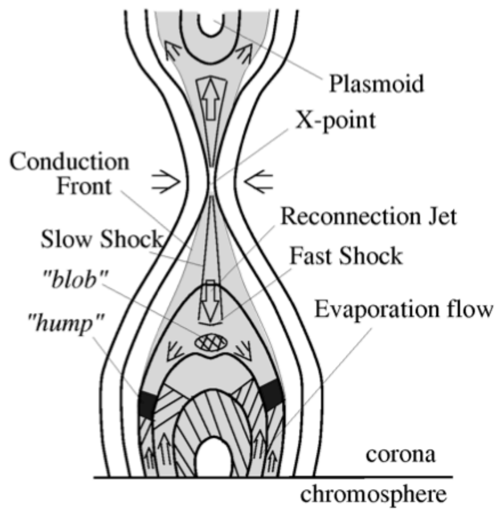


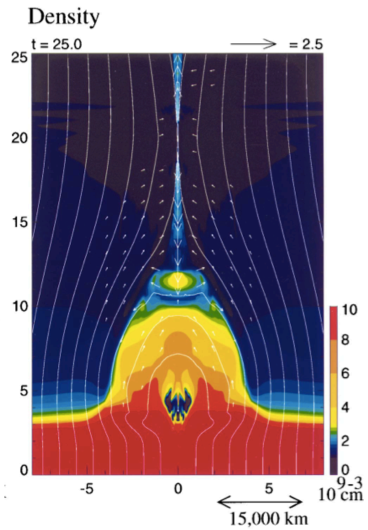
$$c_A = \frac{B}{\sqrt{4\pi m n}}$$



- Example: a magnetic island ("plasmoid")







Ugai 1995 PoP

Yokoyama & Shibata 1998 ApJ

Plasma beta

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

- β << 1 in Solar corona and other applications
- An indicator of **high-speed fluid effects**

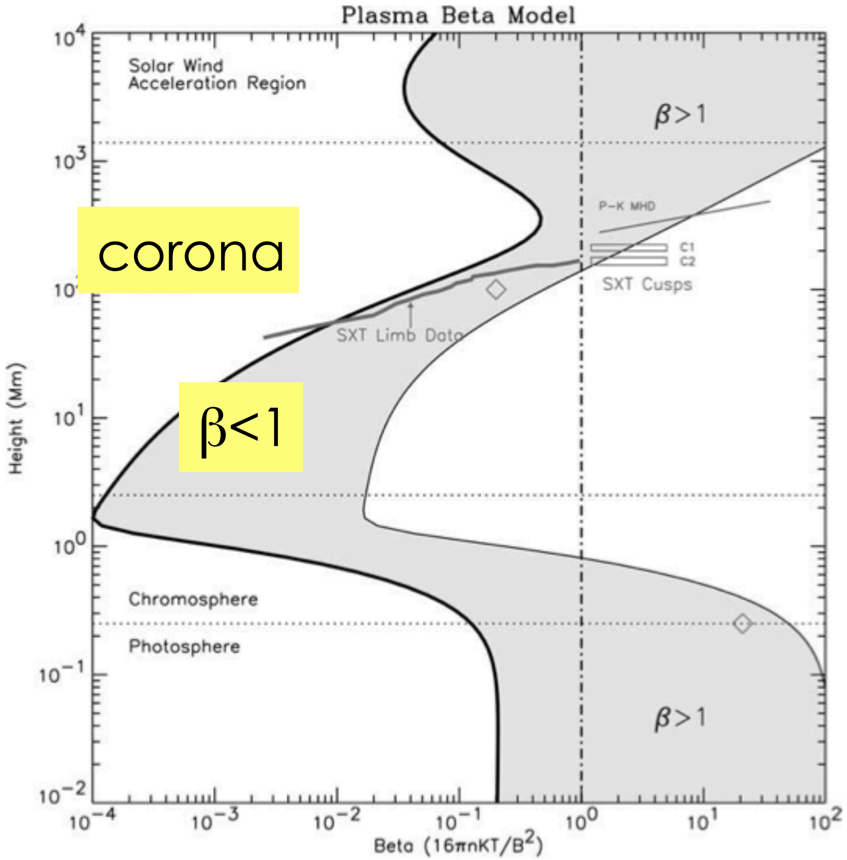
Sound velocity

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

Alfvén velocity

Typical velocity

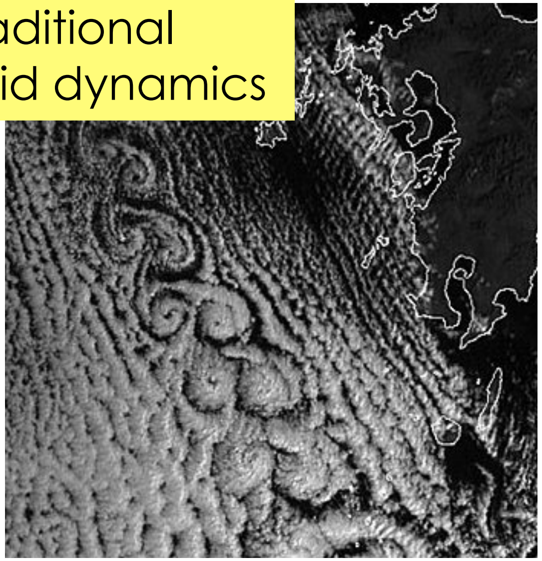
$$\beta \propto \mathcal{M}^{-2}$$



Gary 2001 Sol. Phys.

