THE INTERACTION OF TURBULENCE WITH THE HELIOSPHERIC SHOCK

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Heliospheric observations

- Heliosheath expected to be turbulent [1], the result of upstream turbule ... density enhanc ... nd interac

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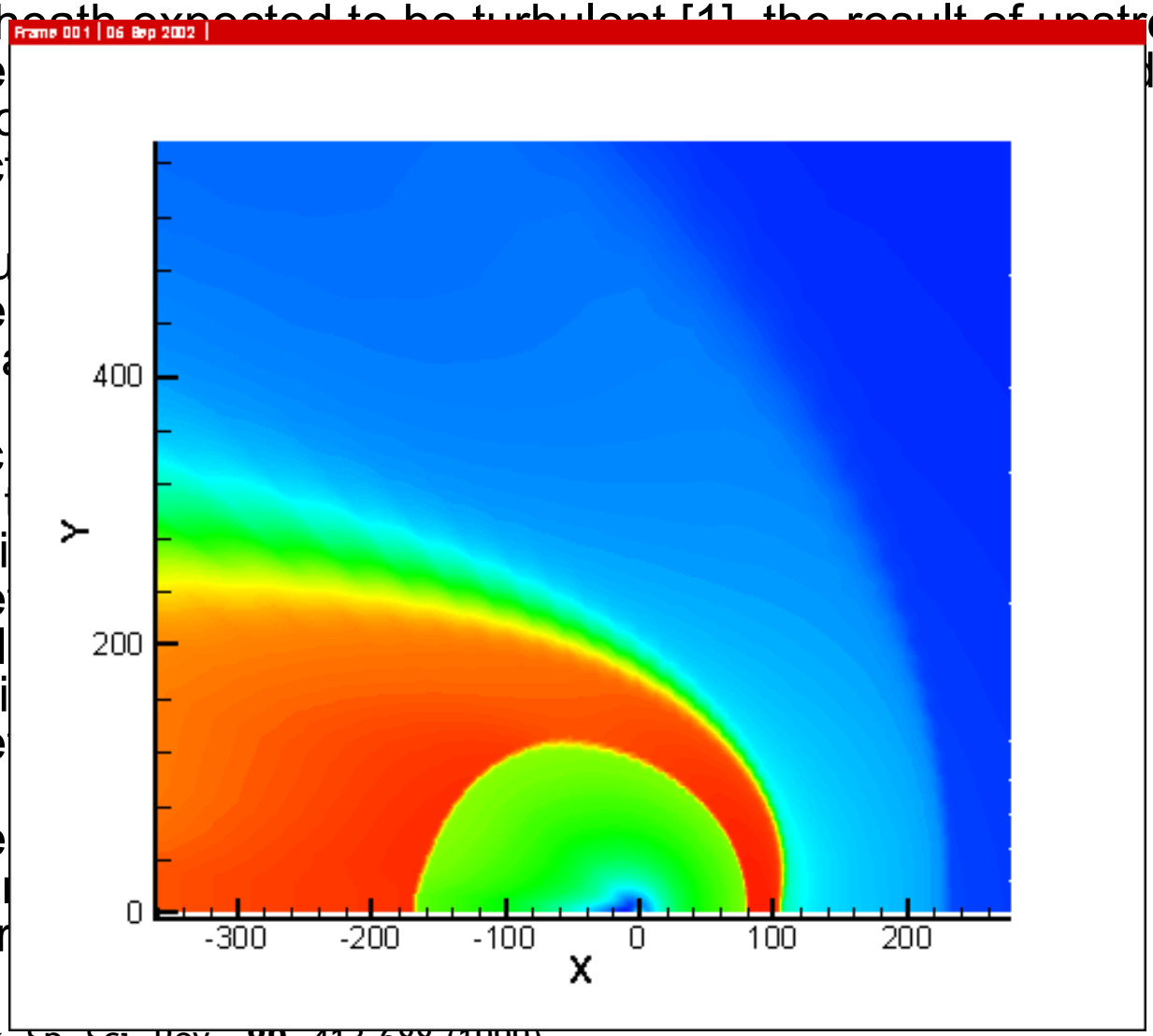
- 48-sec ... ed by [3] reveal ... s a Gaussi ... e magne ... he log-normal ... ne Gaussi ... f the magne

- The se ... substa ... ges of **B** is greater



1. G. P. Zank, Sp. Sci. Rev., **89**, 413-688 (1999).
2. T. R. Story, and G. P. Zank, JGR, A8, 17381 (1997); Zank & Mueller, JGR, 2003.
3. L. F. Burlaga, N. F. Ness, M. H. Acuña, ApJ., 642, 584B (2006)

Burlaga, Ness, and Acuna, ApJ, 2005

averages of B, λ, and δ from 2005 DOY 50–70 shown in Figure 5. Turbulence in the solar wind (Coleman 1968; Sari & Ness 1969) has a very small compressive component (Burlaga & Turner 1976). The turbulence has been treated as a quasi-two-dimensional and nearly incompressible fluid (Bruno & Carbone 2005; Zhou et al. 2004; Marsch 1992; Matthaeus et al. 1990; Zank & Matthaeus 1992). In the heliosheath, the opposite is observed; the fluctuations in the magnetic field strength B are large.

The distribution of the 48 s averages of B in interval B of Figure 2 (2005 DOY 50–70) is shown by the points in Figure 6*a*. A Gaussian fit to the points (Fig. 6*a*, *solid curve*, representing eq. [1]) and the 95% confidence band (shown by the dashed curves) indicate that B in this 20 day interval has a Gaussian distribution. The width of the B distribution gives $\sigma = 0.030 \pm 0.002$ nT, demonstrating that B has a broader distribution than the components, for which $\sigma = (0.023 \pm 0.002)$ nT. This shows that the turbulence is primarily compressible.

The turbulence in the heliosheath in interval B (Fig. 2) is isotropic, as shown by the distributions of $B_i - \langle B_i \rangle$, $i = R, T, N$ given by the points in Figure 6*b*. A single Gaussian fit to the points in all three of the distributions (Fig. 6*b*, *solid curve*) fits the distributions of the fluctuations of B_R, B_T, and B_N very well

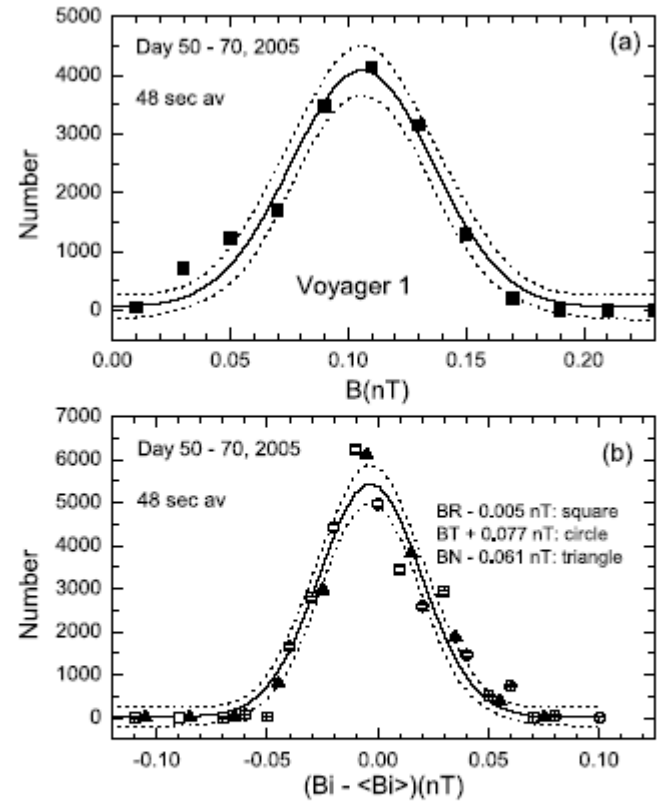


FIG. 6.—(*a*) *Squares*: Distribution of the 48 s averages of the magnetic field strength measured in the sector from 2005 DOY 50–70. The solid curve, a Gaussian fit to the observations, shows that the fluctuations of the magnetic field strength are Gaussian. (*b*) *Points*: Distributions of the 48 s average components of the magnetic field minus their mean values observed from 2005 DOY 50–70. The solid curve is a Gaussian fit to the data, which illustrates that the fluctuations in $\boldsymbol{B}$ are isotropic.

- Clearly MHD turbulence in the inner heliosheath is different from that upstream of the HTS in the supersonic solar wind.

- Since the character of the turbulence is different immediately downstream of the HTS, it suggests that “processing” by the HTS plays an important role in modifying turbulent upstream fluctuations.

- There is little doubt that the subsonic, very hot plasma in the heliosheath will contribute to the distinctive turbulence observed by Voyager 1 but we need to understand the role of the HTS in providing the inner boundary or source for evolving turbulence in the heliosheath.

- *Explore physics and implicit numerical problems of interaction of turbulence with shock waves – basic physics not as well understood as one would like.*

- *Investigate the reaction of turbulence on shock structure.*

- *On the basis of a linear model, we examine the transmission, amplification, and generation of turbulence by the HTS.*

- *Put both together in simulations to examine assumptions and expectations*

Structure of shock in response to upstream turbulence

Hypersonic approximation corresponds to weak shock approximation

$$\frac{\partial u_{x1}}{\partial \tau} + \frac{f - \gamma g}{2}\frac{\partial u_{x1}}{\partial \xi} + \frac{\gamma - 1}{2} u_{x1}\frac{\partial u_{x1}}{\partial \xi} = \frac{\lambda}{2}\frac{\partial u_{y1}}{\partial \eta} + \frac{1}{2}\frac{\partial g}{\partial \tau}$$

$$\frac{\partial u_{y1}}{\partial \xi} = \frac{\partial}{\partial \eta}\left(u_{x1} - g\right)$$

$$\frac{\partial}{\partial \xi}\left(\frac{\partial u_{x1}}{\partial \tau} + \frac{f - \gamma g}{2}\frac{\partial u_{x1}}{\partial \xi} + \frac{\gamma - 1}{2} u_{x1}\frac{\partial u_{x1}}{\partial \xi}\right) = \frac{\lambda}{2}\frac{\partial^2}{\partial \eta^2}\left(u_{x1} - g\right) + \frac{\partial}{\partial \xi}\left(\frac{1}{2}\frac{\partial g}{\partial \tau}\right)$$

Two-dimensional Burger's equation

Pressure

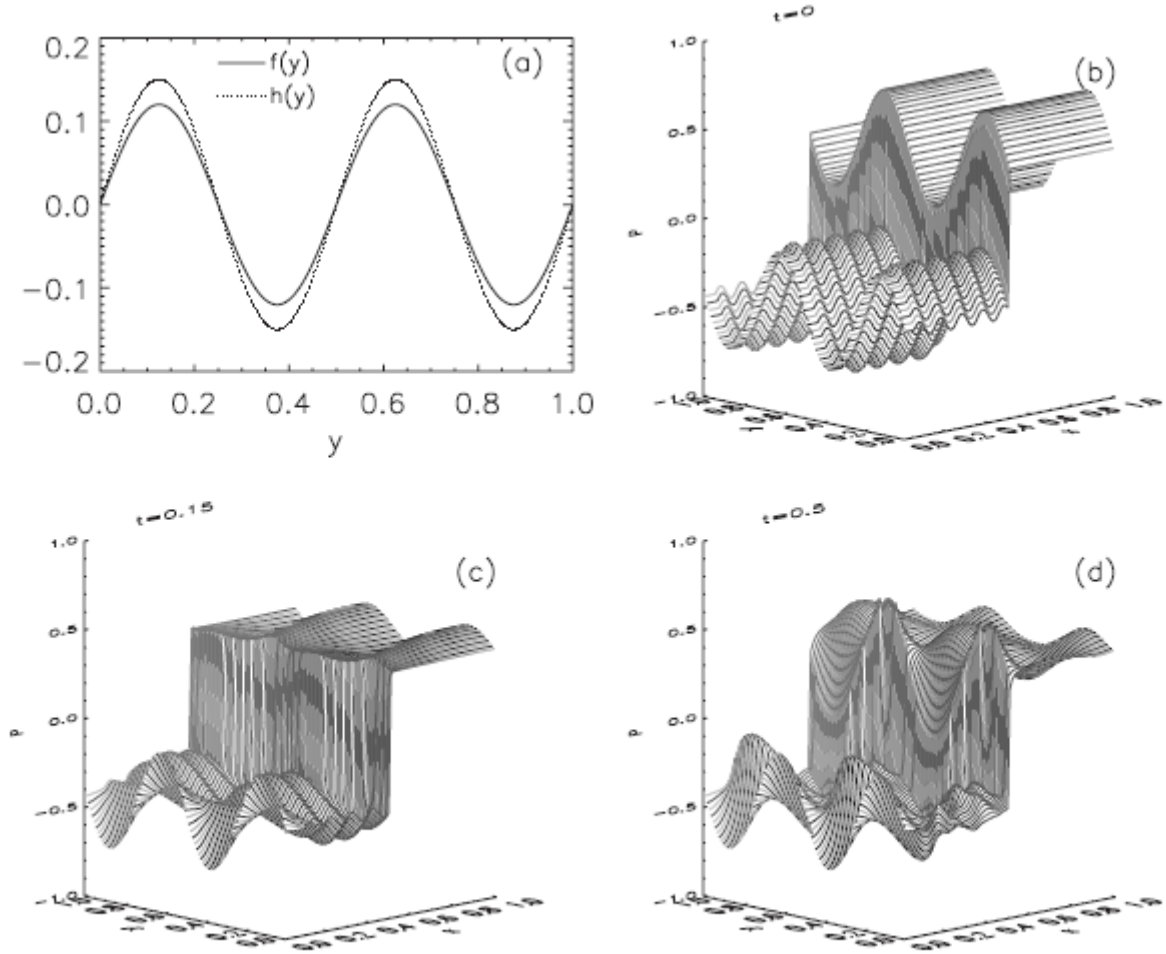


FIG. 2. Interaction between a fluctuating upstream state and a perpendicular MHD shock with $\gamma \approx 2$: (a) $f=0.12\sin(4\pi y)$ and $h=0.15\sin(4\pi y)$; (b) the initial condition; (c) the total pressure $p=p_1+B_{z_0}B_{z_1}/\mu$ profile in normalized units at time $t=0.15$; (d) the total pressure profile at time $t=0.5$.

Structural evolution of a perpendicular shock front, including “turbulent broadening” and “overshoots.”

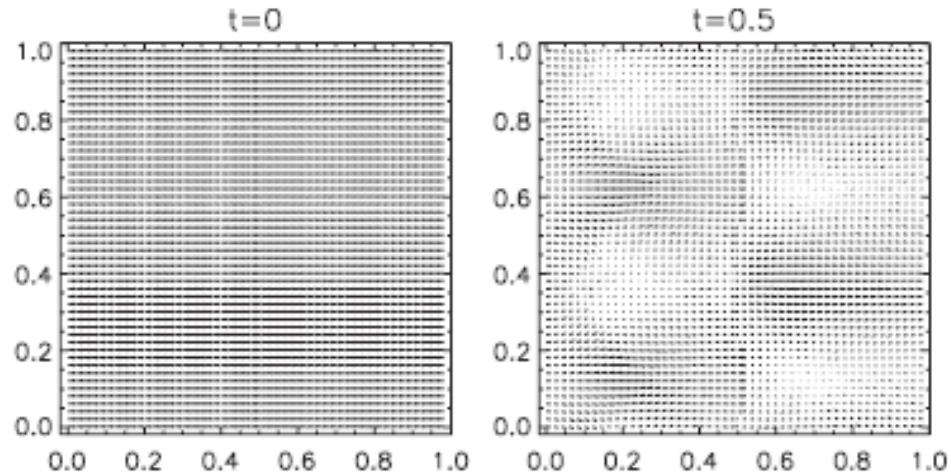


FIG. 4. Interaction between a fluctuating upstream state and a perpendicular MHD shock. Left panel: velocity vector of the initial condition. Right panel: velocity vector at $t=0.5$.

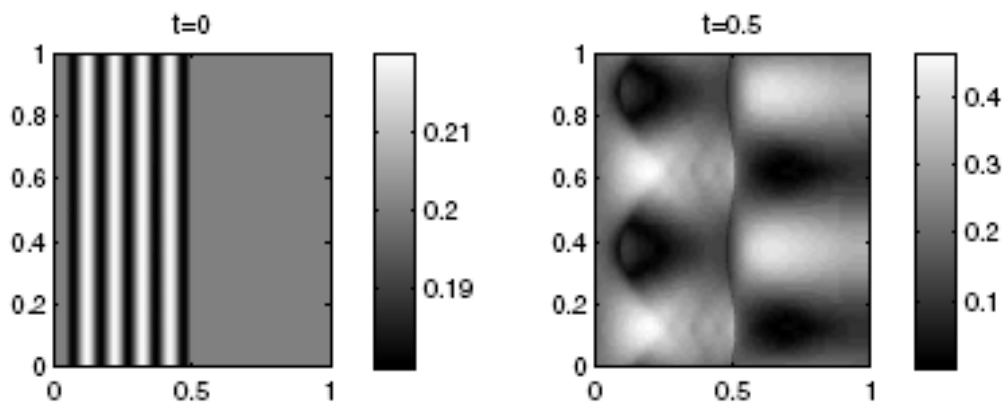


FIG. 5. Interaction between a fluctuating upstream state and a perpendicular MHD shock. Left panel: velocity magnitude of the initial condition. Right panel: velocity magnitude at $t=0.5$.

N-wave interacting with upstream sinusoidal fluctuations

Pressure

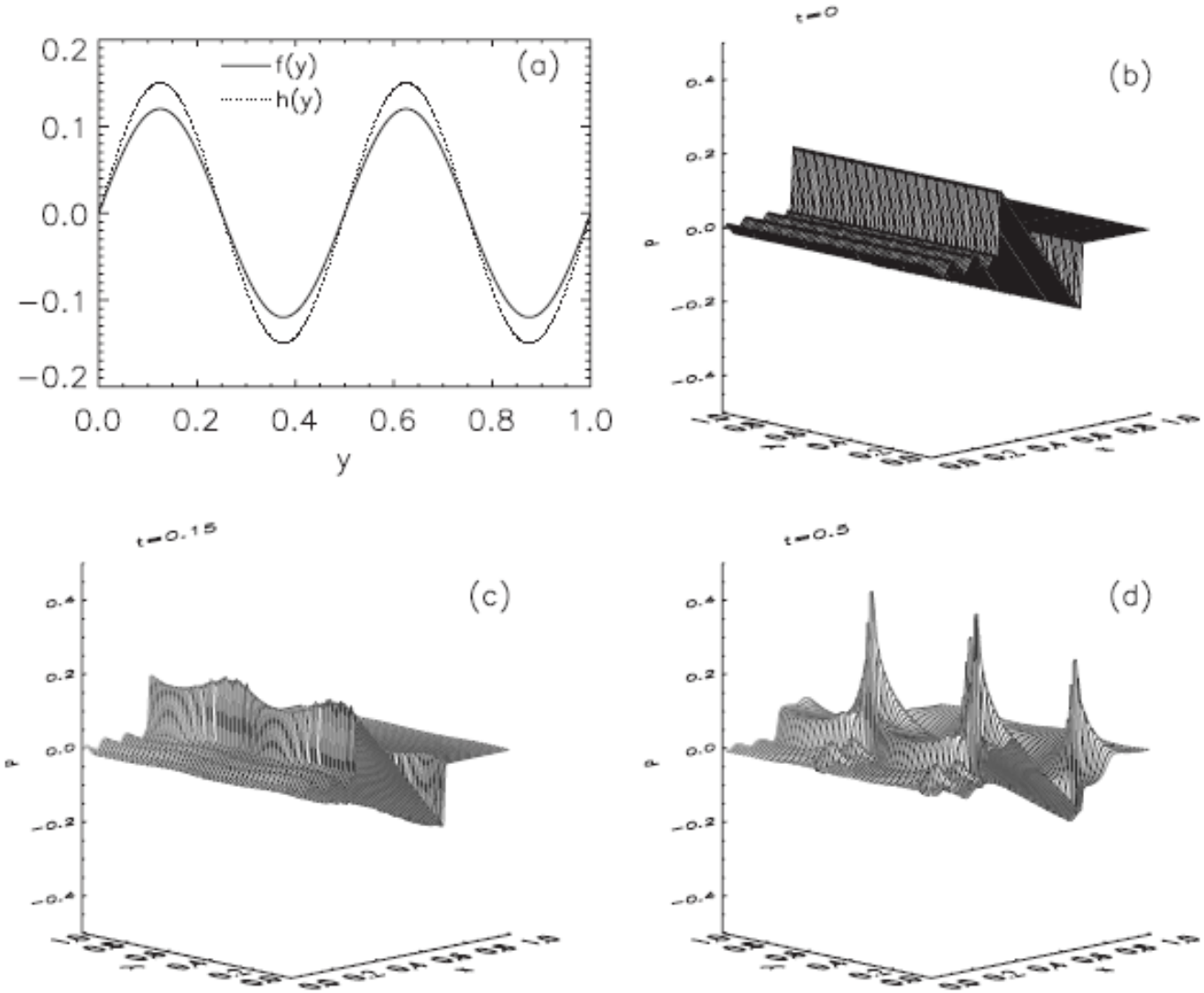


FIG. 10. Interaction between a fluctuating upstream state and a perpendicular MHD N-wave: (a) $f=0.12\sin(4\pi y)$ and $h=0.15\sin(4\pi y)$; (b) the initial condition; (c) the total pressure $p=p_1+B_{z_0}B_{z_1}/\mu$ profile at time $t=0.15$; (d) the total pressure profile at time $t=0.5$.

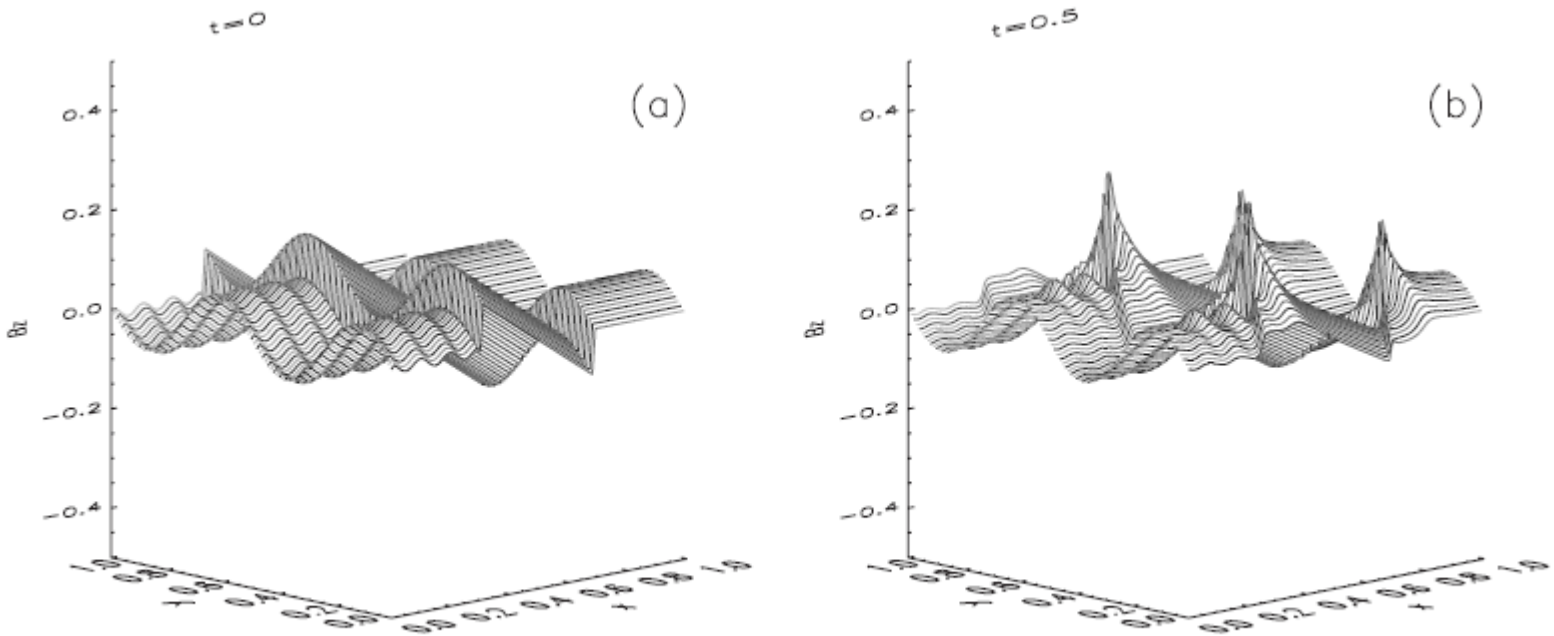


FIG. 11. Normalized magnetic field fluctuation B_z: (a) the initial magnetic field fluctuation B_z; (b) the magnetic field fluctuation B_z at time t=0.5.

MATHEMATICAL FORMULATION

- The interaction of upstream waves with a shock wave has been investigated in several papers, some of the most important of which are those by McKenzie & Westphal [4], Scholer & Belcher [5], Achterberg et al. [6], and Vainio & Schlickeiser [7], Ribner [8]

- With the exception of [4] and [6], these papers all focus on the reduced 2D problem of a fast shock interacting with an Alfvén wave when what is really needed is the interaction of an upstream fully turbulent spectrum of fluctuations interacting with a 3D shock wave.

- This problem is prohibitively difficult analytically for the full MHD problem but it can be solved hydrodynamically.

- Some numerical investigations: Balsara (supersonic interstellar turbulence), Jackson et al., Lele (hydrodynamics, aerodynamics), …

MHD JUMP RELATIONS

$$\left[B_n\right] = 0 \quad (1)$$

$$\left[\rho u_n\right] = 0 \quad (2)$$

$$\left[u_n \mathbf{B}_t - B_n \mathbf{u}_t\right] = 0 \quad (3)$$

$$\left[\rho u_n \left(\frac{1}{2}u^2 + w\right) + \frac{1}{4\pi}\left(B^2 u_n - \left(\mathbf{u}\bullet\mathbf{B}\right) B_n\right)\right] = 0 \quad (4)$$

$$\left[\rho u_n^2 + P + \frac{B^2}{8\pi}\right] = 0 \quad (5)$$

$$\left[\rho u_n \mathbf{u}_t - \frac{1}{4\pi} B_n \mathbf{B}_t\right] = 0 \quad (6)$$

$$w = \frac{\gamma}{\gamma - 1}\frac{P}{\rho}$$

MATHEMATICAL FORMULATION – cont.

- In equations (1) - (6), we use a single-fluid description for the solar wind plasma, essentially assuming that interstellar PUIs co-move with the solar wind flow. This is certainly a reasonable assumption. It is further straightforwardly estimated that the pressure contribution of PUIs in the far outer heliosphere far exceeds the thermal solar wind pressure (e.g., *Zank et al.,* [9]), making for a high plasma beta state ahead of the HTS. Observations of pressure-balanced structures by *Burlaga et al.,* [10] indicate the dominance of the PUI pressure in the outer heliosphere.

- Thus, the total pressure P in the one-fluid model (1) - (6) may be regarded as the PUI pressure.

- The adiabatic index γ must therefore reflect the PUI distribution. γ can vary between 5/3 and 2 for PUIs.

- For a bispherical PUI distribution, $\gamma = 5/3$ whereas for an unscattered ring-beam distribution, $\gamma = 2$. We will assume that because the scattering mfp is long, the PUI gas satisfies $\gamma = 2$.

MATHEMATICAL FORMULATION – cont.

- For a perpendicular shock wave, $u_n \neq 0$, $B_n = 0$, and the jump conditions are

$$[\rho u_n] = 0 \quad [\rho u_n \mathbf{u}_t] = 0 \quad \left[\rho u_n^2 + P + \frac{B^2}{8\pi}\right] = 0$$

$$\left[\frac{1}{2}u^2 + w + \frac{1}{4\pi}\frac{B^2}{\rho}\right] = 0 \quad [B/\rho] = 0$$

- Observe that if we use $\gamma = 2$ and introduce $P^* = P + B^2/8\pi$ we immediately obtain

$$[\rho u_n] = 0 \quad [\rho u_n \mathbf{u}_t] = 0 \quad \left[\rho u_n^2 + P^*\right] = 0 \qquad (7)$$

$$\left[\frac{1}{2}u^2 + \frac{2P^*}{\rho}\right] = 0 \quad [B/\rho] = 0 \qquad (8)$$

- Structurally identical to the usual hydrodynamic jump conditions with a magnetic field contribution to the total pressure P* (i.e., P* is the sum of the PUI and magnetic pressures). “Sound speed" for system is fast mode speed for waves propagating perpendicularly to the magnetic field

$$V_\perp^2 = 2P^*/\rho = 2P/\rho + 2B^2/(8\pi\rho) = C_s^2 + V_A^2$$

HIGH-BETA PLASMA/HYDRO. MODEL

- Consider the interaction of fluctuations with oblique shock wave. Classical problem, beginning with Ribner [2] and McKenzie & Westphal [1].

- Reconsider using a somewhat more general formulation which has advantage of indicating how to develop a non-linear model.

- For simplicity, consider the interaction of entropy fluctuations with a shock wave.

1. J. F. McKenzie and K. O. Westphal, P&SS, 17, 1029 (1969)
2. H.S. Ribner, Report 1164 1957, pp. 199–215; Report 1233, pp 683–701

HIGH-BETA PLASMA/HYDRO. MODEL

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \mathbf{u} \right) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \bullet \left(\Pi \right) = 0$$

$$\frac{\partial}{\partial t}\left(\rho u^2 + \rho \varepsilon \right) + \nabla \bullet \left(\rho \mathbf{u} \left(\tfrac{1}{2} u^2 + w \right) \right) = 0 \quad \varepsilon = \frac{1}{\gamma - 1}\frac{P}{\rho} \quad w = \frac{\gamma}{\gamma - 1}\frac{P}{\rho}$$

$$\Pi_{ij} = P\delta_{ij} + \rho u_i u_j$$

2D plane $\quad \Pi = \begin{pmatrix} P + \rho u_x^2 & \rho u_x u_y \\ \rho u_x u_y & P + \rho u_y^2 \end{pmatrix}$

$$\frac{\partial}{\partial t}\left(\rho u_x \right) + \frac{\partial}{\partial x}\left(\rho u_x^2 + P \right) + \frac{\partial}{\partial y}\left(\rho u_x u_y \right) = 0$$

$$\frac{\partial}{\partial t}\left(\rho u_x \right) + \frac{\partial}{\partial x}\left(\rho u_x u_y \right) + \frac{\partial}{\partial y}\left(\rho u_{xy}^2 + P \right) = 0$$

HIGH-BETA PLASMA/HYDRO. MODEL

- Dispersion relation for hydrodynamics:

$$\omega' \equiv \omega - \mathbf{u}\bullet\mathbf{k}$$

$$\omega'^2\left(\omega'^2 - C_s^2 k^2\right) = 0$$

$$\omega' = 0$$

Entropy mode: $\delta\rho^e \neq 0 \qquad \delta\mathbf{u}^e = 0 \qquad \delta P = 0$