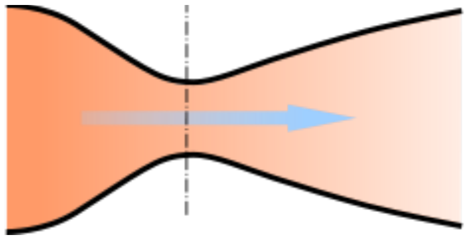
Branches of fluid dynamics

Traditional fluid dynamics

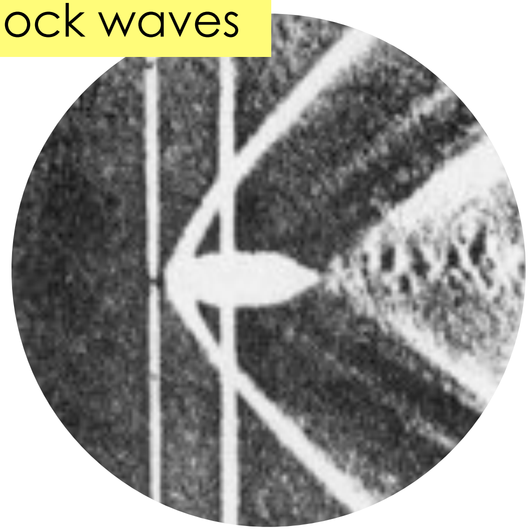


tenki.jp 2015

Laval Nozzle



Shock waves



Mach 1887

1

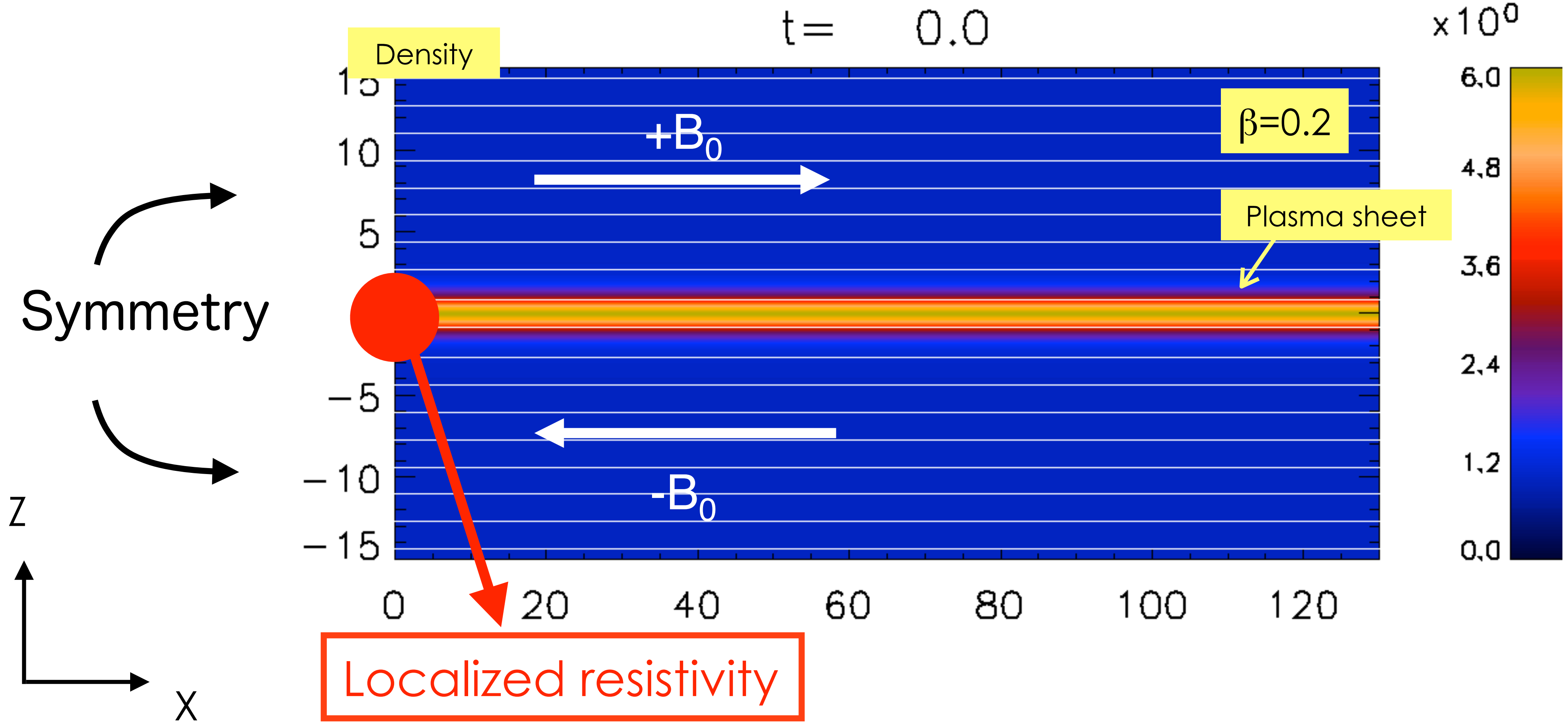
$$\mathcal{M} = \frac{V}{c_s}$$

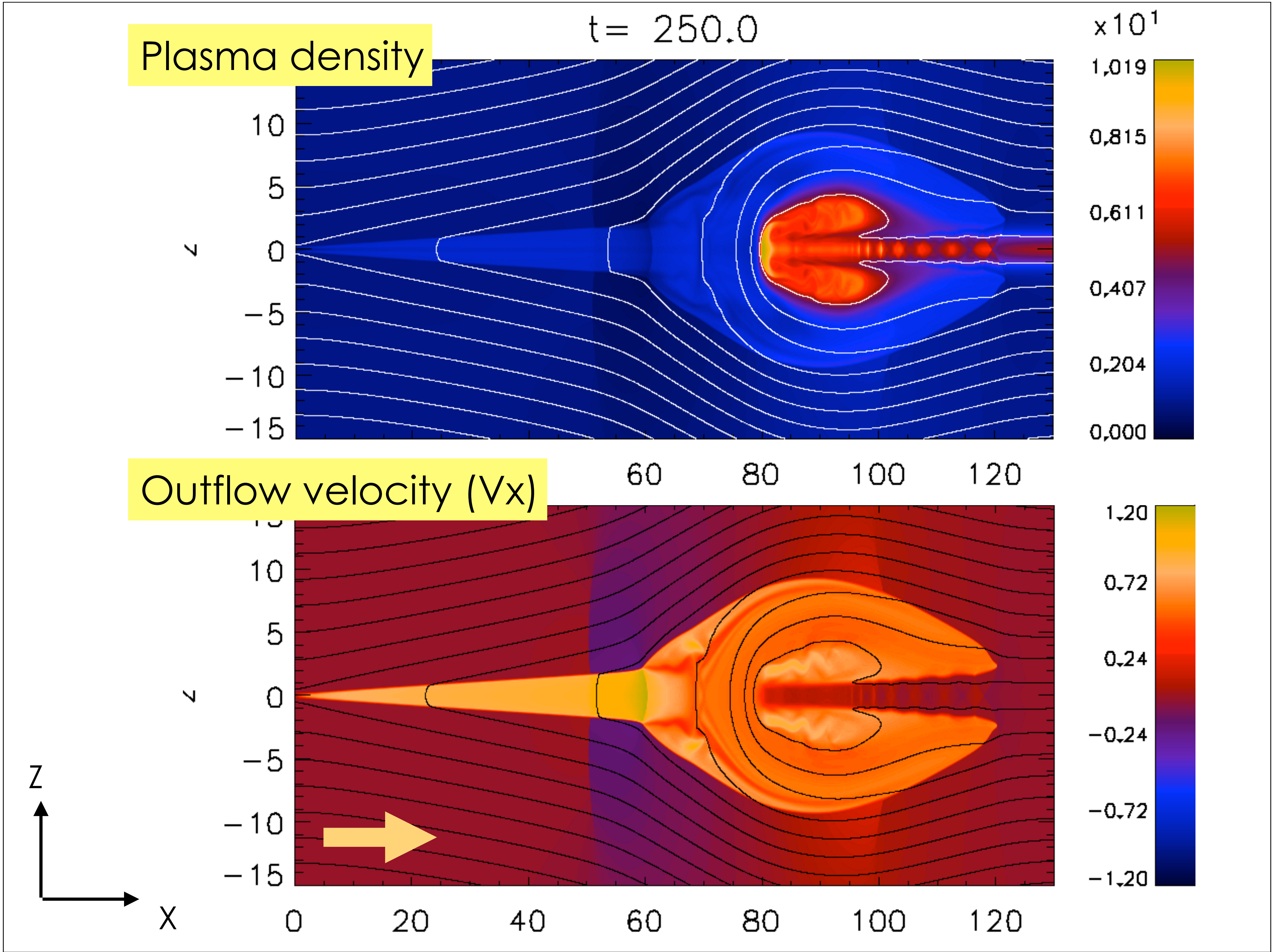
Subsonic | 0.7~ | Transonic | ~1.2 | Supersonic

- Incompressible fluids
- High-speed (compressible) fluid dynamics
  - Adiabatic effects
  - **Shocks**
  - **Shock=Shock interaction**

MHD simulation

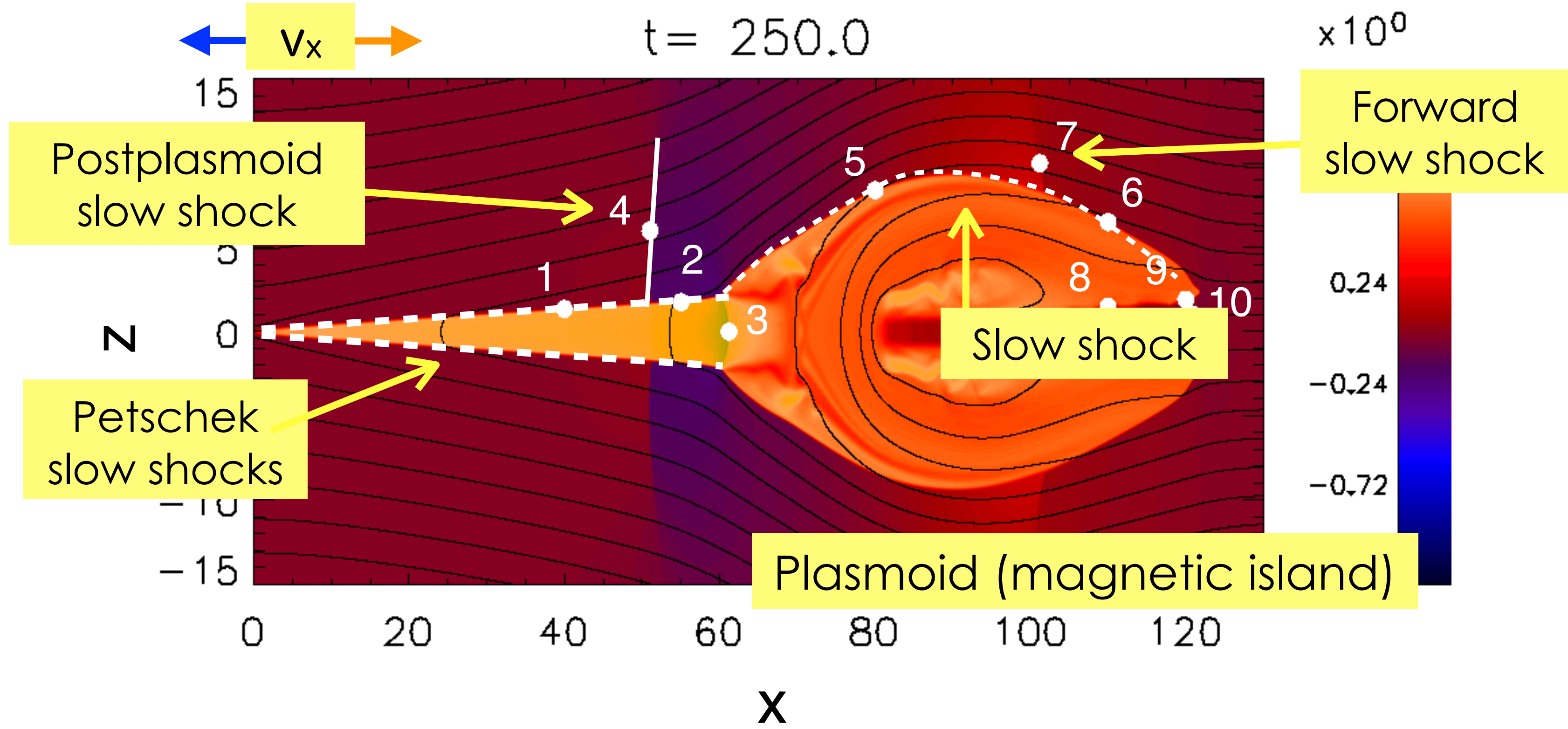
- HLL solver, HLLD solver, 2nd-order TVD
- Domain: [0, 200] x [0, 150]
- 6000 x 4500 or 12000 x 9000 cells





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)