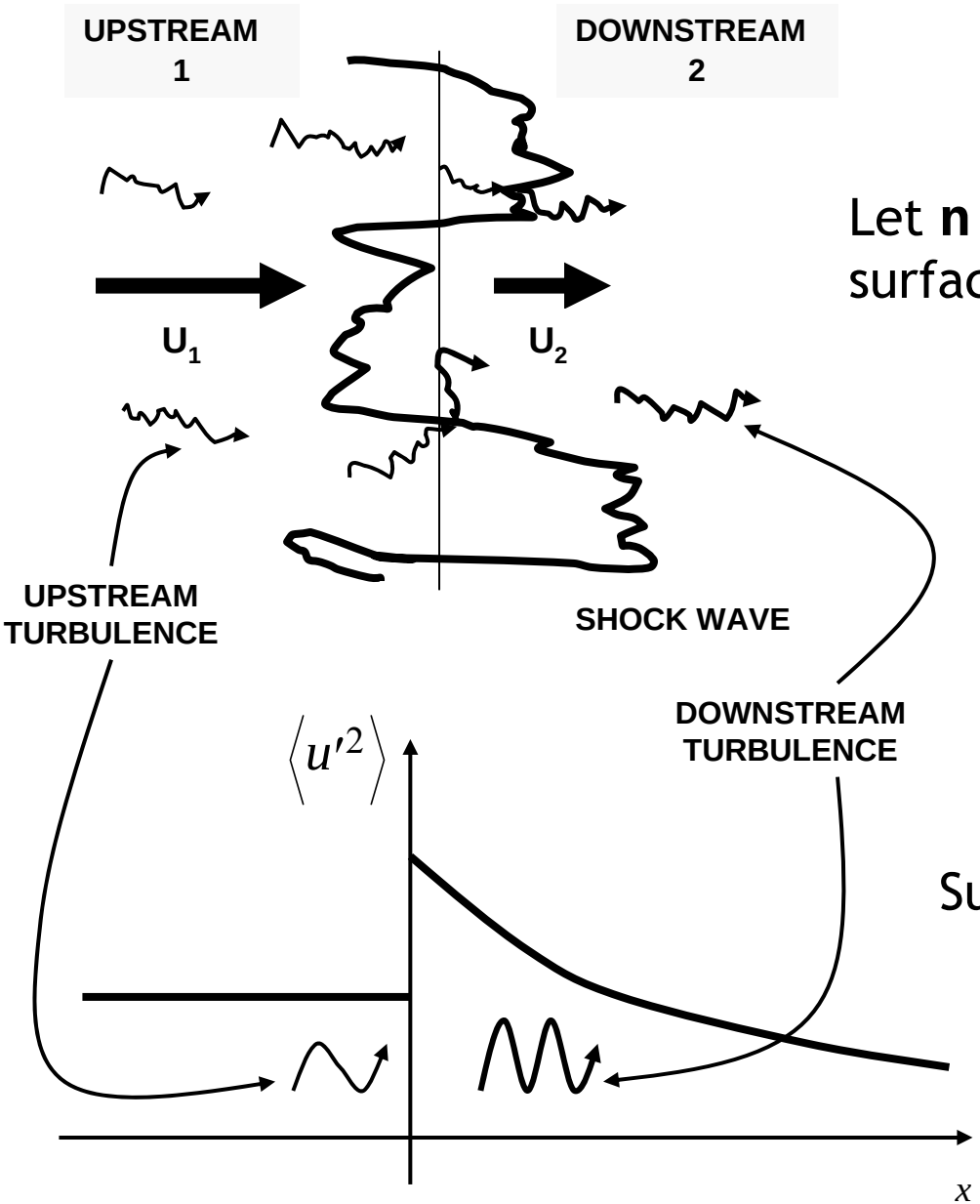
Vorticity mode: $\delta\rho = 0 \qquad \delta\mathbf{u}^v = \delta u^v\left(-\sin\phi^v, \cos\phi^v\right) \qquad \delta P = 0$

$$\omega'^2 = C_s^2 k^2$$

(Fast) Acoustic mode: $\delta\mathbf{u}^a = \pm C_s \dfrac{\delta\rho}{\rho}\left(\cos\phi^a, \sin\phi^a\right) \qquad \delta \mathrm{P}^a = C_s^2 \delta\rho^a \qquad \delta\rho^a \neq 0$

NB REMINDER: Recall that for this case $P^* = P + B^2/8\pi$

MATHEMATICAL FORMULATION – cont.



Let **n** denote the normal to the surface of discontinuity, defined by

$$\varphi(x,y,t) = x - \xi(y,t)$$

$\Rightarrow$ normal to surface given by

$$\hat{\mathbf{n}} = \frac{(\varphi_t, \underline{\varphi}_{\mathbf{x}})}{\sqrt{\underline{\varphi}_{\mathbf{x}} \bullet \underline{\varphi}_{\mathbf{x}}}} = \frac{(-\xi_t, 1, -\xi_y)}{\sqrt{1+\xi_y^2}}$$

Suppose eventually that

$$\xi = \xi_0 \exp i\left(k_y y - \omega t\right)$$

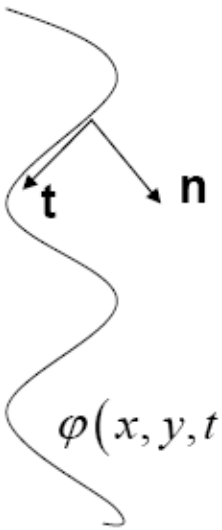
MATHEMATICAL FORMULATION – cont.

- For a system of conservation laws $$\frac{\partial \mathbf{U}}{\partial t} + \sum_j \frac{\partial}{\partial x_j} f_j(\mathbf{U}) = 0$$

the Rankine-Hugoniot conditions are given by

$$[\mathbf{U}]\varphi_t + \sum_j \left[f_j(\mathbf{U}) \bullet \varphi_{x_j} \right] = 0$$

Non-steady R-H conditions with shock front deformation:



$$\varphi(x,y,t) = x - \xi(y,t)$$

$$-[\rho]\xi_t + \left[\rho(u_x,u_y)\bullet(1,-\xi_y)\right] = 0$$

$$\Rightarrow \quad -[\rho]\xi_t + \left[\rho(u_x - u_y\xi_y)\right] = 0 \quad \text{(mass flux)}$$

$$-[\rho u_x]\xi_t + \left[\rho u_x(u_x - u_y\xi_y) + P\right] = 0 \quad \text{(normal momentum flux)}$$

$$-\left[\tfrac{1}{2}\rho u^2 + \rho\varepsilon\right]\xi_t + \left[\rho(u_x - u_y\xi_y)\left(\tfrac{1}{2}u^2 + w\right)\right] = 0 \quad \text{(energy flux)}$$

Yields the boundary condition: $\left[\mathbf{u}_t\right] = 0$

And now impose linearity i.e., $\xi_{y,t}^2 \ll 1$

$$\mathbf{u}_t = \mathbf{u} - u_n(1,-\xi_y) \simeq (u_y\xi_y, u_y + u_x\xi_y)$$

Five variable and 5 equations therefore well posed.

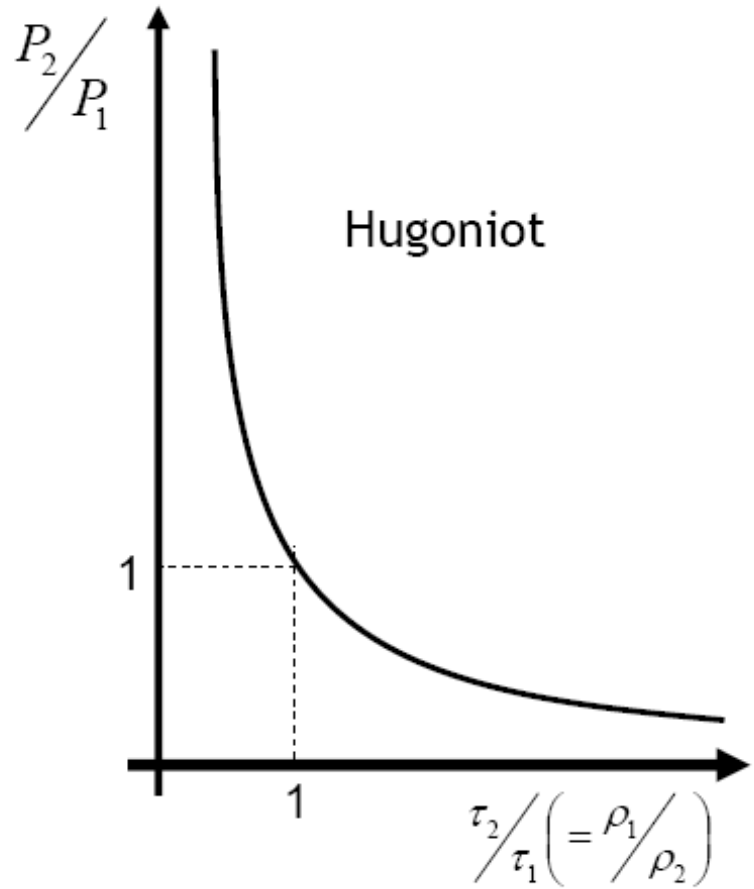
- Recover standard R-H conditions in steady frame i.e., $\xi_t = 0$

$$\left[\rho u_n\right] = 0$$

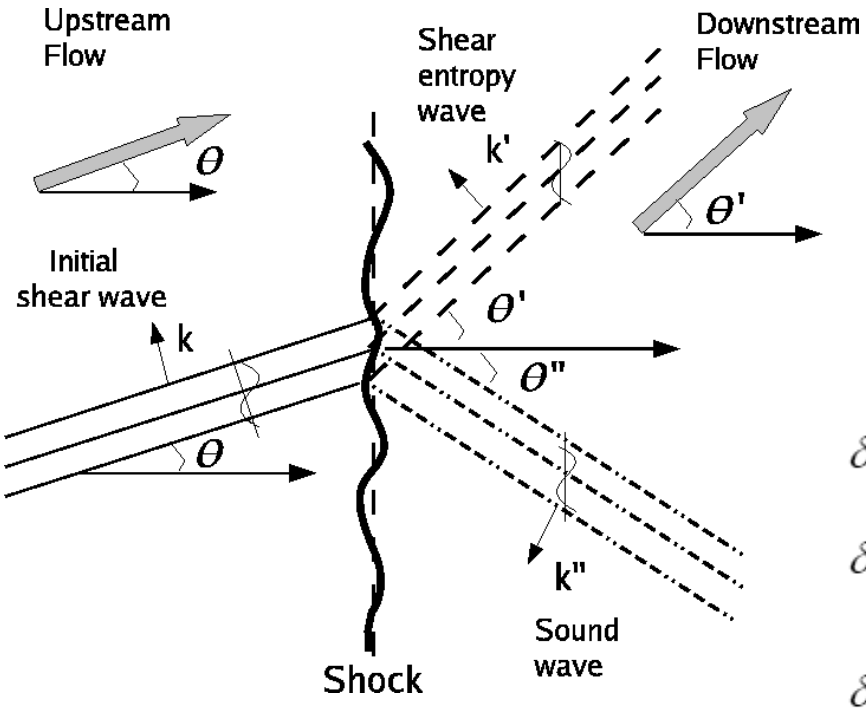
$$\left[\rho u_n^2 + P\right] = 0$$

$$\left[\mathbf{u}_t\right] = 0$$

$$\left[\tfrac{1}{2} u_n^2 + w\right] = 0$$



NB REMINDER: Recall that for this case $P^* = P + B^2/8\pi$



Consider simplest case of incident entropy wave:

$$\tau \equiv 1/\rho$$

Upstream: $\delta P_1 = 0 \quad \delta u_{x1} = \delta u_{y1} = 0 \quad \delta\tau_1 = \delta\tau_1^e$

$$\delta\tau_2 = \delta\tau_2^a + \delta\tau_2^e = \delta\tau_2\left(P_2; P_1, \tau_1\right)$$

$$\delta P_2 = \delta P_2^a = -C_{s2}^2 \frac{\delta\tau_2^a}{\tau_2^2}$$

$$\delta\mathbf{u}_2 = \delta\mathbf{u}_2^a + \delta\mathbf{u}_2^v = \pm\frac{\tau_2}{C_{s2}}\left(\alpha_2^a, \beta_2^a\right)\delta\rho_2^a + \delta u_2^v\left(-\beta_2^v, \alpha_2^v\right)$$

$$\left(\alpha_2^a, \beta_2^a\right) = \left(\cos\phi_2^a, \sin\phi_2^a\right) \quad \left(\alpha_2^v, \beta_2^v\right) = \left(\cos\phi_2^v, \sin\phi_2^v\right)$$

Downstream: Excites acoustic and entropy-vorticity waves:

$$\delta\tau_2 = \left(\frac{\partial\tau_2}{\partial P_2}\right)_H \delta P_2 + \left(\frac{\partial\tau_2}{\partial\tau_1}\right)_H \delta\tau_1 + \left(\frac{\partial\tau_2}{\partial P_1}\right)_H \delta P_1$$

$$= -\left(\frac{\partial\tau_2}{\partial P_2}\right)_H \frac{C_{s2}^2}{\tau_2^2}\delta\tau_2^a + \left(\frac{\partial\tau_2}{\partial\tau_1}\right)_H \delta\tau_1$$

NB REMINDER:
Recall that for this case $P^* = P + B^2/8\pi$

- Linear analysis of deformed shock front equations assuming perturbed shock front amplitude small. Very clear analysis of transmission and excitation of downstream fluctuations.

- Continuity of frequency and transverse wave number across deformed shock yields downstream propagation angles for transmitted and excited fluctuations.

- Can validate calculation numerically.

- Can impose upstream spectrum and calculate the downstream spectrum, ratio of compressive to incompressible fluctuations, distribution, anisotropy, amplification of incident turbulence.

- Note the generation of magnetic field at the shock.

VORTICITY-ENTROPY WAVE/SHOCK INTERACTION: Simulations

Simulate a two-dimensional interaction between a plane vorticity-entropy wave and a oblique shock wave.

Shock wave parameters: M – Mach number of upstream flow;
α – angle between shock wave and upstream flow.

Disturbed upstream flow:

$$\rho = \bar{\rho} + \bar{\rho} A_e \cos(k_x x + k_y y - k_t t)$$

$$u = \bar{u} + U A_v \sin\psi_1 \cos(k_x x + k_y y - k_t t)$$

$$v = \bar{v} - U A_v \cos\psi_1 \cos(k_x x + k_y y - k_t t)$$

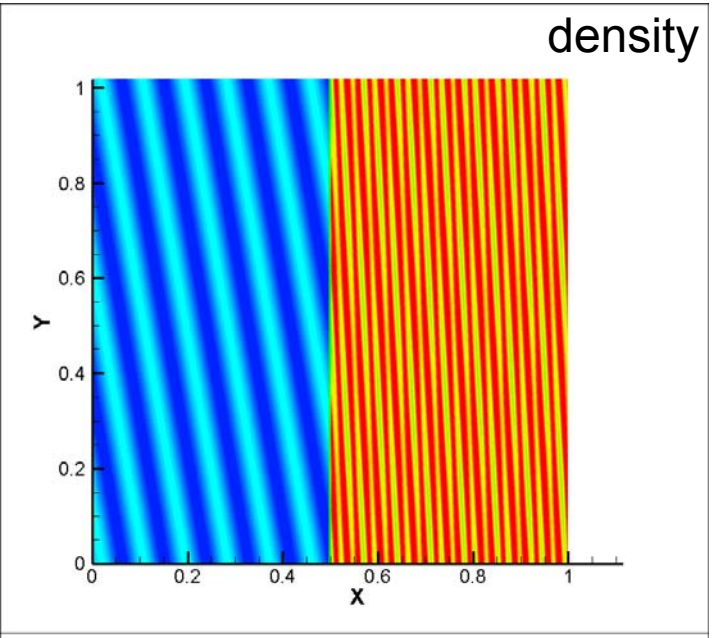
$$p = \bar{p}$$

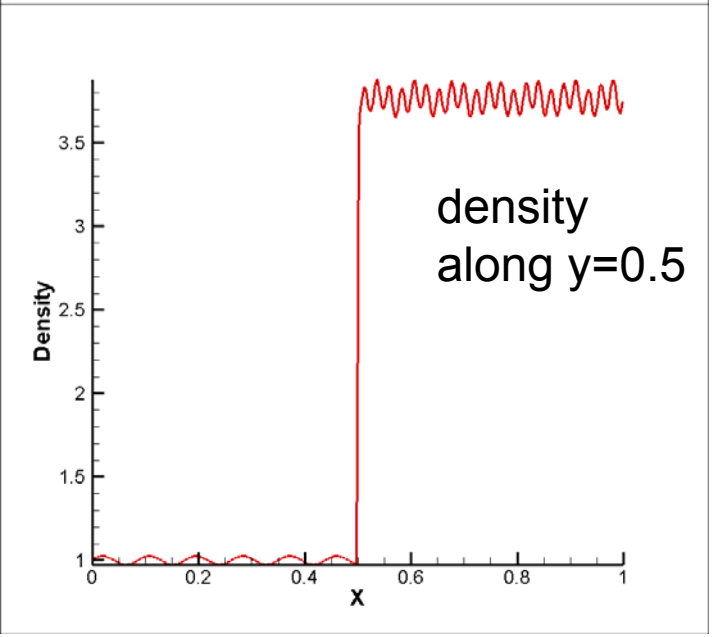
where

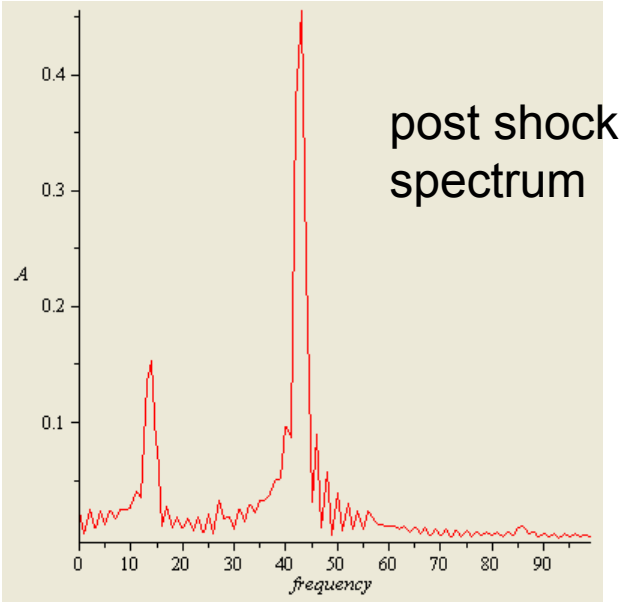
$$U = \sqrt{\bar{u}^2 + \bar{v}^2}, \quad k_t = k_x \bar{u} + k_y \bar{v}, \quad k_x = k\cos\psi_1, \quad k_y = k\sin\psi_1$$

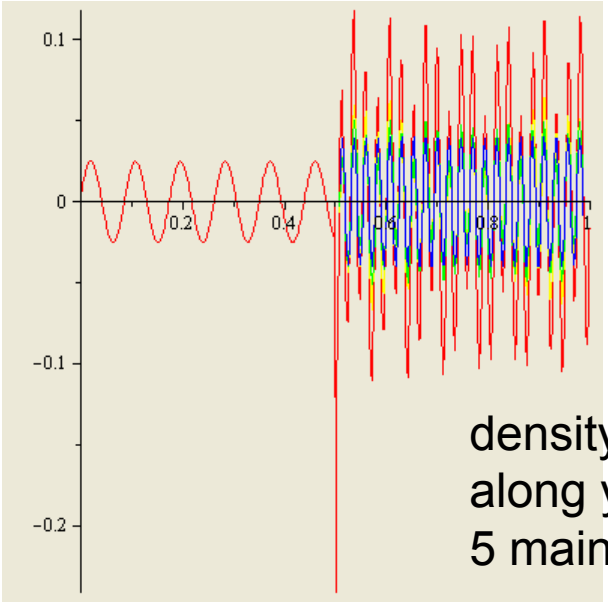
k is the magnitude of the wavenumber vector
ψ_1 denotes the angle between the wavenumber vector and x
A_v and A_e are intensity of velocity and density upstream of the shock wave.

Entropy wave A_e = 0.025, α = 90°, M = 2.9, k = 2, ψ=10°

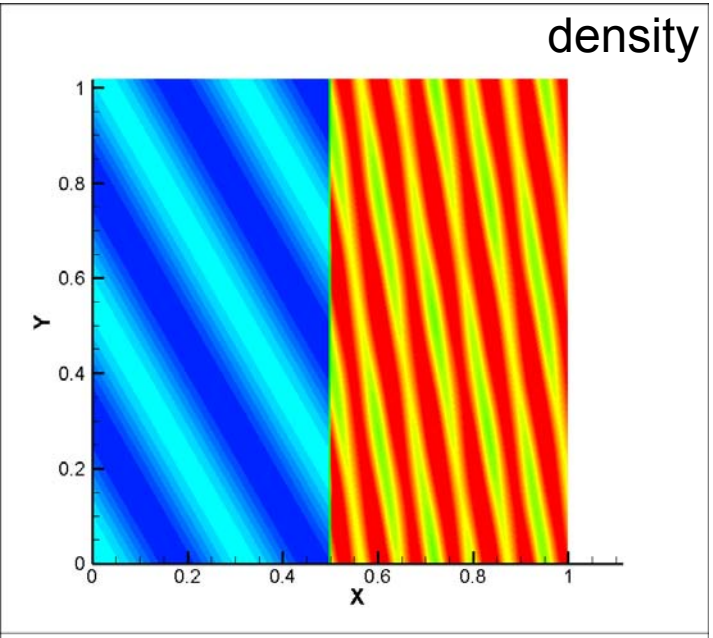


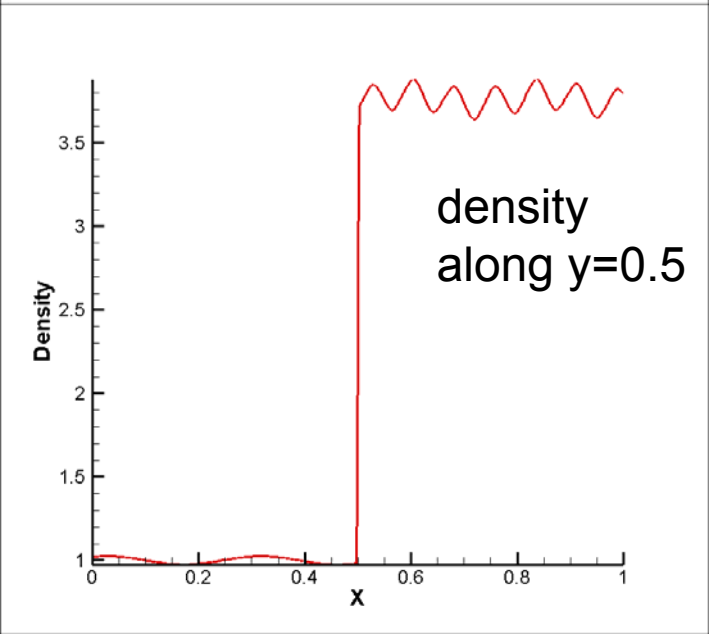


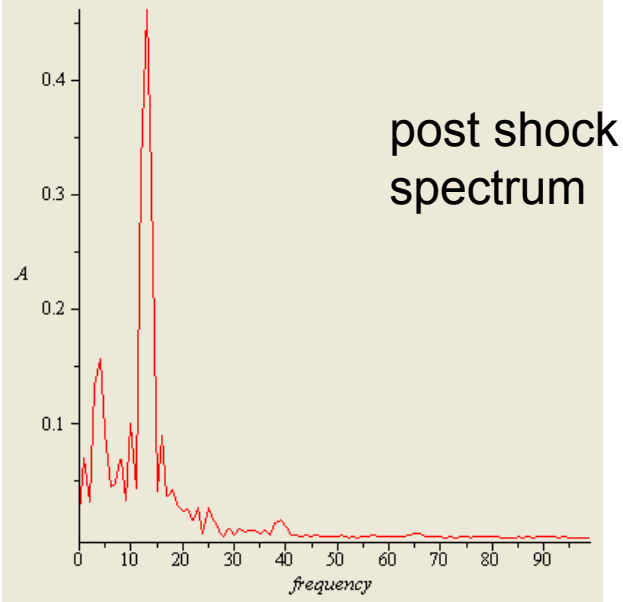


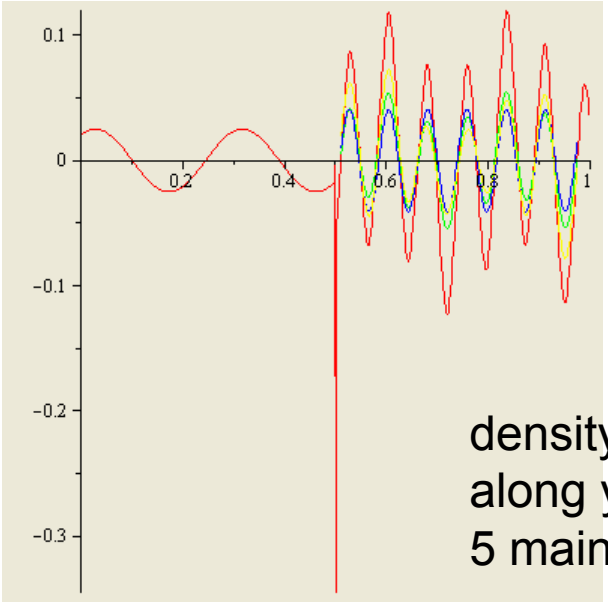


Entropy wave A_e = 0.025, α = 90°, M = 2.9, k = 2, ψ=30°

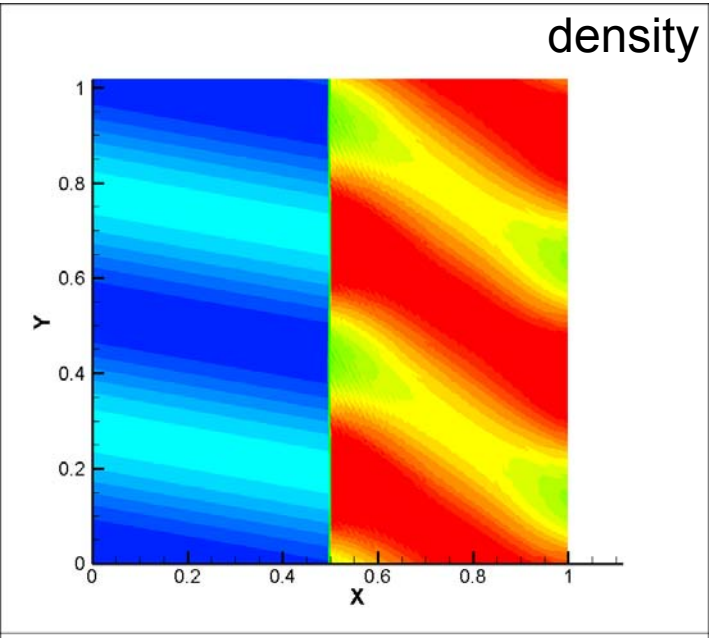


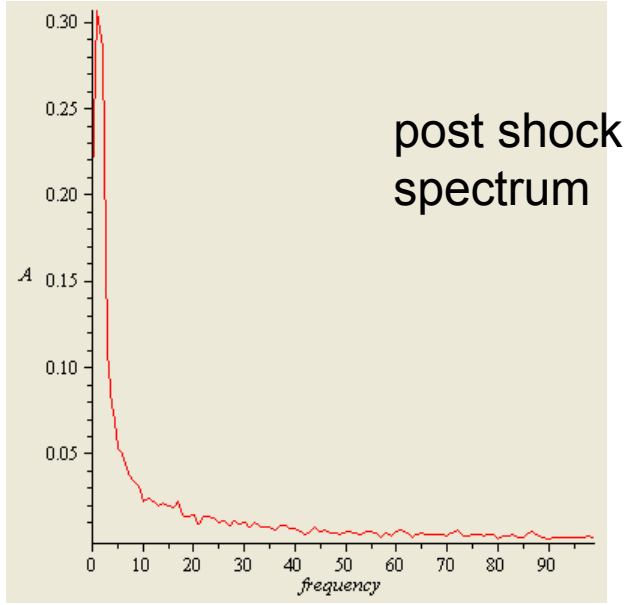


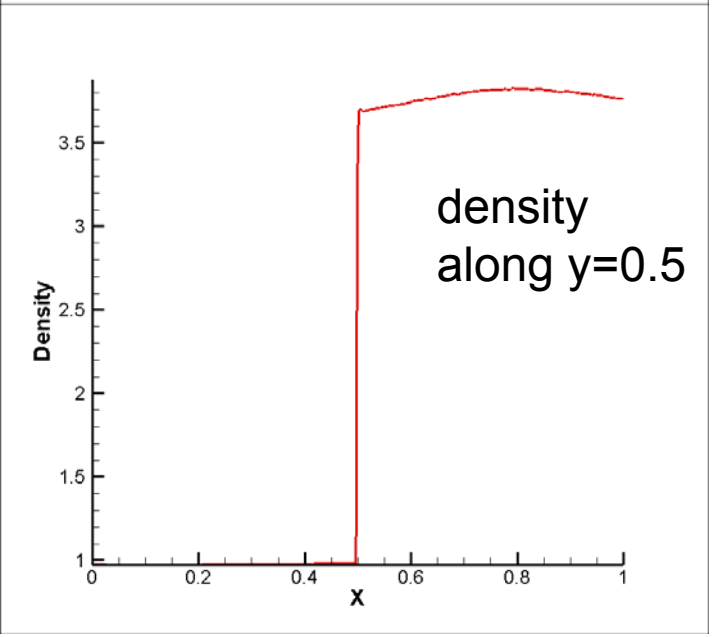


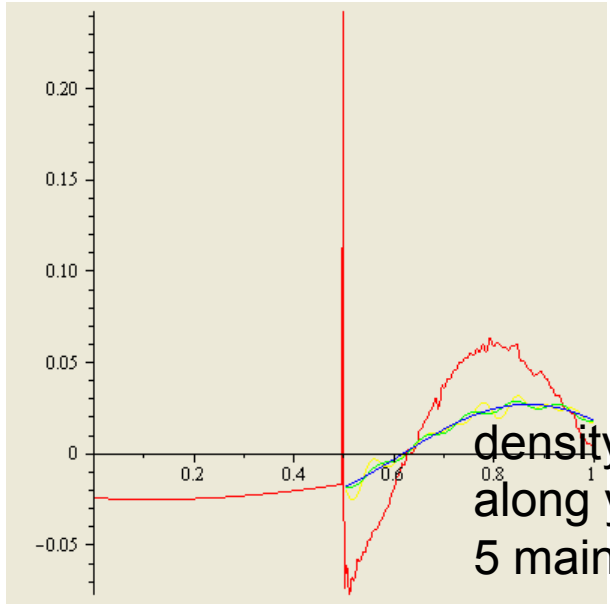


Entropy wave A_e = 0.025, α = 90°, M = 2.9, k = 2, ψ=80°



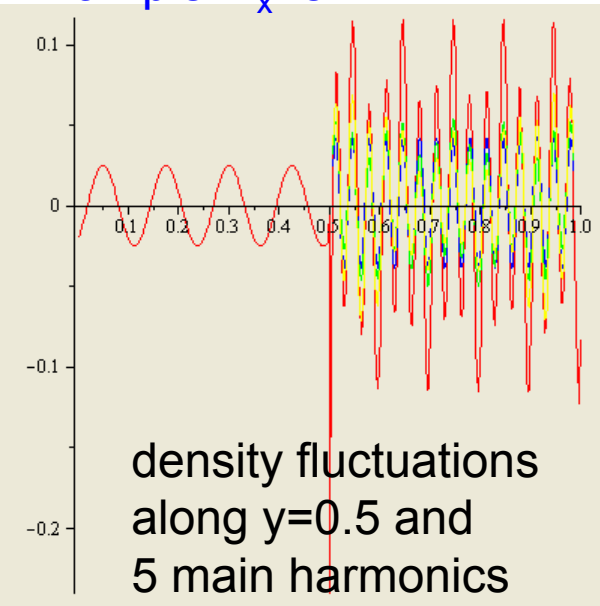


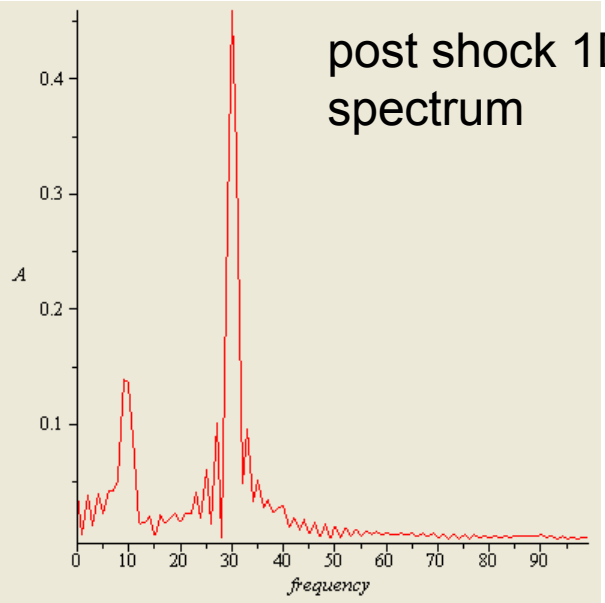


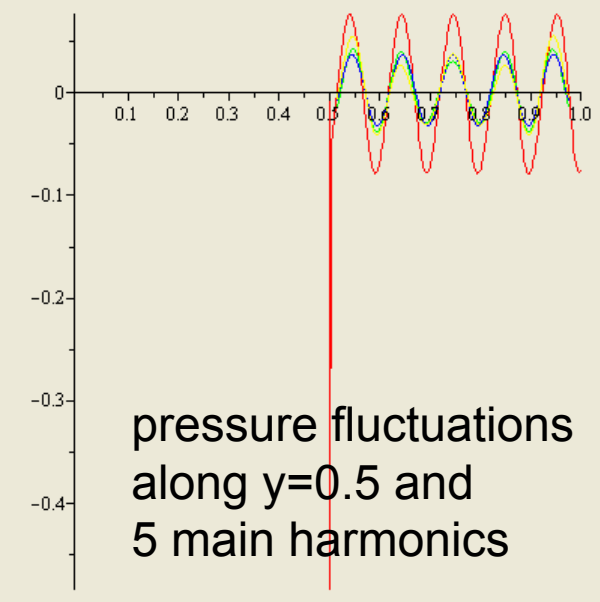


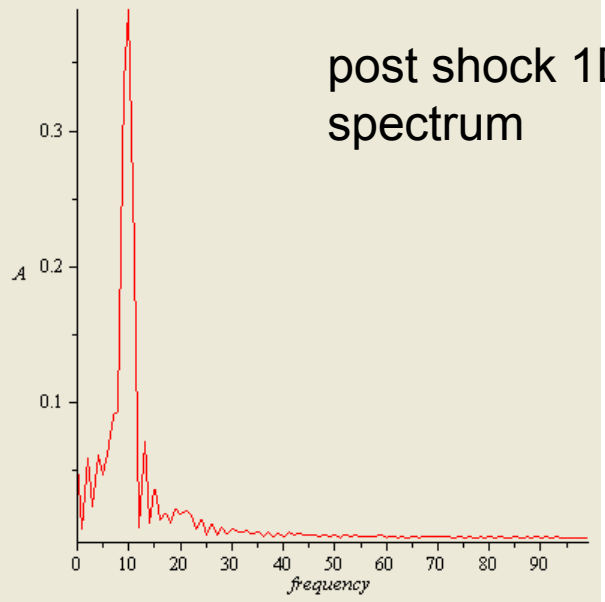
Entropy wave A_e = 0.025, α = 90°, ψ=0° vs. k_x (k_y=0)