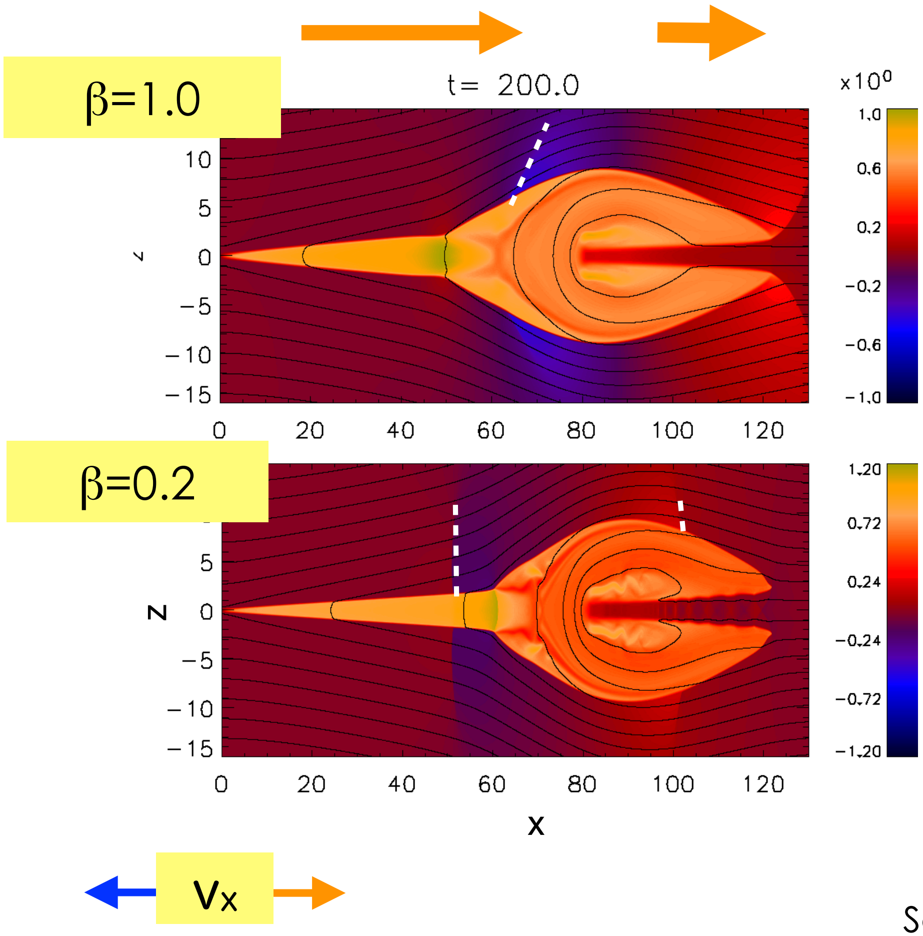
TABLE I. Rankine–Hugoniot analysis. The subscripts 1 and 2 denote the upstream and downstream quantities. The locations (x,z) in the simulation domain [see also Fig. 1(b)], the shock normal vector $\hat{n}$, the shock velocity v_{sh}, the angle between $\hat{n}$ and the upstream magnetic field B_1, the 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.

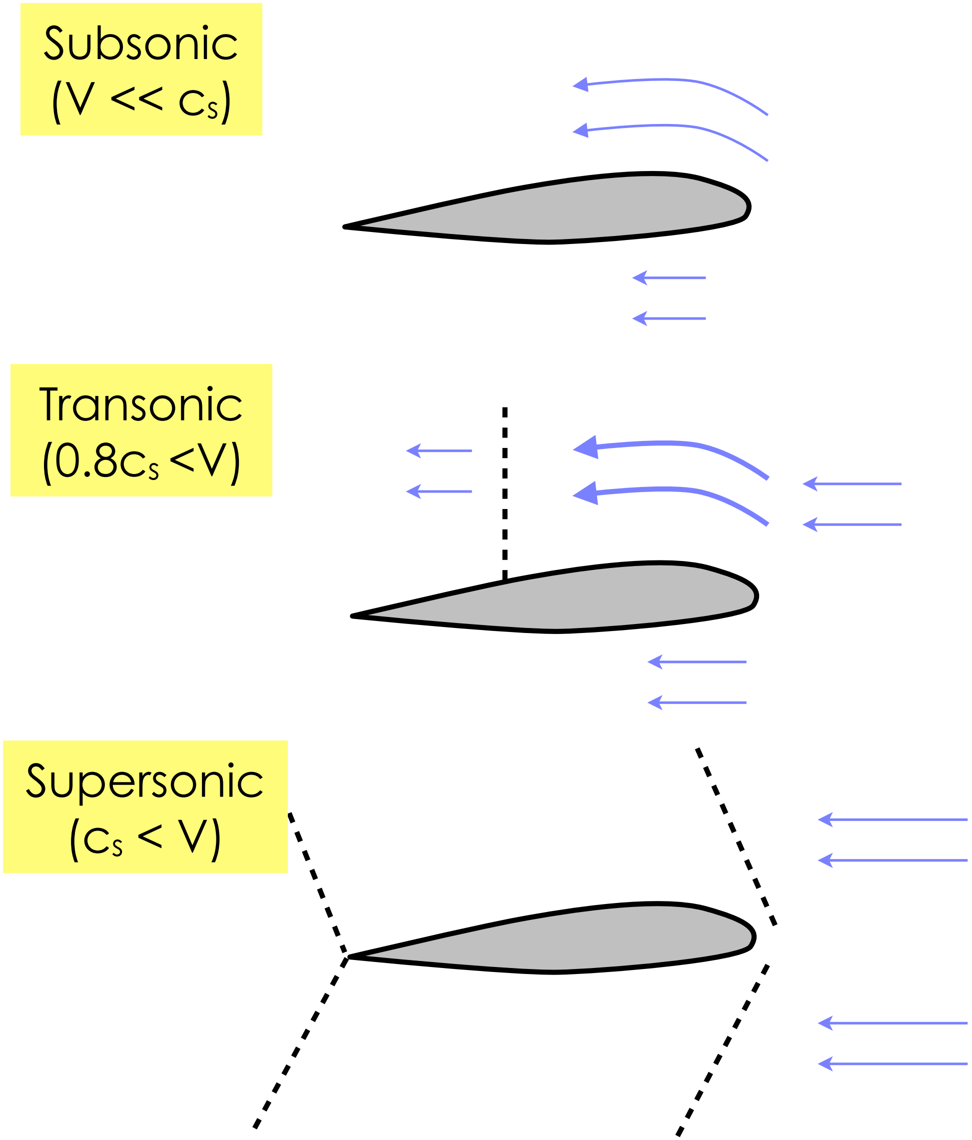
No.	Location	(n_x, n_z)	v_{sh}	$\lvert\theta_{BN}\rvert$	β_1	$\mathcal{M}_{f1}$	$\mathcal{M}_{i1}$	$\mathcal{M}_{s1}$	$\mathcal{M}_{f2}$	$\mathcal{M}_{i2}$	$\mathcal{M}_{s2}$	T_2/T_1	
1	(40.0, 1.35)	(−0.03, 1.00)	0.0	86.3	0.22	0.06	0.98	2.49	0.04	0.69	0.69	2.72	(S) Petschek shock
2	(55.0, 1.75)	(−0.04, 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 (Recompression shock)

- MHD slow shock
- Analogy to airfoil

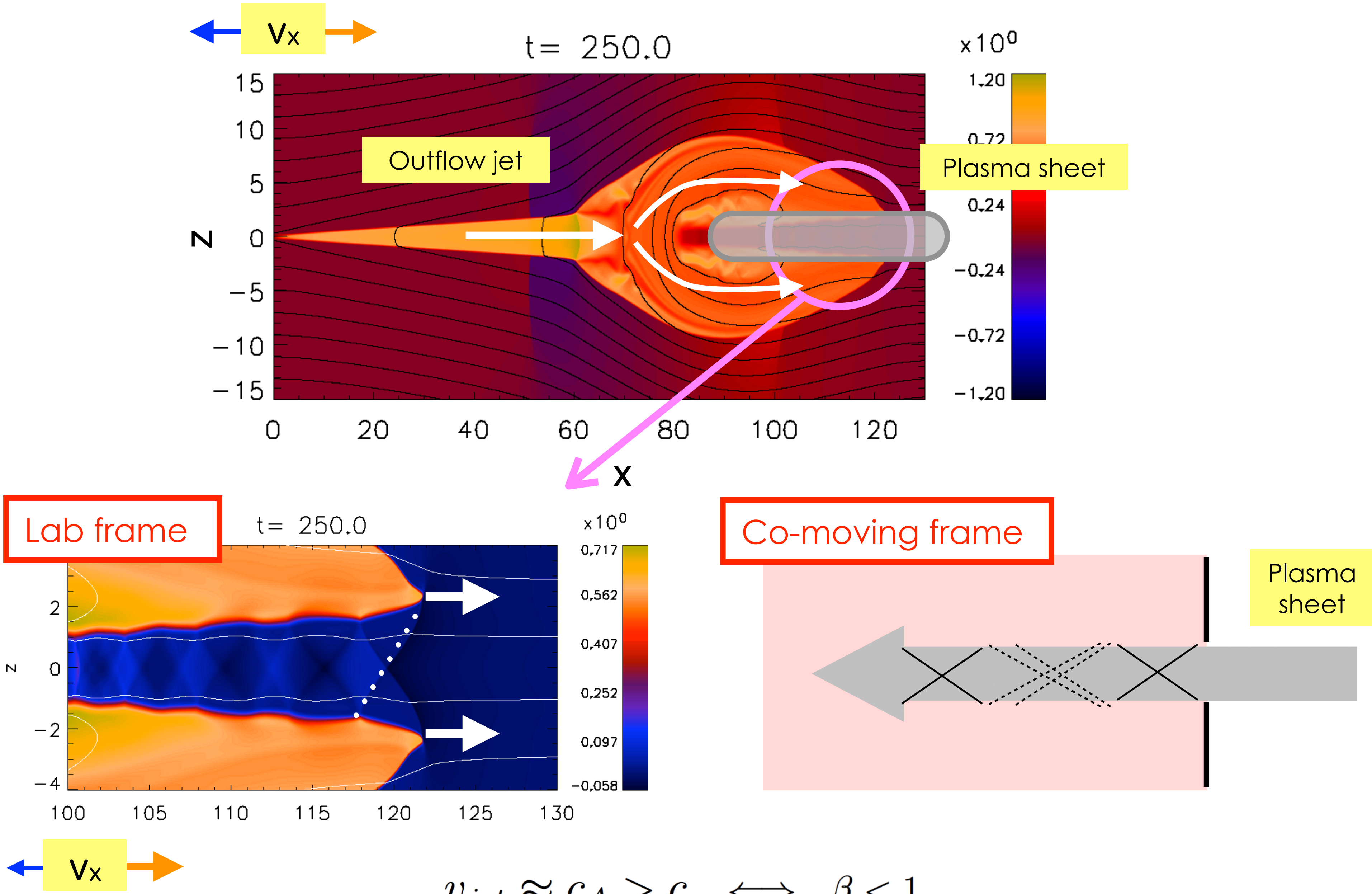
$v_{jet} \approx c_A$ jet leading edge





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

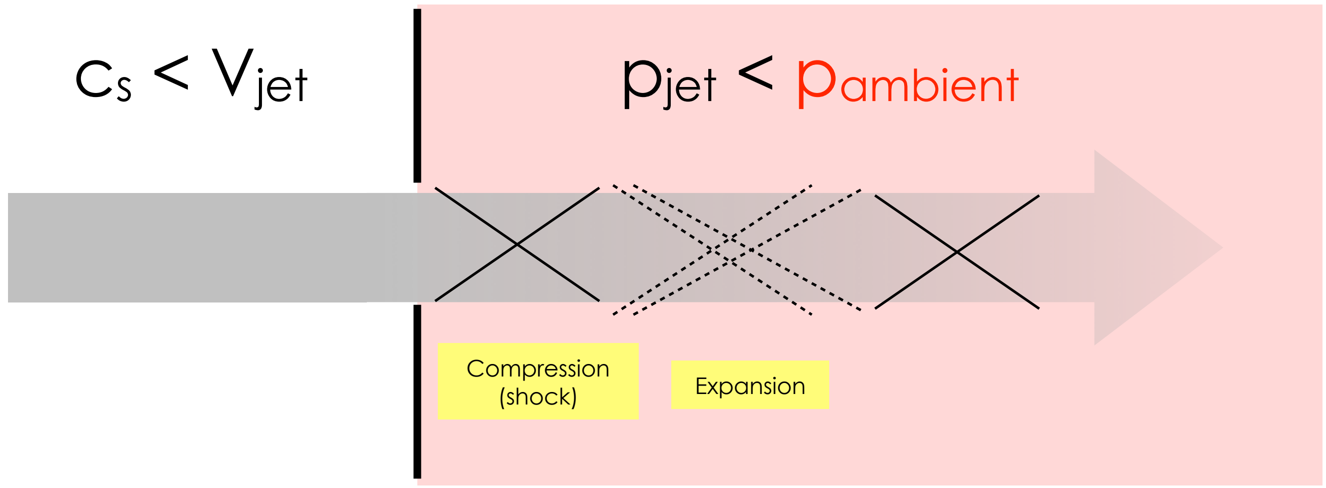
Shock diamond



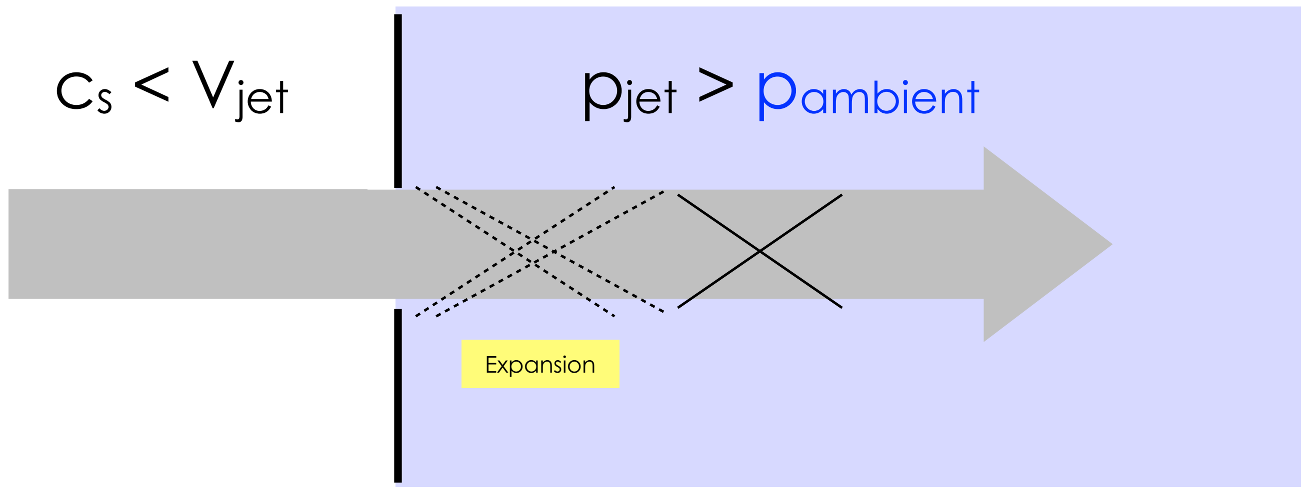
$$v_{jet} \approx c_A > c_s \iff \beta < 1$$

Shock diamond

- (a) Over-expanded flow (過膨張)



- (b) Under-expanded flow (不足膨張)