Example: k_x=8

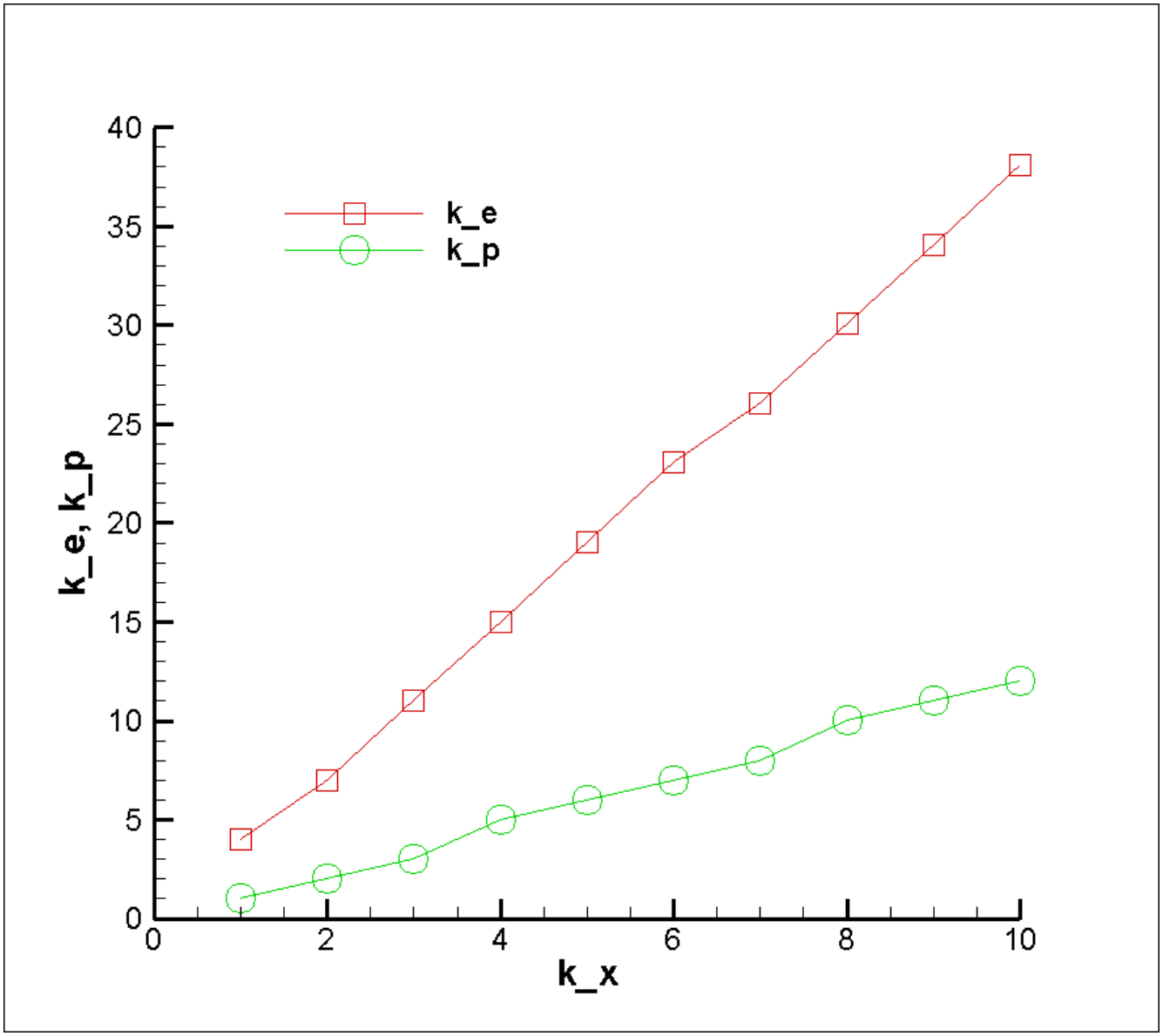








Dependence of post shock wave number against pre-shock wave number

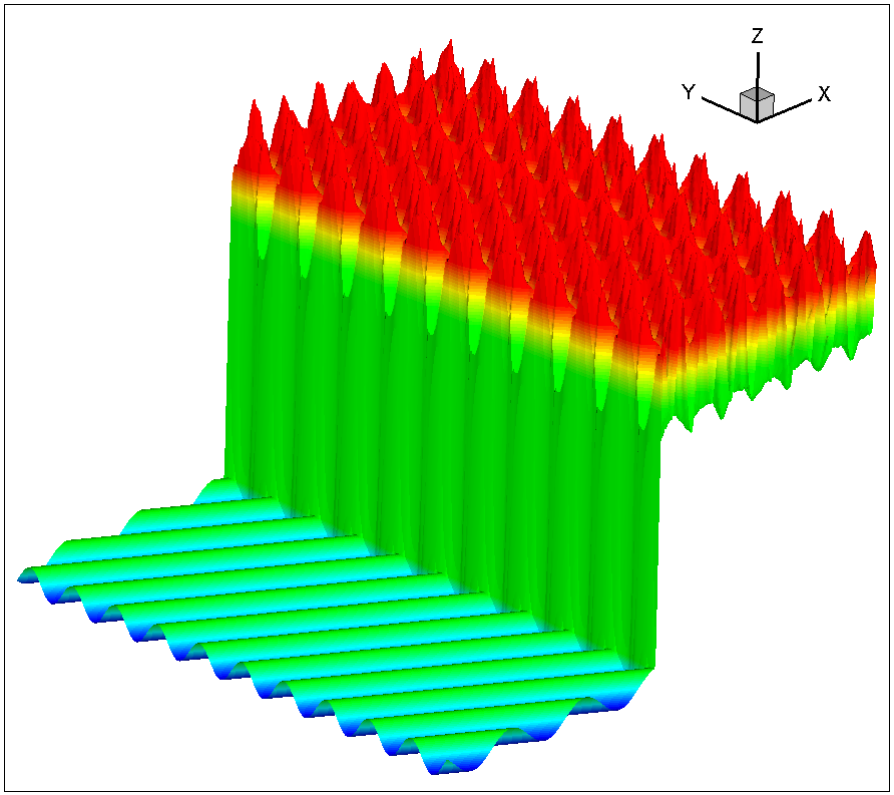


k_e – entropy wave frequency;
k_p – acoustic wave frequency;

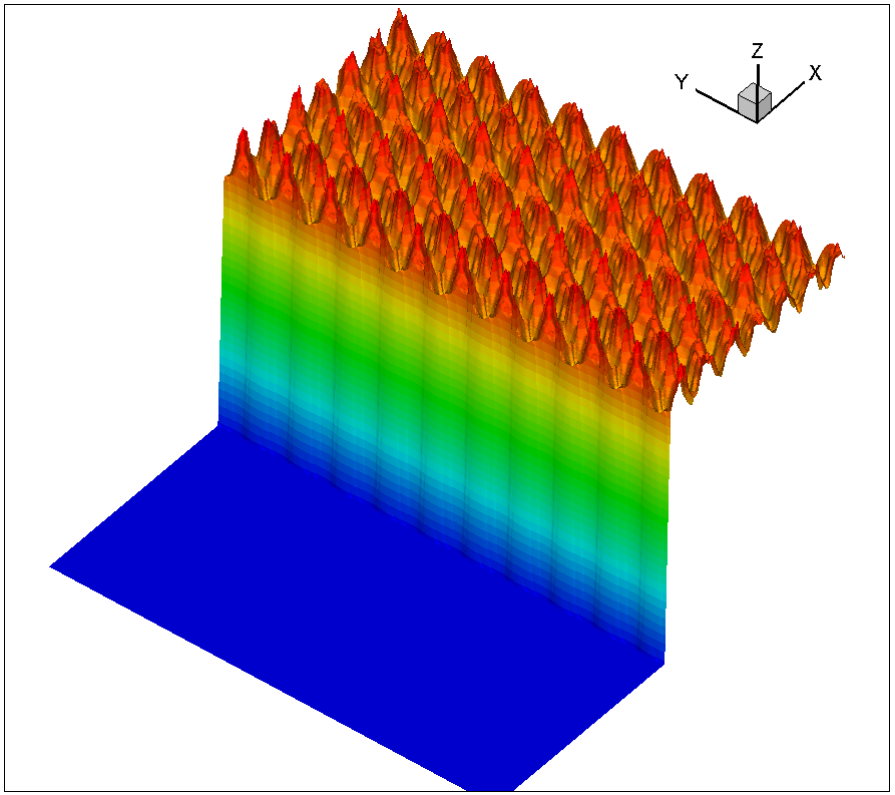
$\Delta\rho_1=0.025$
$\Delta\rho_2=0.114\div0.008$