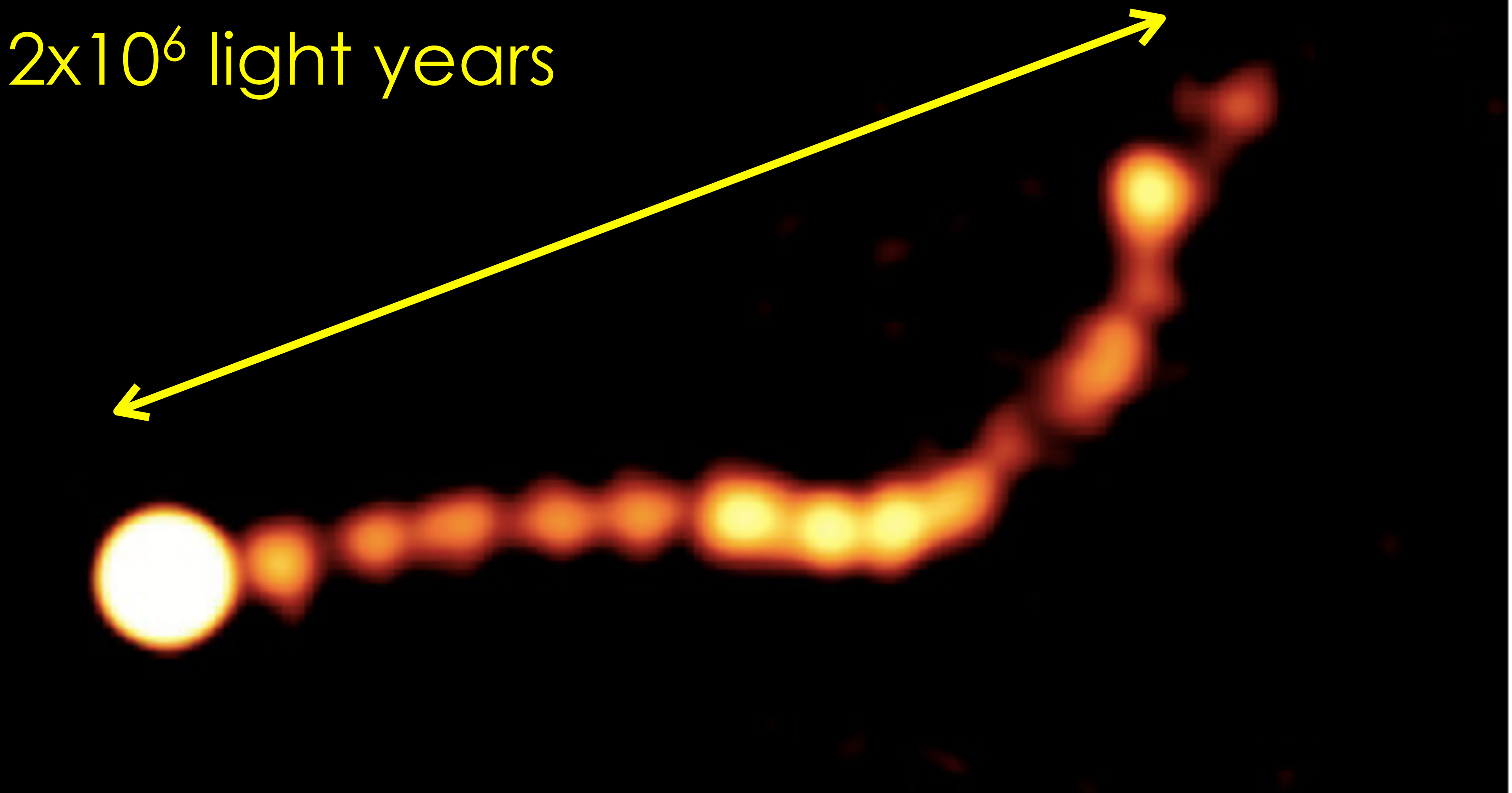
Shock diamonds in aeronautics

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

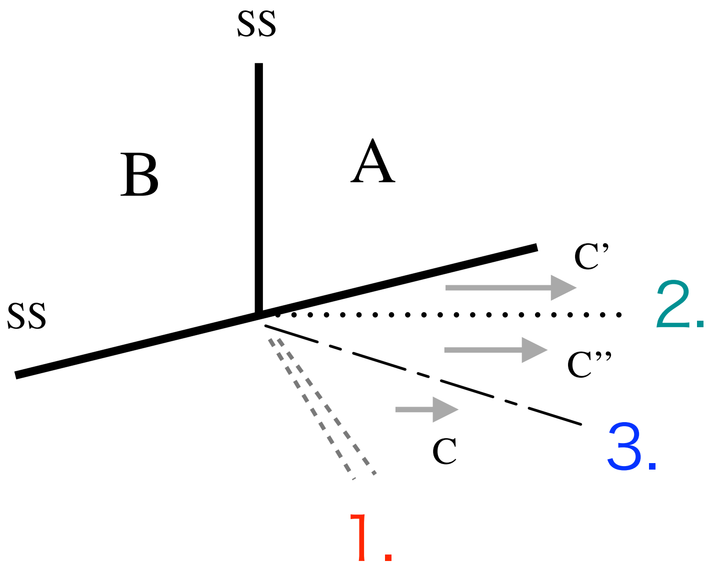
Shock diamonds in astrophysics

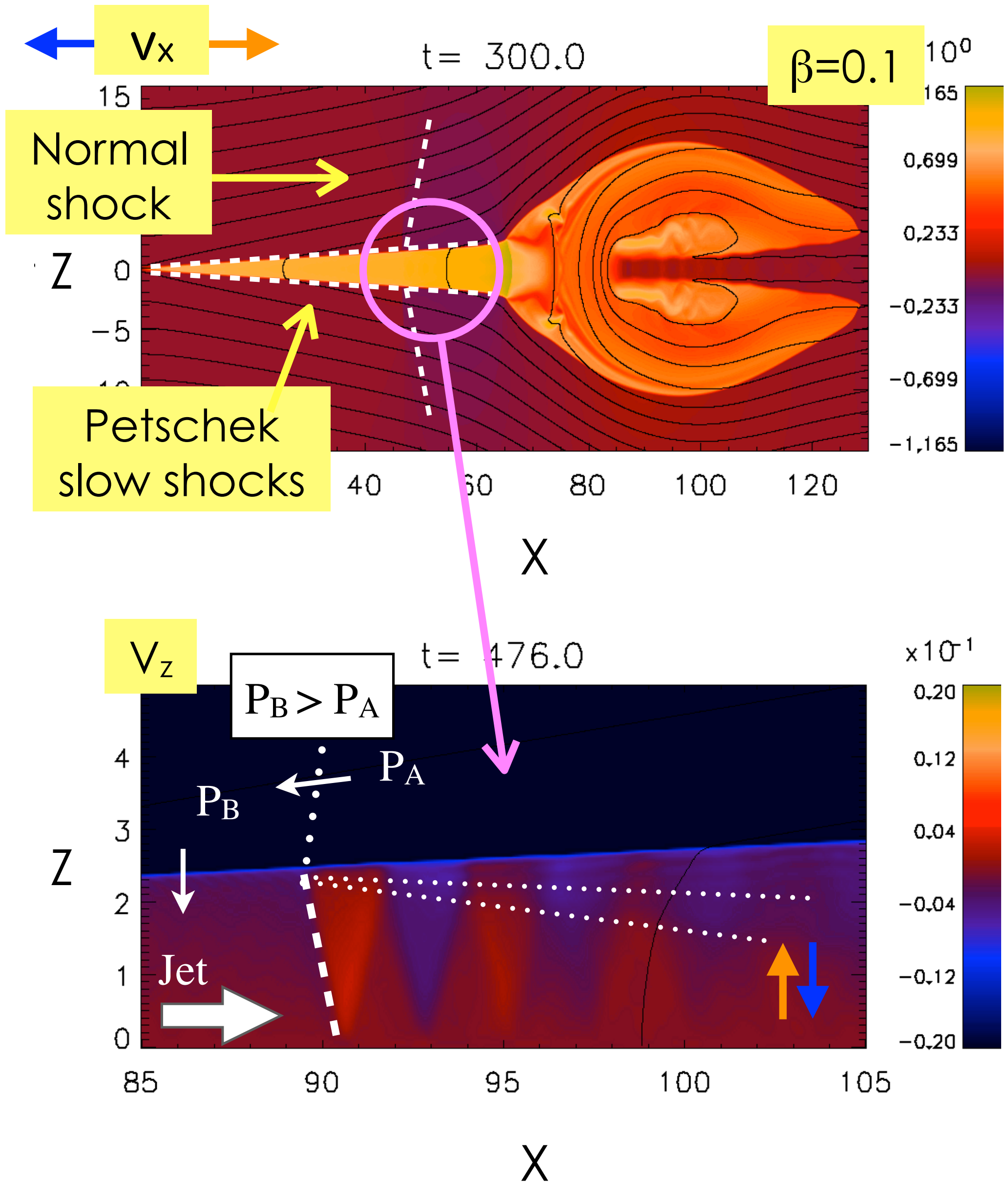


PKS 0637-752 Godfrey+ 2012 ApJ

Hidden shock-diamonds

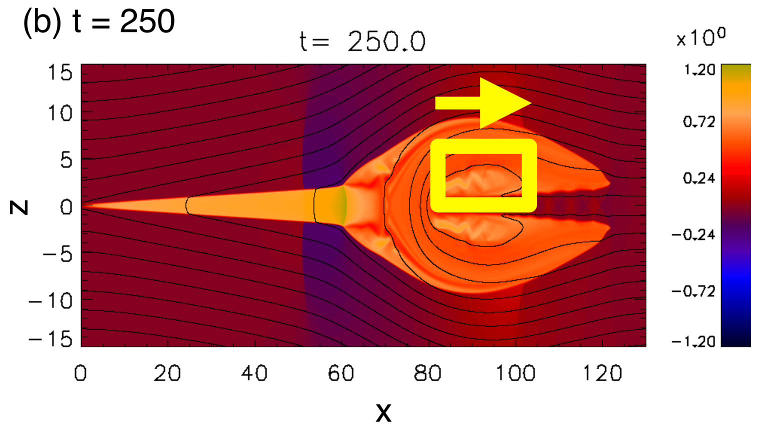
- At the shock crossing, we recognize
  - 1. Fast expansion wave (shock-diamond)
  - 2. Contact discon. ≠ Slip line
  - 3. Slow expansion wave

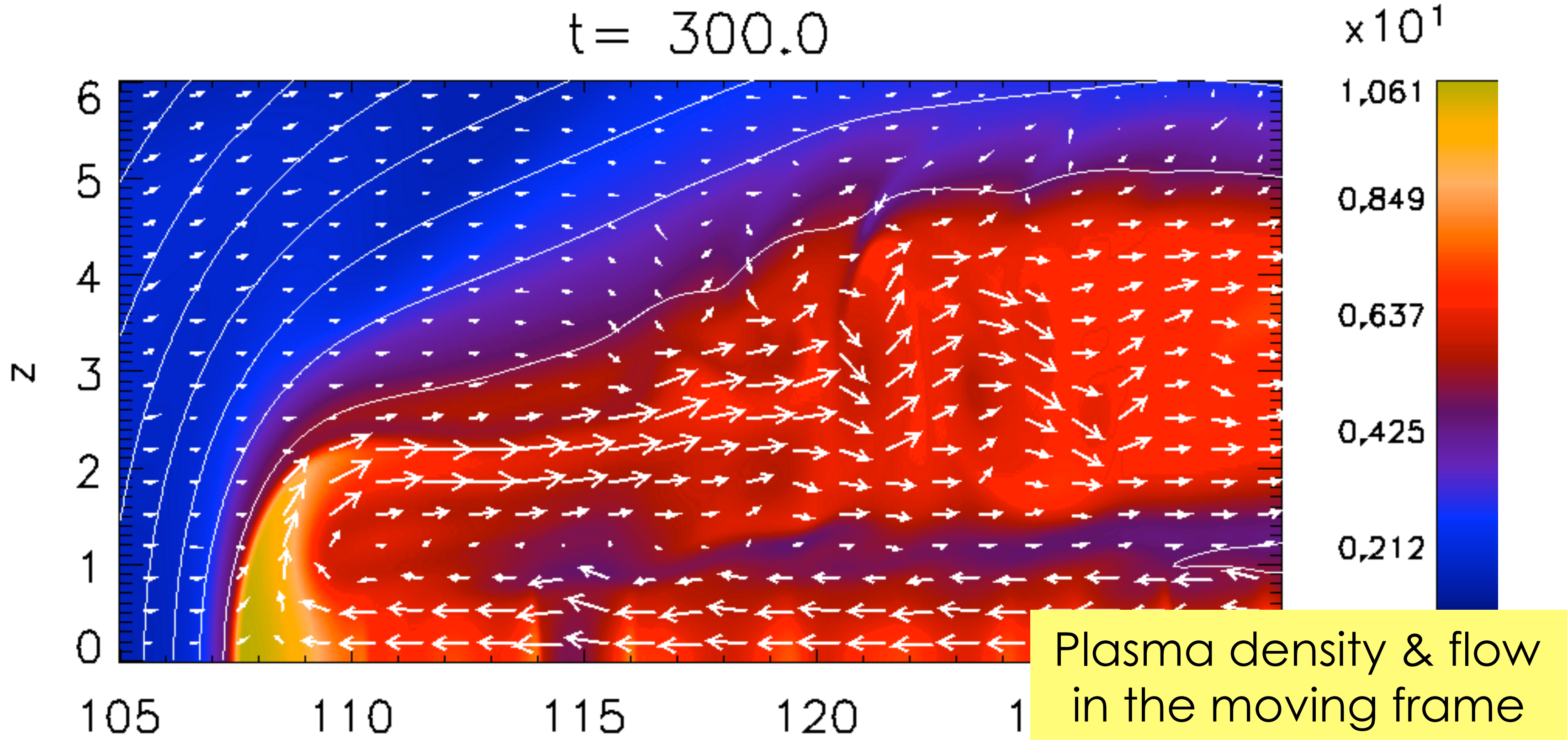




Kelvin-Helmholtz instability inside the plasmoid

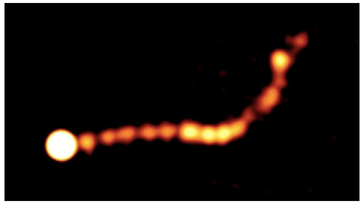
- Plasmas are hit and reflected by the reconnection jet front
- KH instability due to the reflected flow

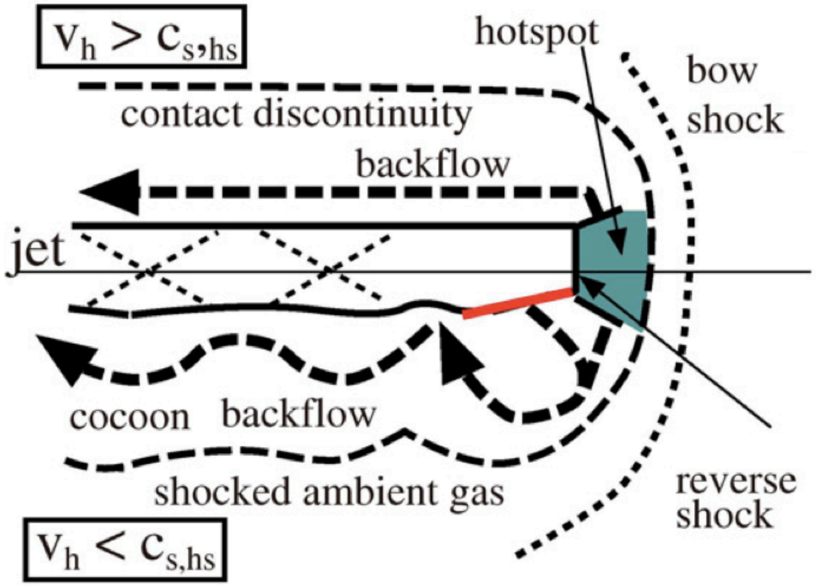


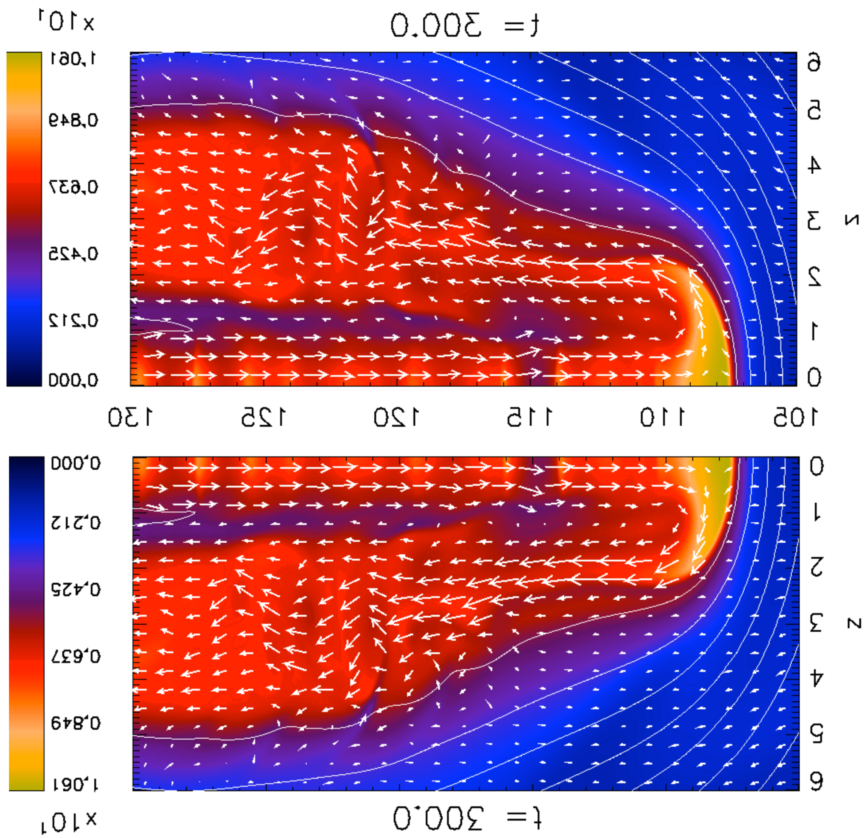


Comparison with astrophysical jet model

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





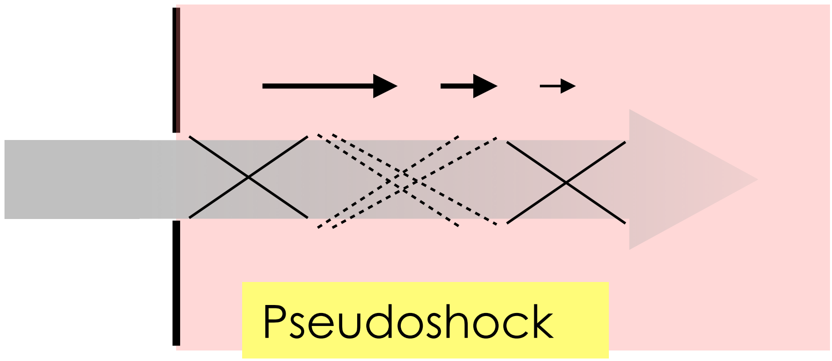


Mizuta+ 2010 ApJ

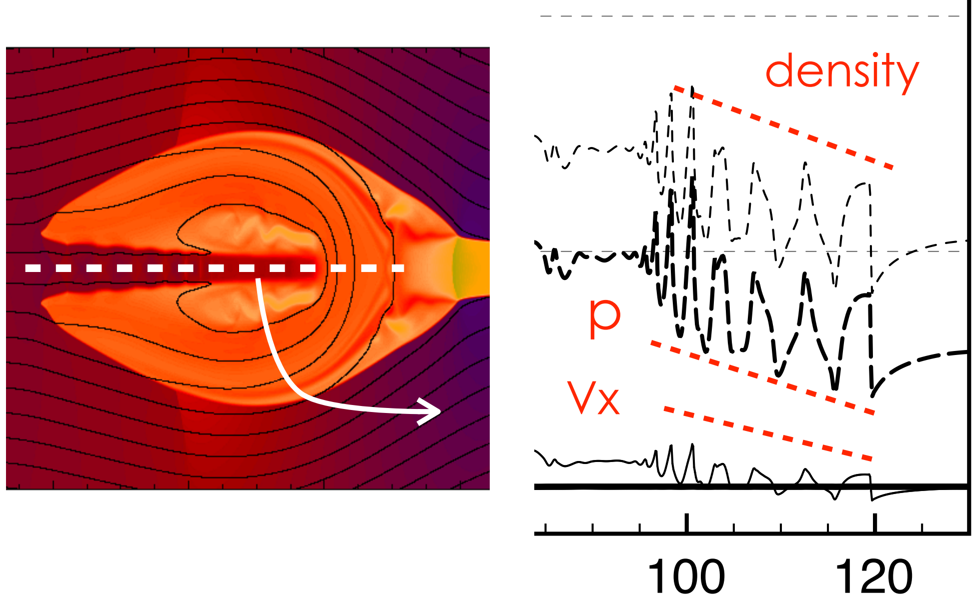
Pseudo-shock (oblique diffuser)