$\Delta p_1=0$
$\Delta p_2=0.078$

Entropy wave A_e = 0.25, α = 90°, ψ=60°, k_y=10

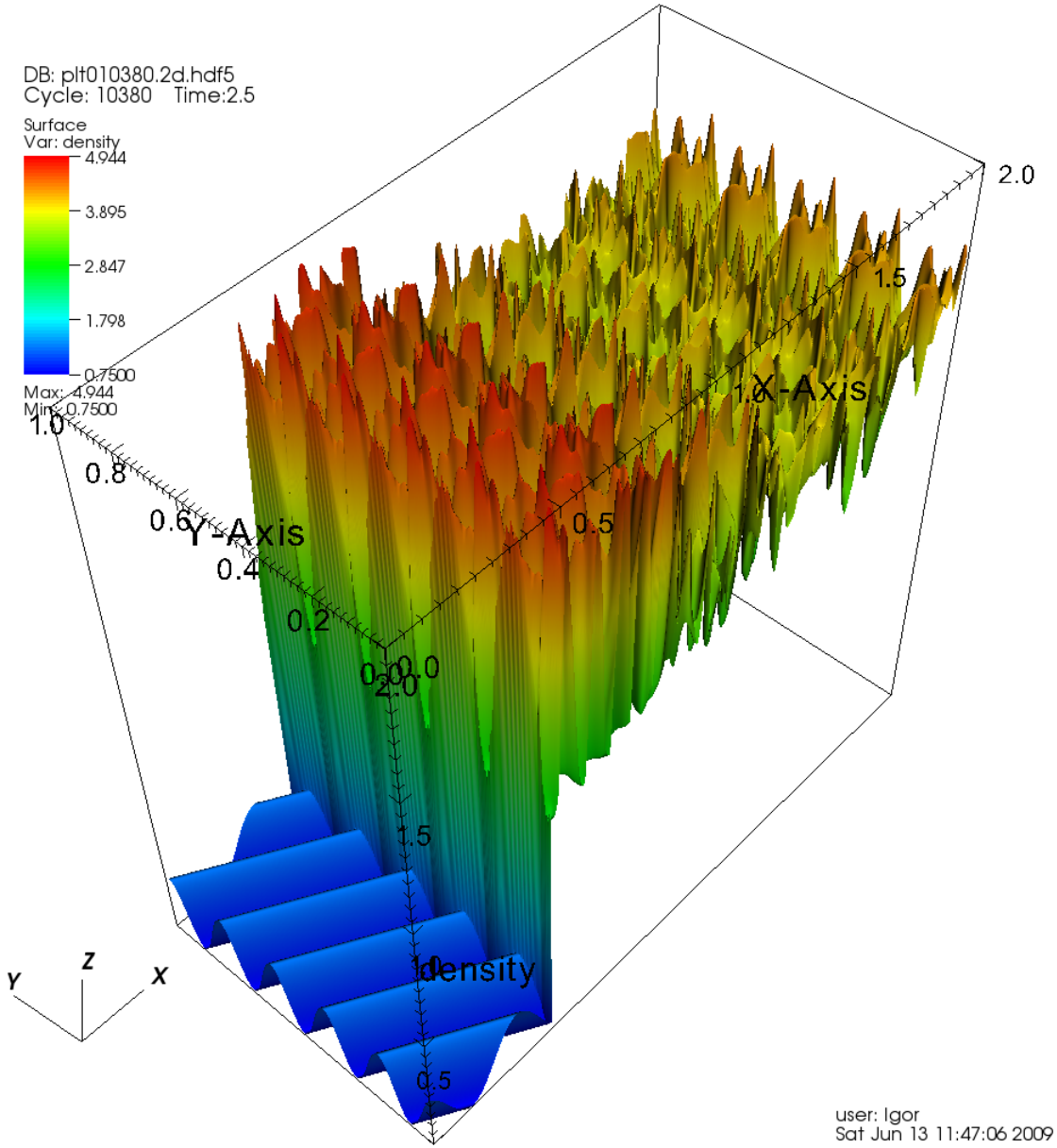


Density



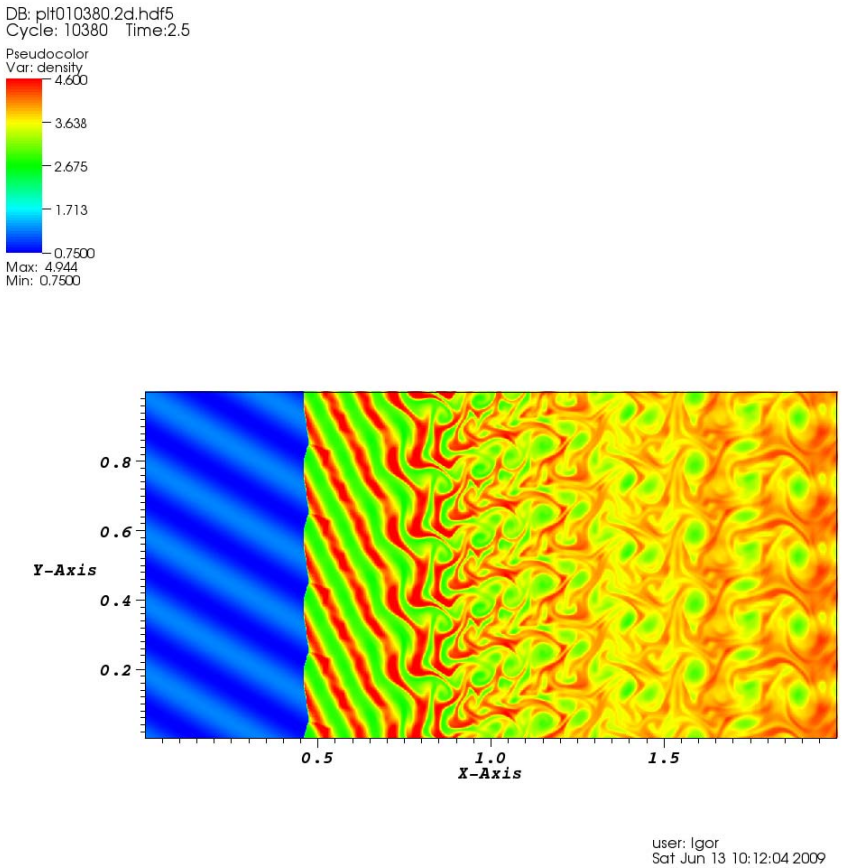
Pressure

Entropy wave A_e = 0.25, α = 90°, ψ=60°, k_y=5

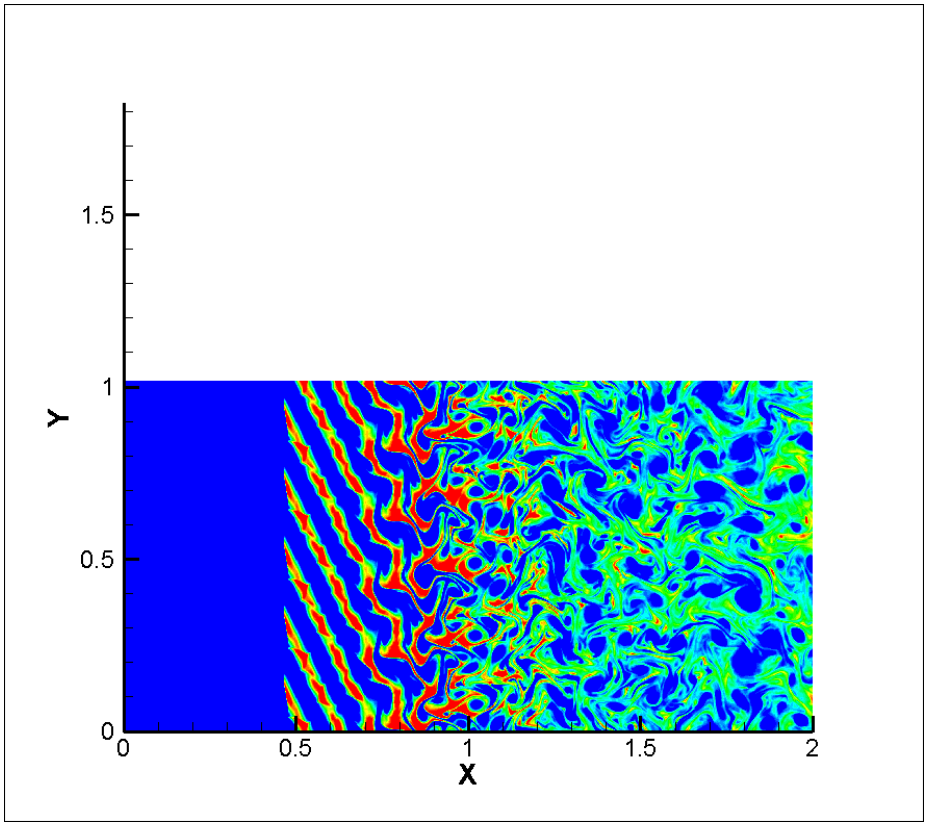


Density

Entropy wave A_e = 0.25, α = 90°, ψ=60°, k_y=5 (continue)



MS-FLUKSS

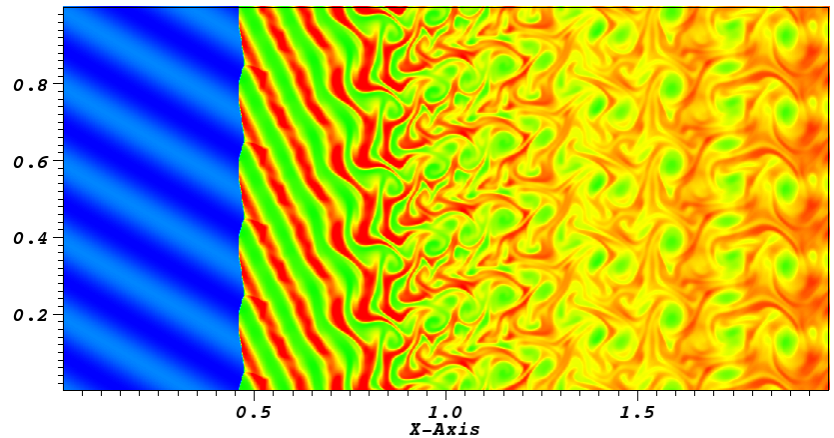


ADPDIS3D

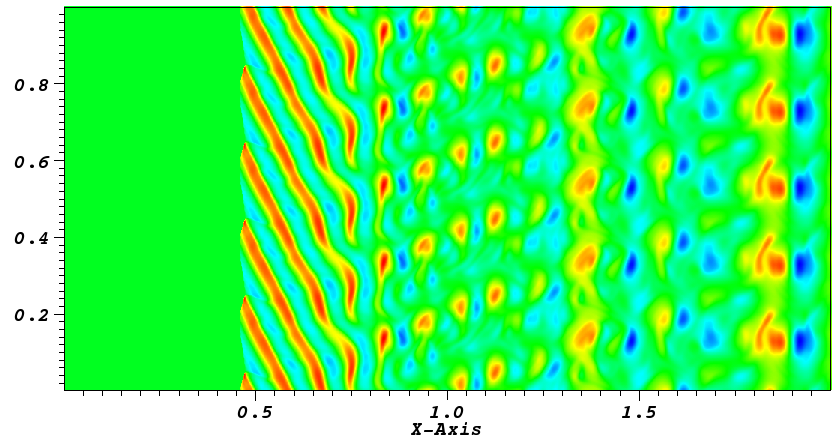
Density

ADPDIS3D loses regularity and symmetry of the flow

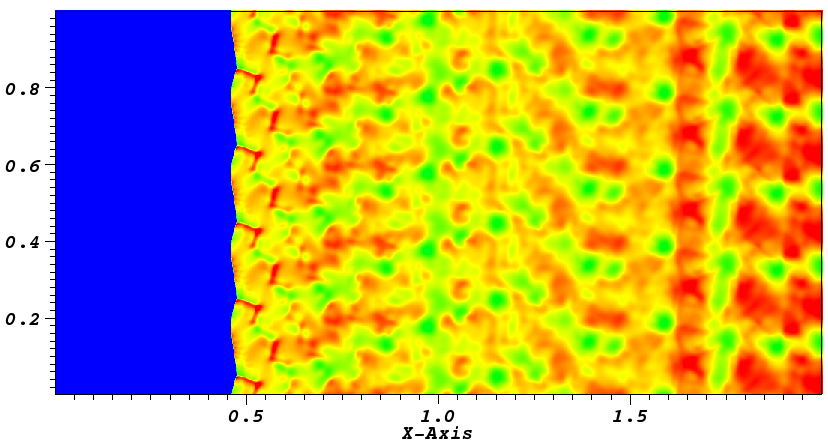
Entropy wave A_e = 0.25, α = 90°, ψ=60°, k_y=5 (continue)



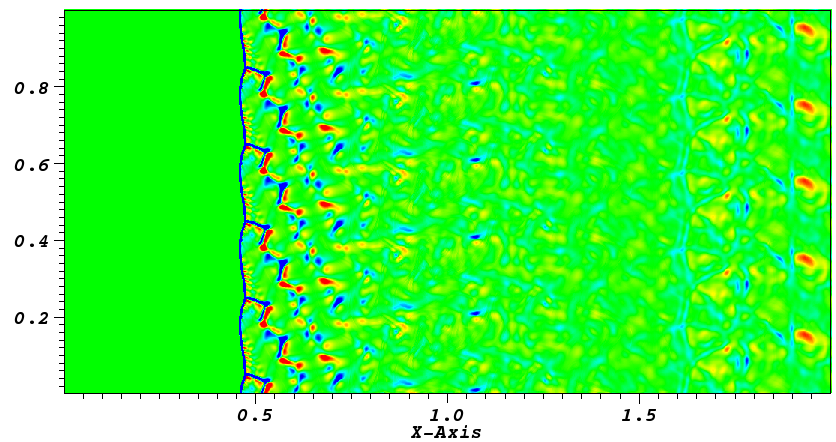
density



y-velocity



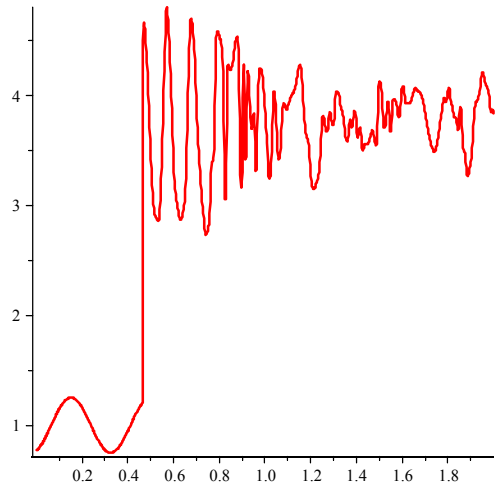
pressure



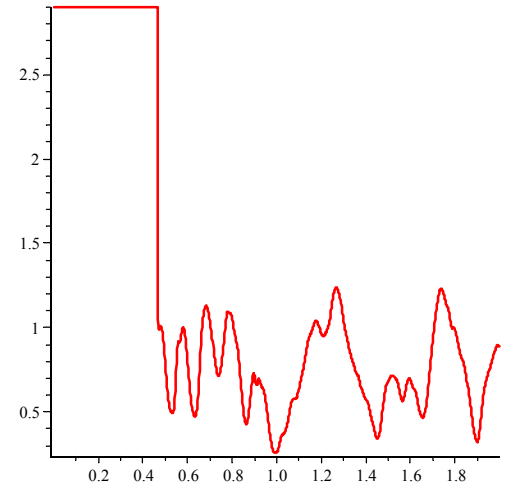
divergence of velocity

Entropy wave A_e = 0.25, α = 90°, ψ=60°, k_y=5 (continue)

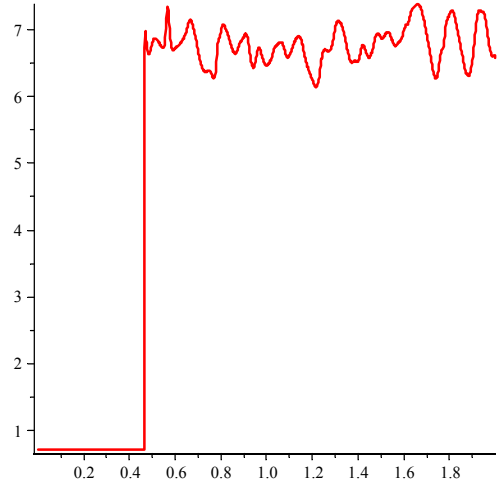
Parameters along y = 0.5



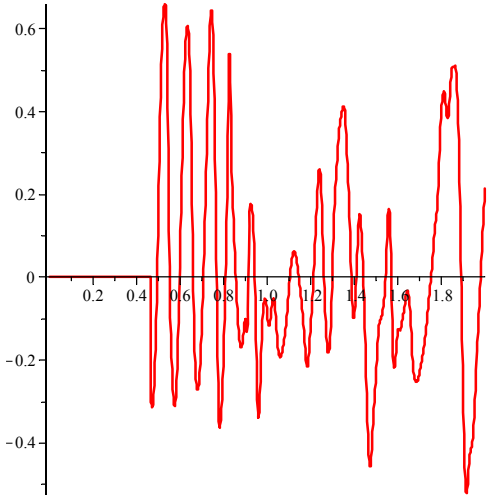
density



x-velocity



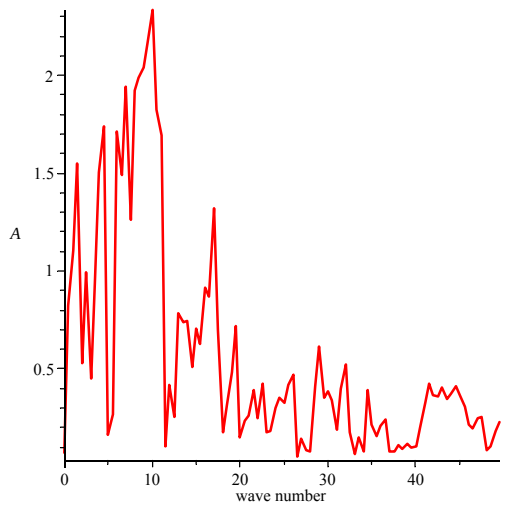
pressure



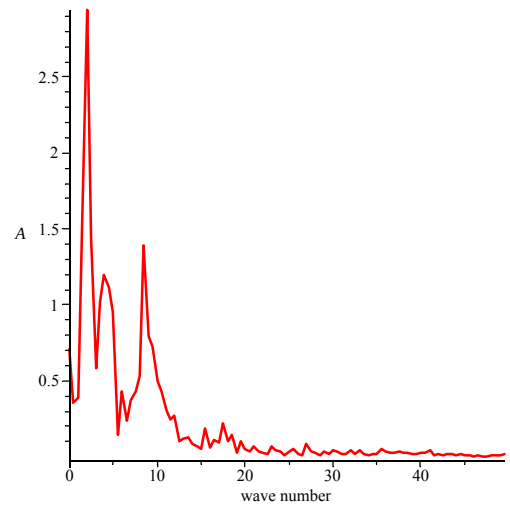
y-velocity

Entropy wave A_e = 0.25, α = 90°, ψ=60°, k_y=5 (continue)

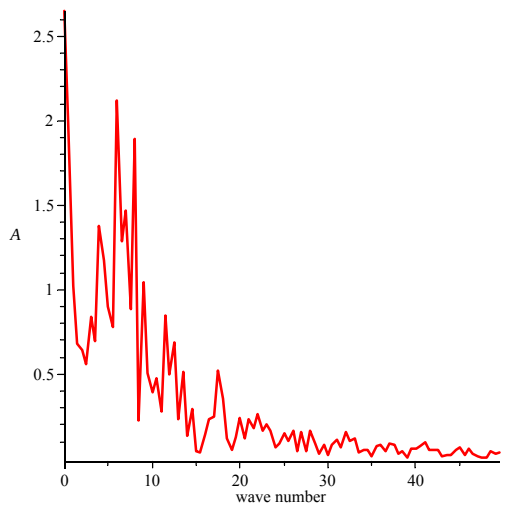
1D spectra (linear scales)



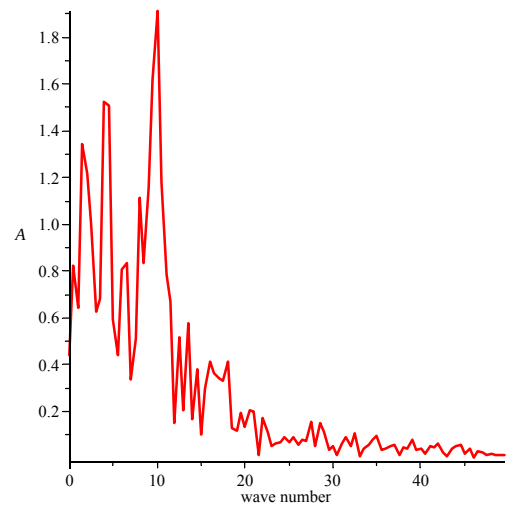
density



x-velocity



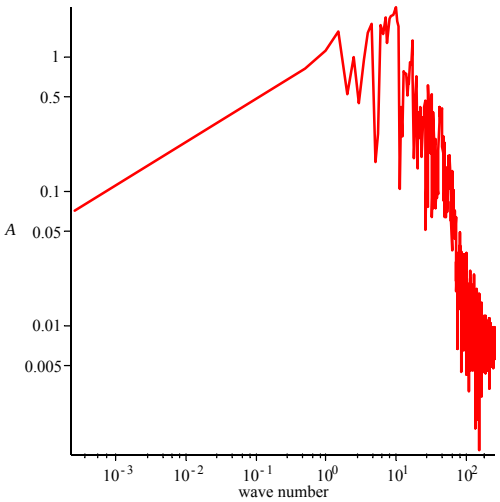
pressure



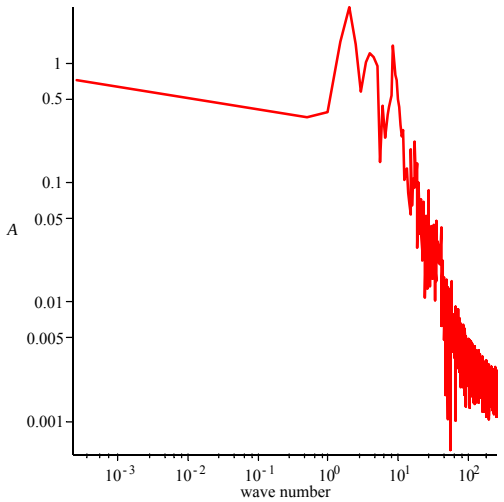
y-velocity

Entropy wave A_e = 0.25, α = 90°, ψ=60°, k_y=5 (continue)

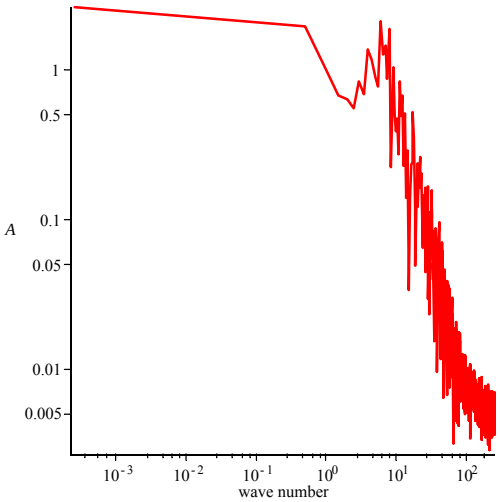
1D spectra (linear scales)



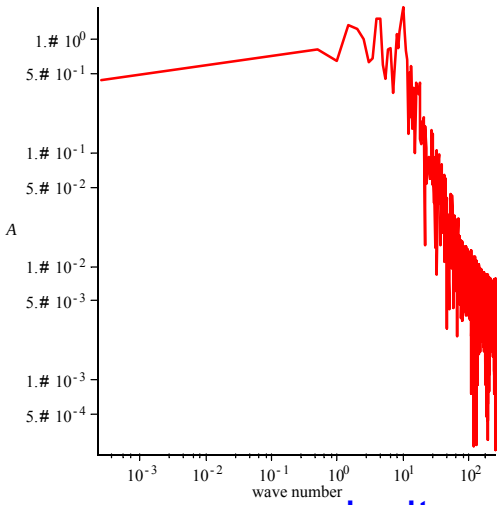
density



x-velocity



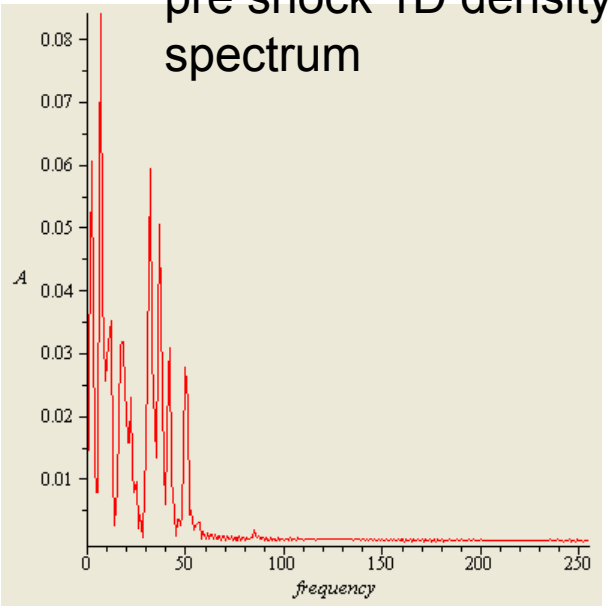
pressure



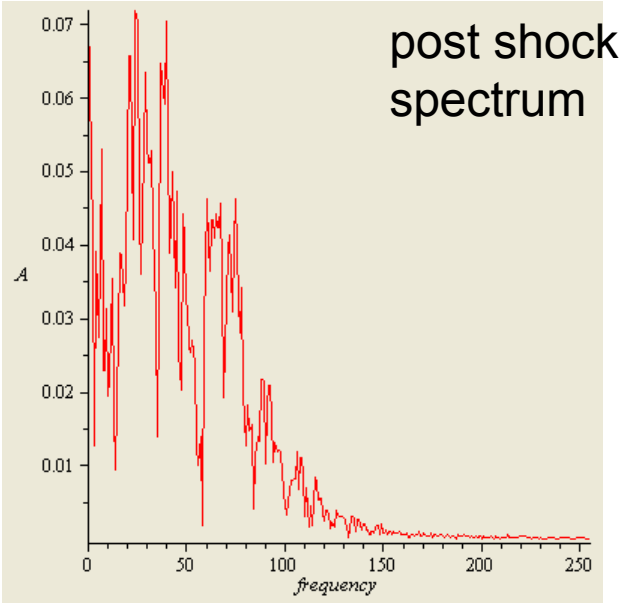
y-velocity

Entropy waves with turbulent incident spectrum

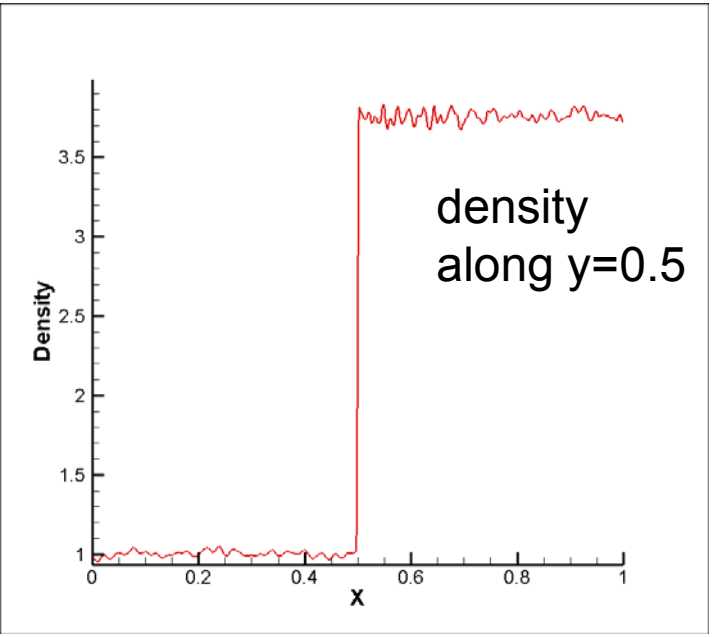
pre shock 1D density spectrum



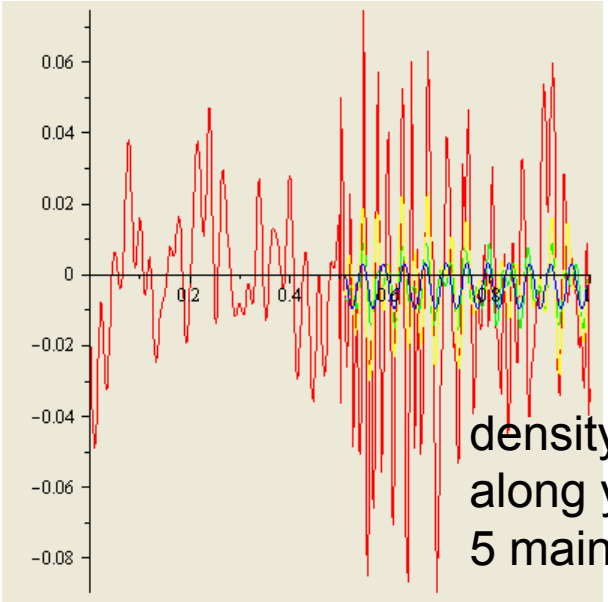
post shock 1D density spectrum



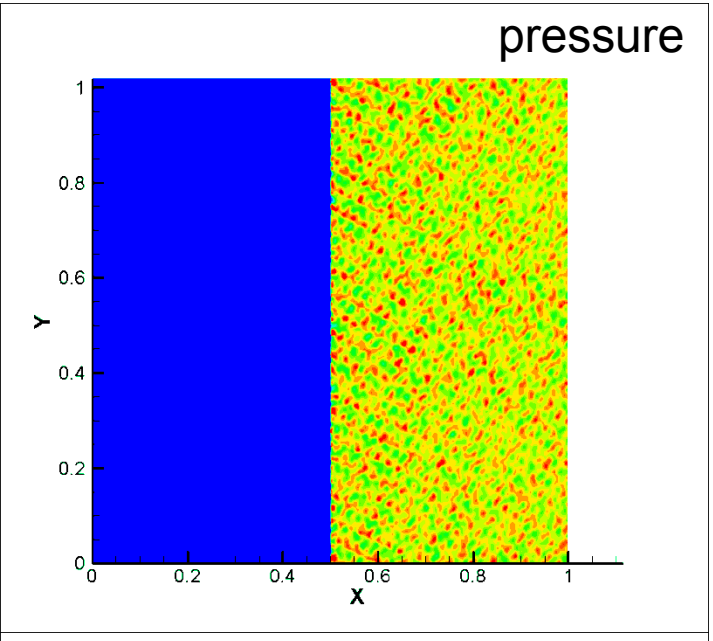
density along y=0.5

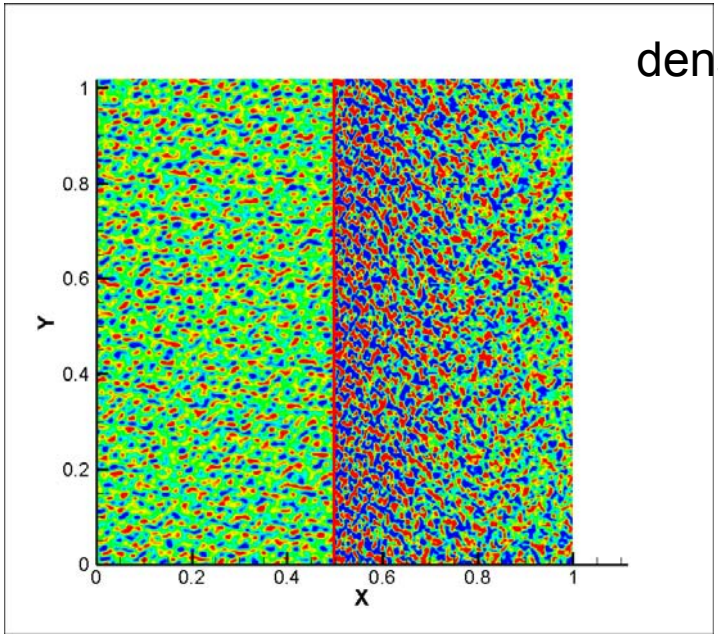


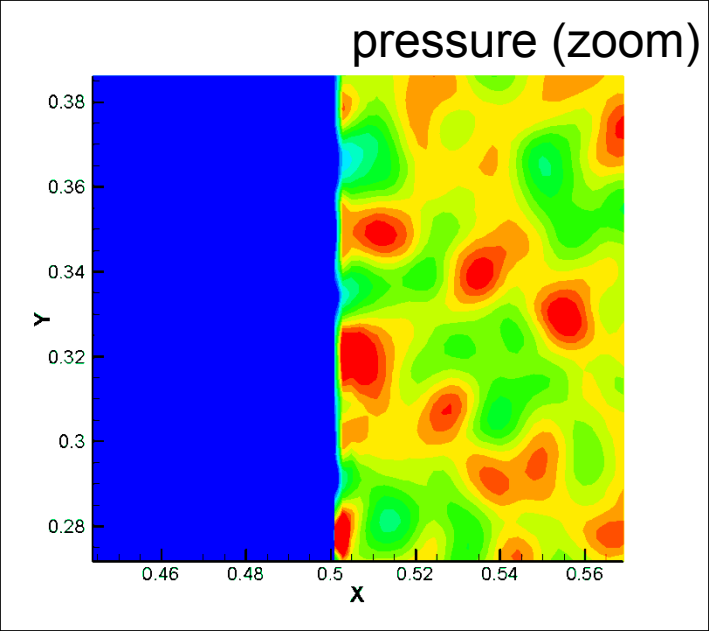
density fluctuations along y=0.5 and 5 main harmonics

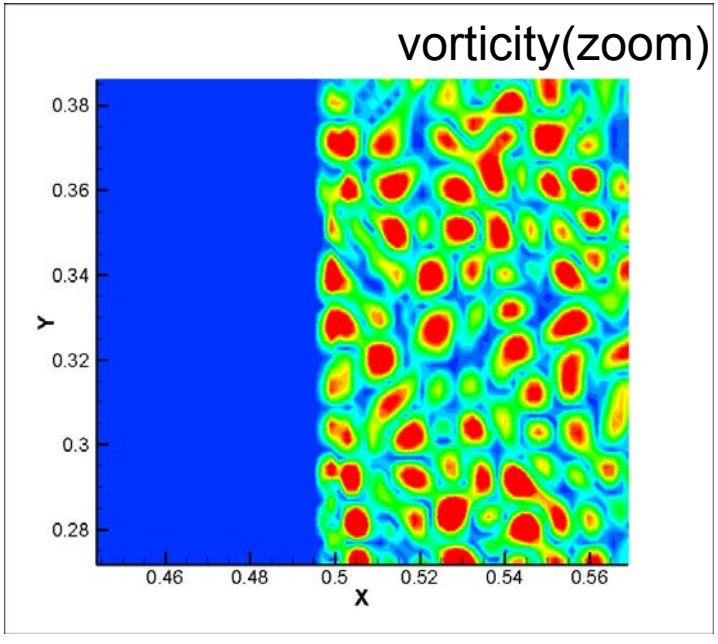


Entropy waves with turbulent spectrum







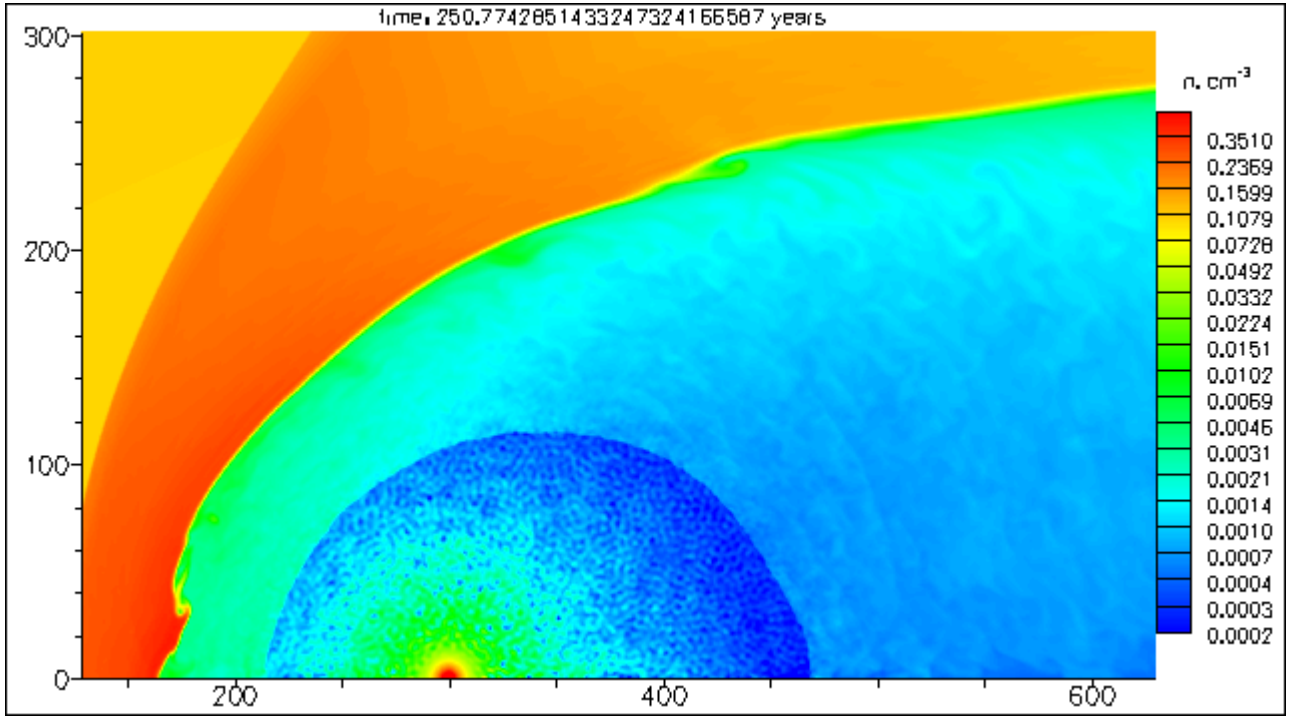


LISM interaction with a randomly perturbed SW

We perturb the SW velocity: $U_R = \overline{U} + \varepsilon U'_R, \quad U_\theta = \varepsilon U'_\theta, \quad \varepsilon = 0.025,$