- (a) Over-expanded flow

$p_{jet} < p_{ambient}$

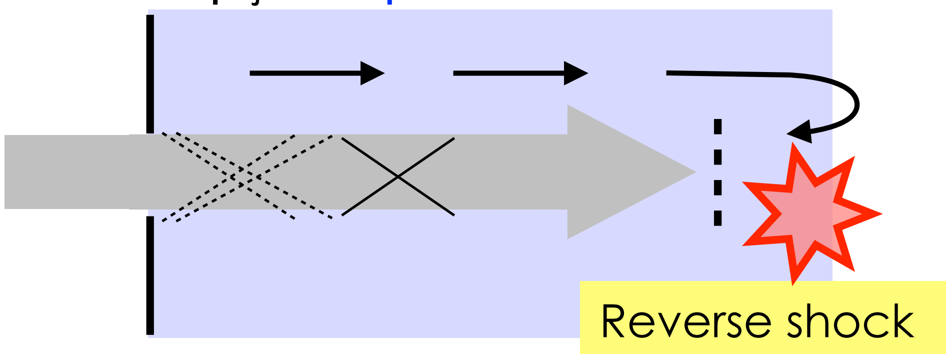


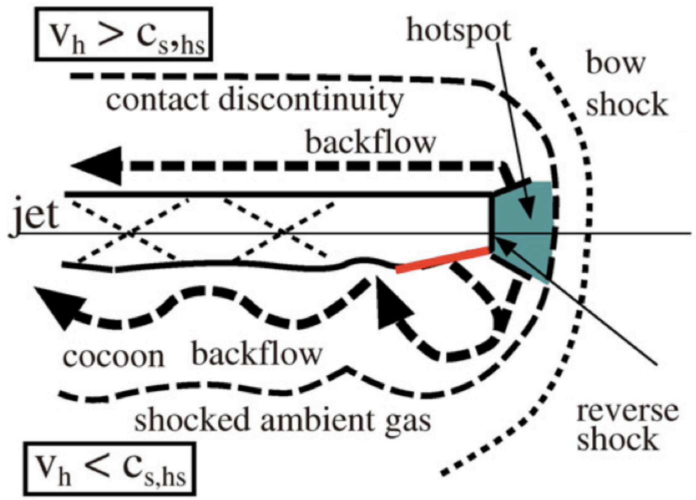
- Shock-train decelerates the flow



- (b) Under-expanded flow

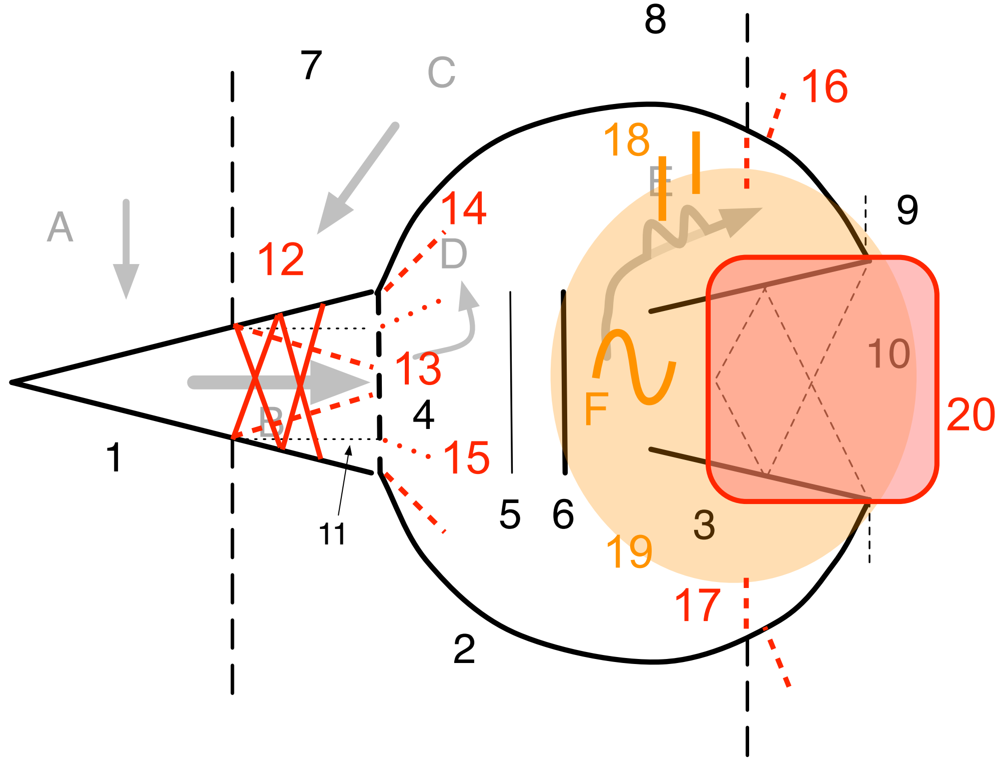
$p_{jet} > p_{ambient}$





A complete catalog of plasmoid structure (2015)

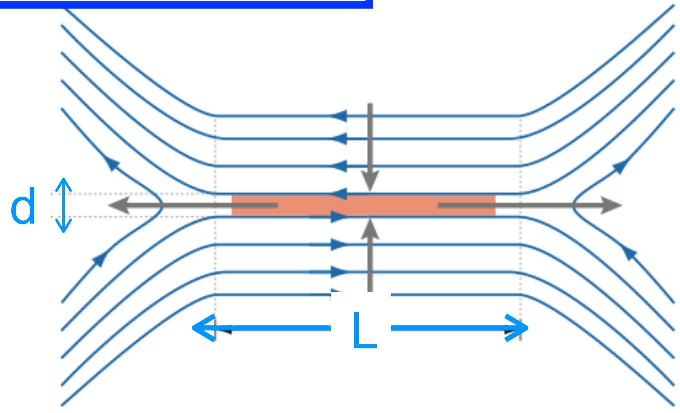
A. reconnection inflow
B. outflow jet
C. post-plasmoid backward flow
D. internal flow
E. flapping jet (KH instability)
F. current-sheet kinking (KH instability) (Wada & Nitta?)



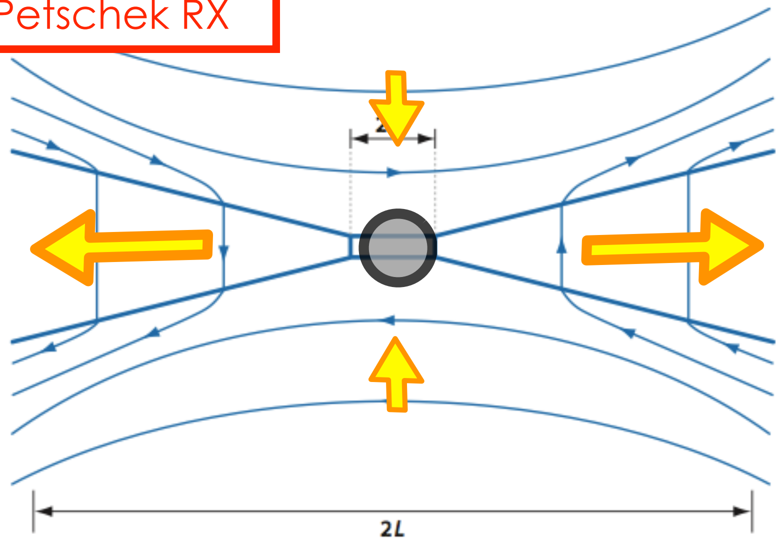
1. Petschek slow shock (Petschek 1964)
2. outer shell = slow shock (Ugai 1995 PoP)
3. intermediate shock (Abe & Hoshino 2001 EPS)
4. fast shock (Forbes & Priest 1983 SoP)
5. loop-top front (Ugai 1987 GRL)
6. tangential discontinuity
7. post-plasmoid vertical slow shock (Zenitani+ 2010 ApJ)
8. outer vertical slow shock (Zenitani & Miyoshi 2011 PoP)
9. fast-mode wave front (Saito et al. 1995 JGR)
10. **overexpanded shock-diamond (Zenitani+ 2010 ApJ)**
11. contact discontinuity (Zenitani & Miyoshi 2011 PoP)
12. **underexpanded shock-diamond**
13. **slow expansion wave**
14. **contact discontinuity**
15. **contact discontinuity**
16. **preshock?**
17. **contact discontinuity**
18. vortex-driven shock
19. inner shell
20. **pseudo shock**

Plasmoid-dominated reconnection

1. Sweet-Parker RX

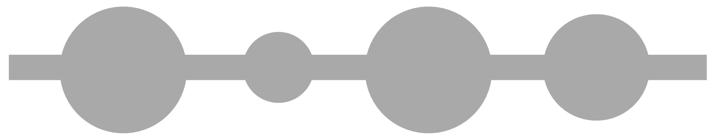


2. Petschek RX

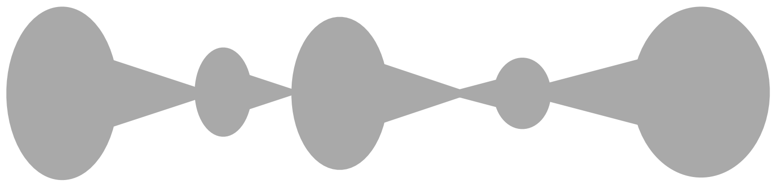


$L/d > 10^2$

3. Plasmoid-dominated RX

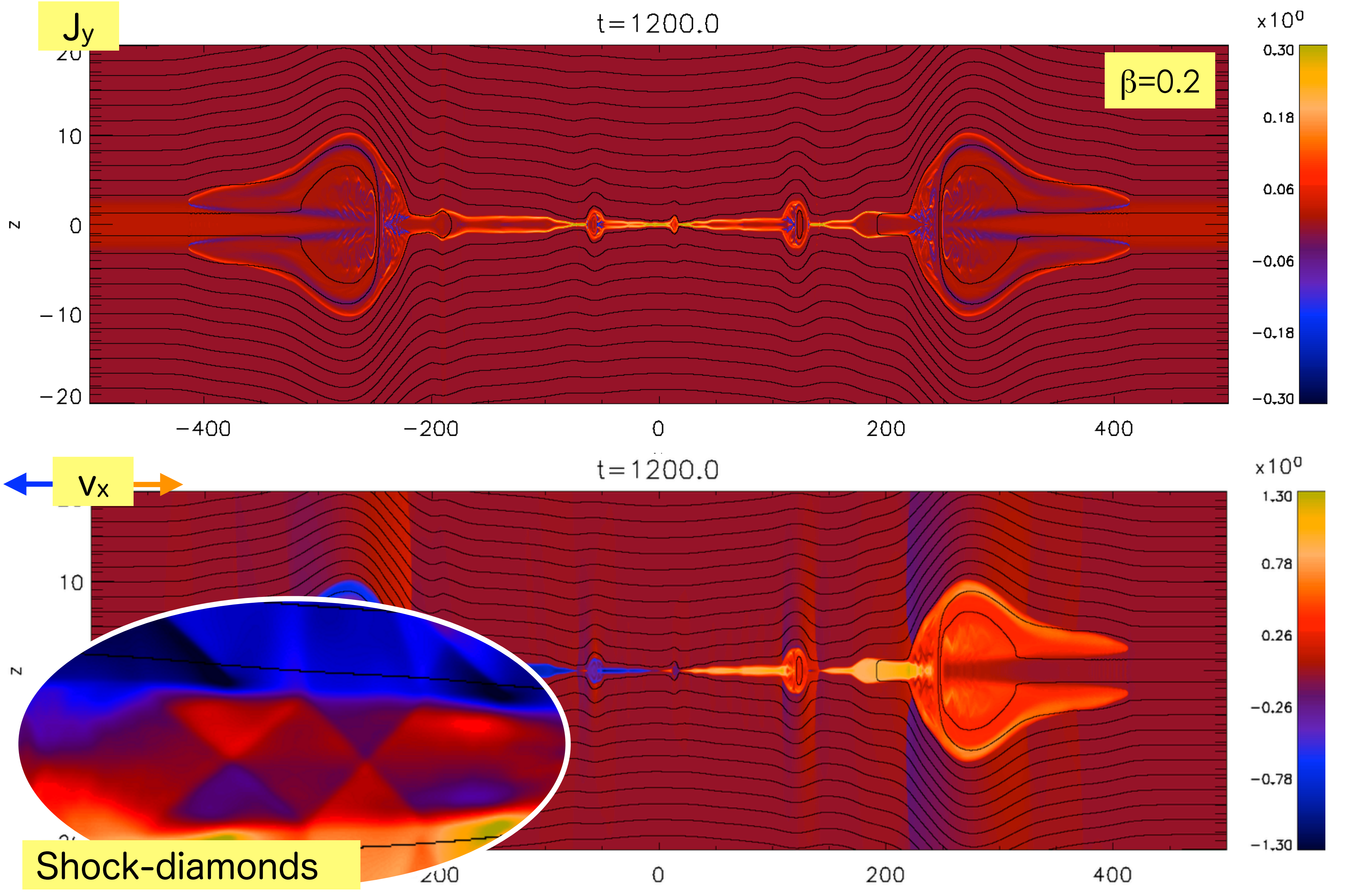


Loureiro 2007, Bhattacharjee 2009



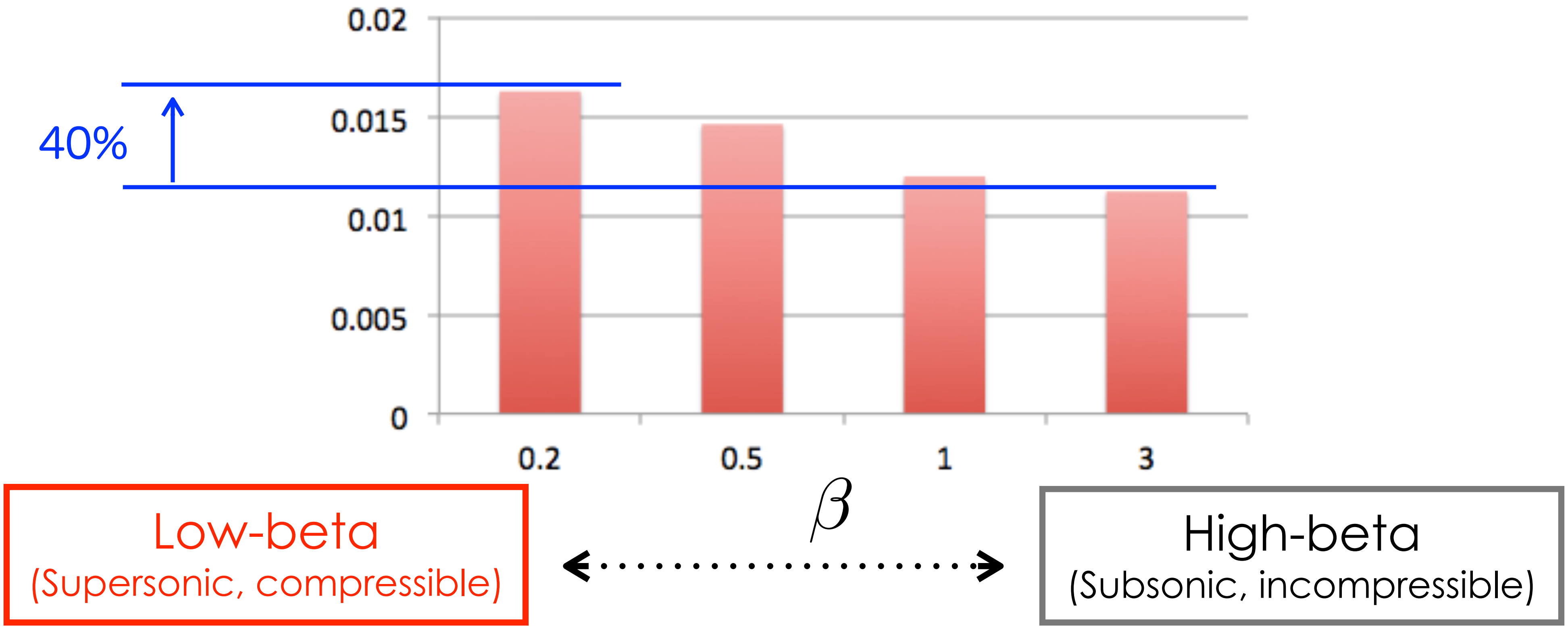
Nakabo & Kusano 2013, Baty 2012

Normal shocks in plasmoid-dominated RX



Flux transfer rate

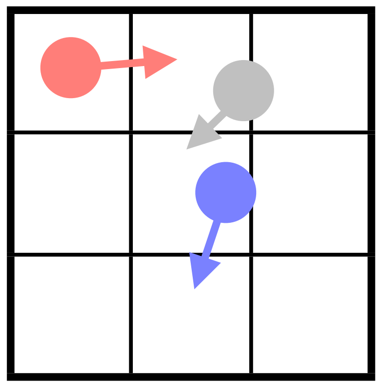
Compressible effects?
(shock dissipation, wave-drag etc.)



- Low-beta reconnection may be faster
- This deserves further investigation

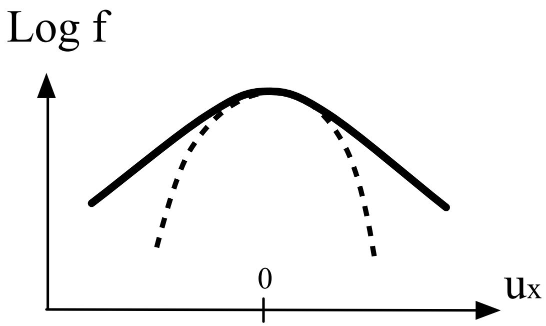
Loading algorithms for relativistic particle distributions

[SZ 2015b]



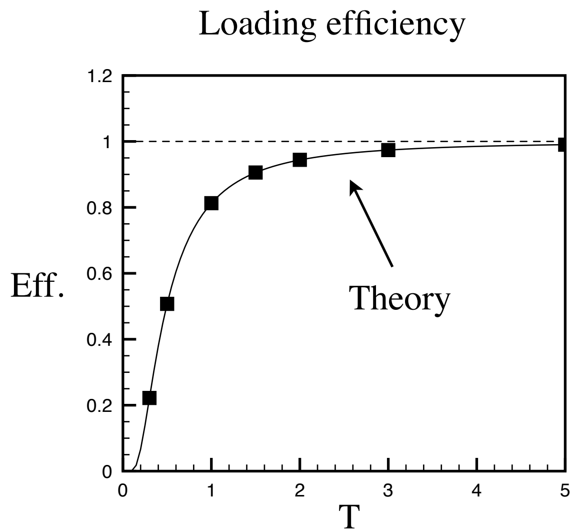
- Jüttner-Synge distribution function (Relativistic Maxwellian)

$$f'(\boldsymbol{u}') = \frac{N}{4\pi T K_2(1/T)} \exp\left(- \frac{\Gamma(\gamma' - \beta u'_x)}{T} \right)$$



- Sobol (1976)'s algorithm for Γ=1, β=0

$$(\eta'')^2 - (\eta')^2 > 1$$



- Proposed in a Russian proceeding
- Mathematical proof - confirmed
- Generalized for $\Gamma \neq 1$, $\beta \neq 0$
- Some analysis

Loading algorithms for relativistic particle distributions

Part of Swisdak (2013) algorithm

Algorithm: Generate a random variate for f, a log-concave distribution function

Require: p_m is the mode of f
p_+ and p_- satisfy $f(p_\pm) = f(p_m)/e$
$\lambda_+ \leftarrow -f(p_+)/f'(p_+)$, $\lambda_- \leftarrow f(p_-)/f'(p_-)$ {can be re-written in terms of $(\log f)'$}
$q_- \leftarrow \frac{\lambda_-}{p_+ - p_-}$, $q_+ \leftarrow \frac{\lambda_+}{p_+ - p_-}$, $q_m \leftarrow 1 - (q_+ + q_-)$
repeat
generate U and V, uniform variates on [0, 1]
if $U \leq q_m$ **then**
$Y \leftarrow U/q_m$
$X \leftarrow (1 - Y)(p_- + \lambda_-) + Y(p_+ - \lambda_+)$
if $V \leq f(X)/f(p_m)$ **then**
done
end if
else if $U \leq q_m + q_+$ **then**
$E \leftarrow -\log\left(\frac{U - q_m}{q_+}\right)$
$X \leftarrow p_+ - \lambda_+(1 - E)$
if $V \leq e^E f(X)/f(p_m)$ **then**
done
end if
else
$E \leftarrow -\log\left(\frac{U - (q_m + q_+)}{q_-}\right)$
$X \leftarrow p_- + \lambda_-(1 - E)$
if $V \leq e^E f(X)/f(p_m)$ **then**
done
end if
end if
until done
return X

Sobol=Zenitani algorithm

Summary

- We have investigated the MHD structure of the reconnection-plasmoid system in detail

- They are the outcome of <u>high-speed (compressible) fluid effects</u> in low-β regimes
  - (Adiabatic acceleration)
  - Recompression shock
  - Shock diamonds, pseudo-shock

$$\beta \propto \mathcal{M}^{-2}$$

- Analogy with jet physics
- Compressible effects may speed-up plasmoid-RX

- Zenitani & Miyoshi, *Phys. Plasmas* **18**, 022105 (2011)
- Zenitani, *Phys. Plasmas* (2015a) - MHD plasmoid
- Zenitani, *Phys. Plasmas* (2015b) - Algorithm for kinetic simulation