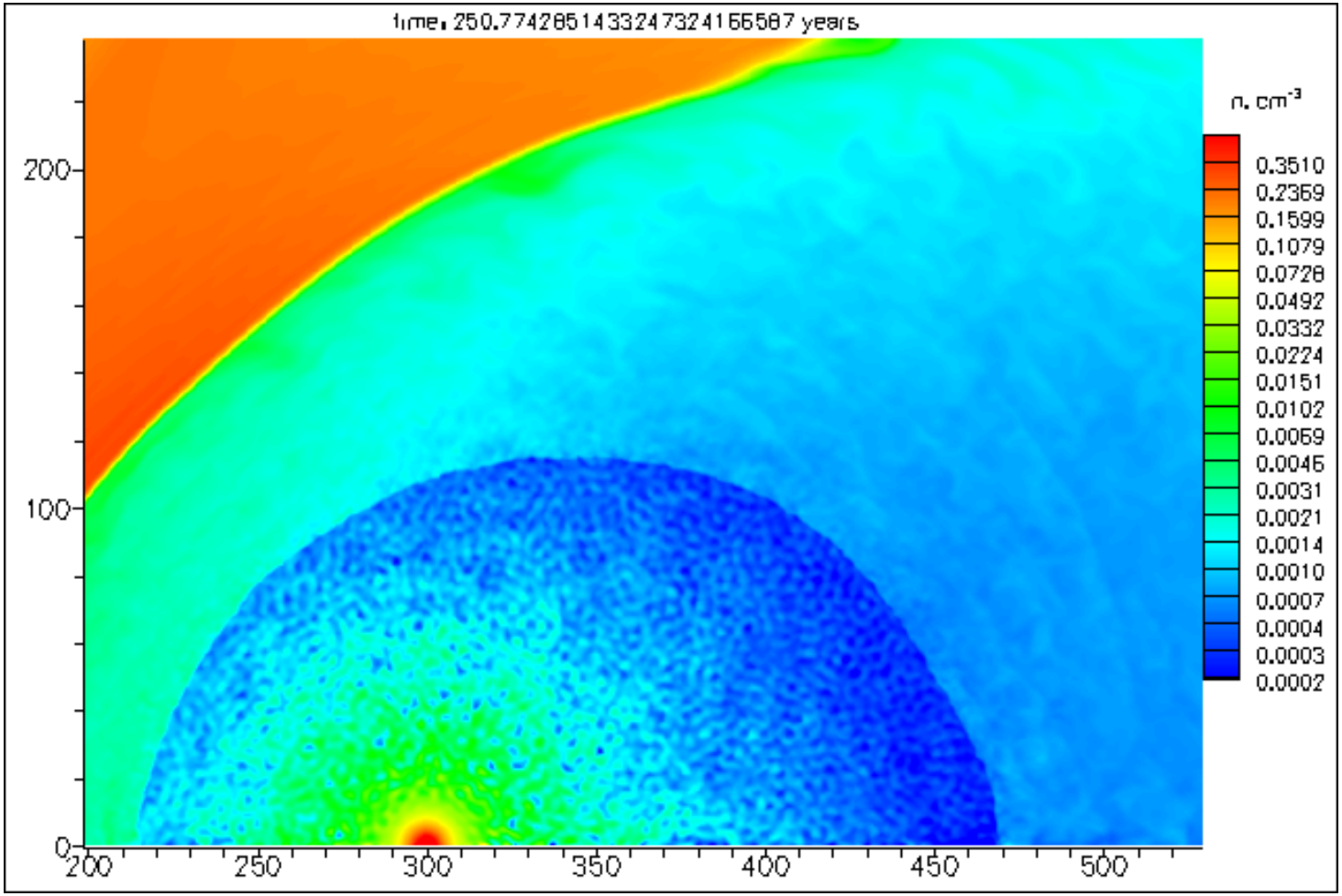
where ε measures the intensity of the input turbulence.

The initial spectrum is $E(k) \sim k^{-2}$. Fluctuations are assumed to be isotropic.

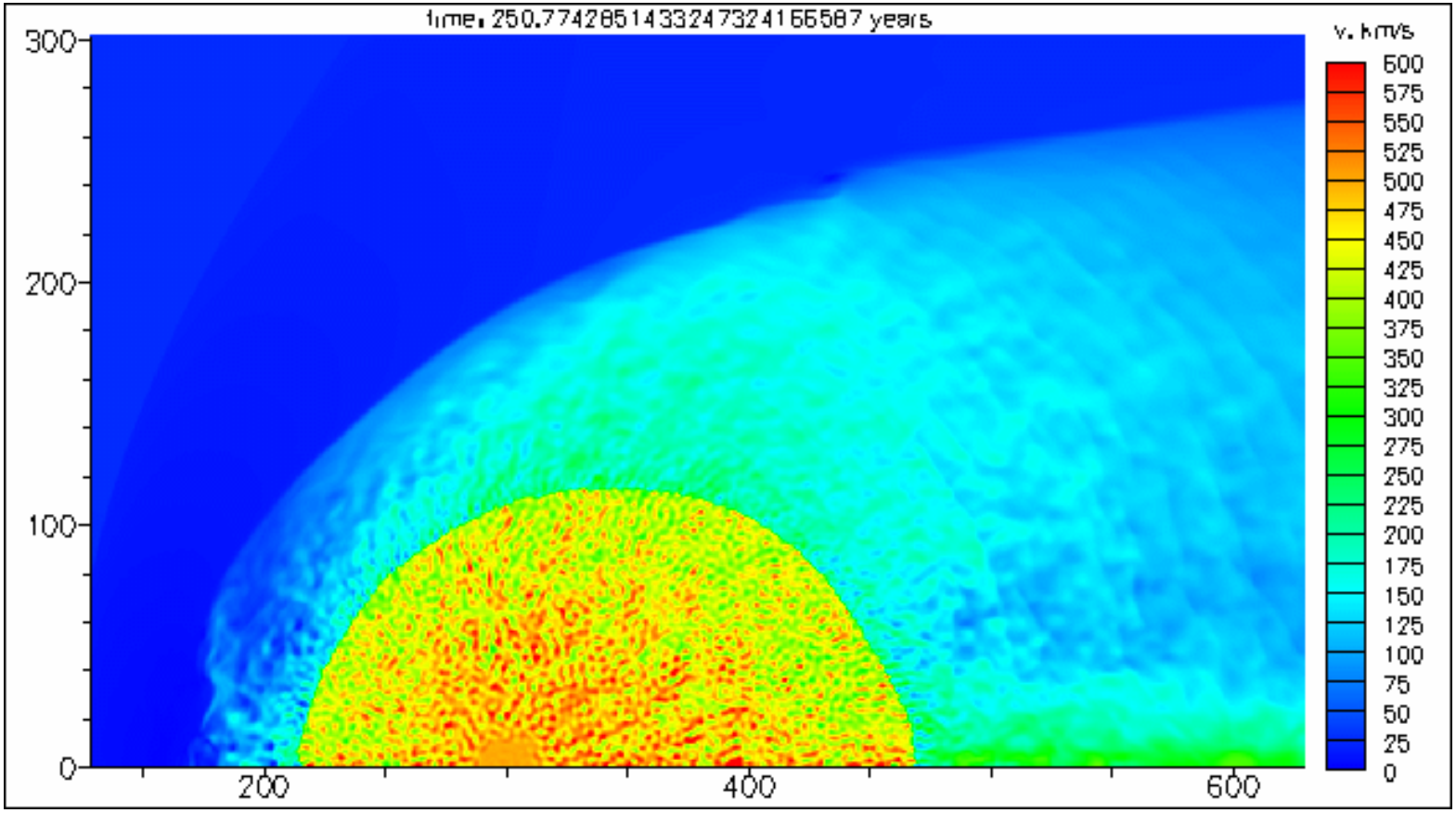


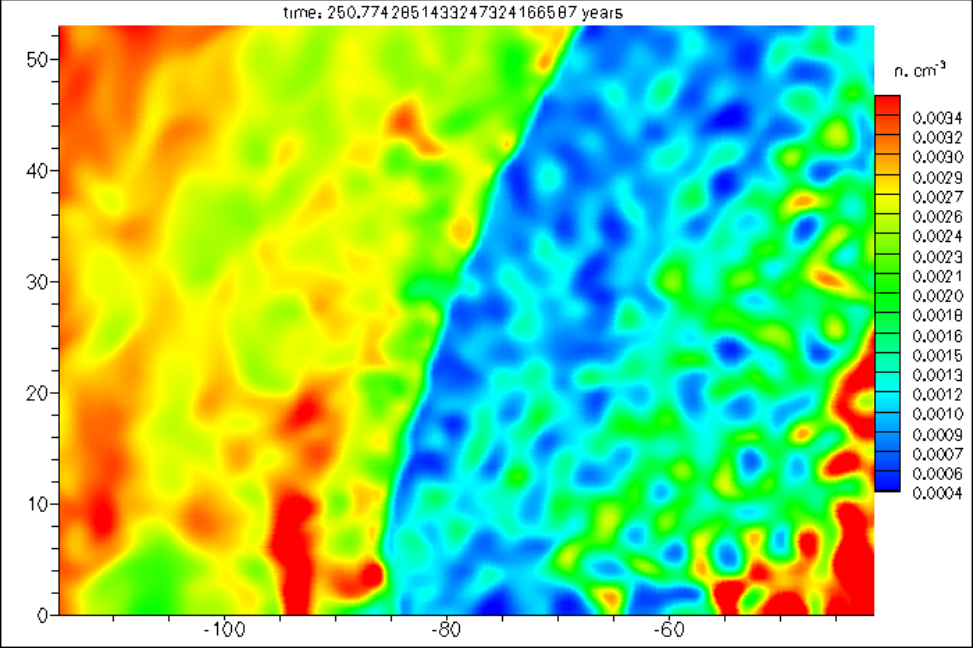
The spectrum is chosen in such a way that the length scale of fluctuations lies between the grid size (0.5 AU) and 5 AU.

Time-variation of the density distribution



Time-variation of the velocity magnitude distribution

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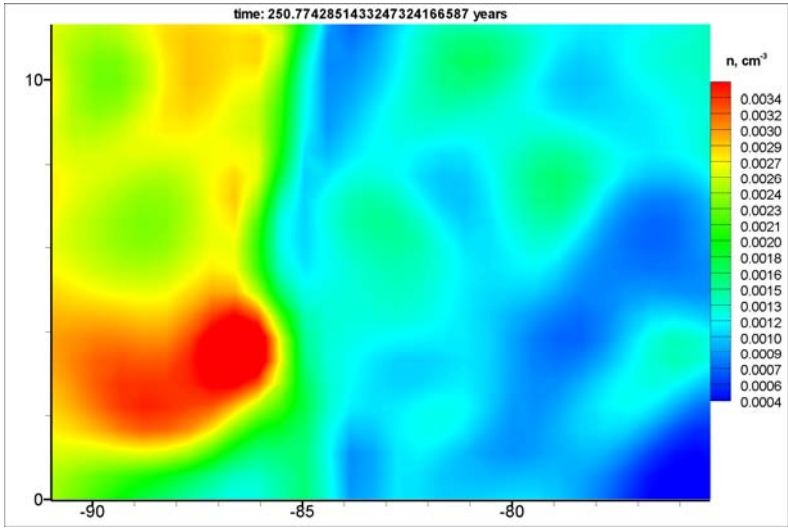
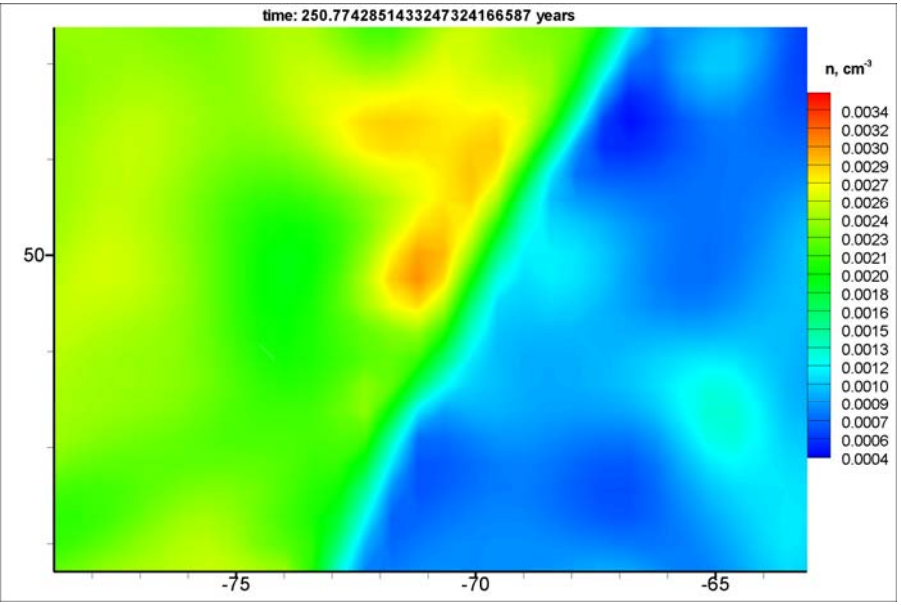
n, cm-3
0.0034
0.0032
0.0030
0.0029
0.0027
0.0026
0.0024
0.0023
0.0021
0.0020
0.0018
0.0016
0.0015
0.0013
0.0012
0.0010
0.0009
0.0007
0.0006
0.0004
50
40
30
20
10
0
-100
-80
-60


time: 250.774285143324732416658 7 years
n, cm-3
0.0034
0.0032
0.0030
0.0029
0.0027
0.0026
0.0024
0.0023
0.0021
0.0020
0.0018
0.0016
0.0015
0.0013
0.0012
0.0010
0.0009
0.0007
0.0006
0.0004
10
0
-90
-85
-80


time: 250.774285143324732416658 7 years
n, cm-3
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0.0032
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0.0029
0.0027
0.0026
0.0024
0.0023
0.0021
0.0020
0.0018
0.0016
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0.0012
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0.0009
0.0007
0.0006
0.0004
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-70
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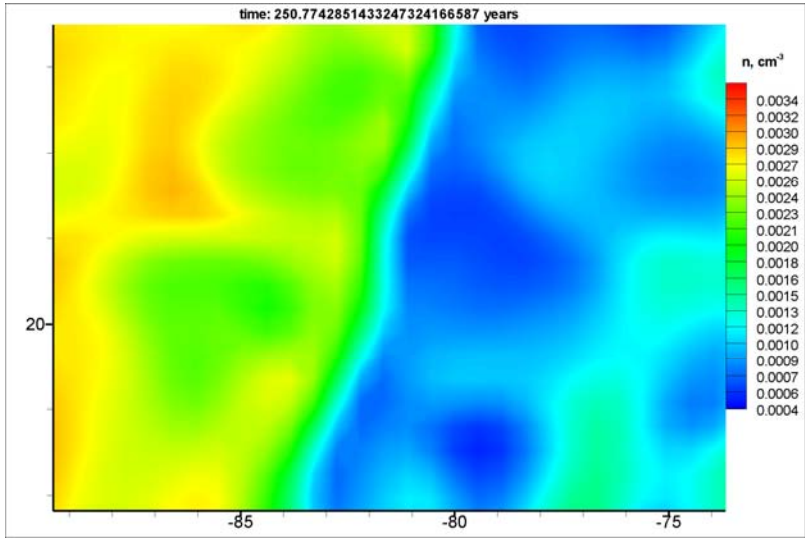
time: 250.774285143324732416658 7 years
n, cm-3
0.0034
0.0032
0.0030
0.0029
0.0027
0.0026
0.0024
0.0023
0.0021
0.0020
0.0018
0.0016
0.0015
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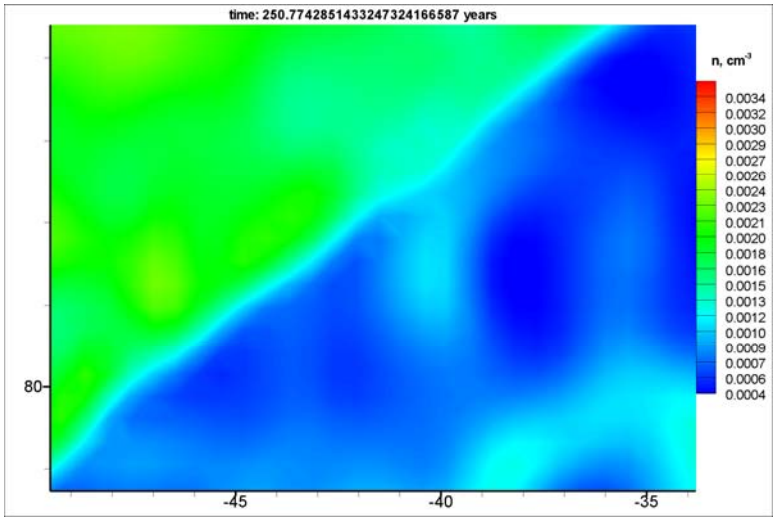
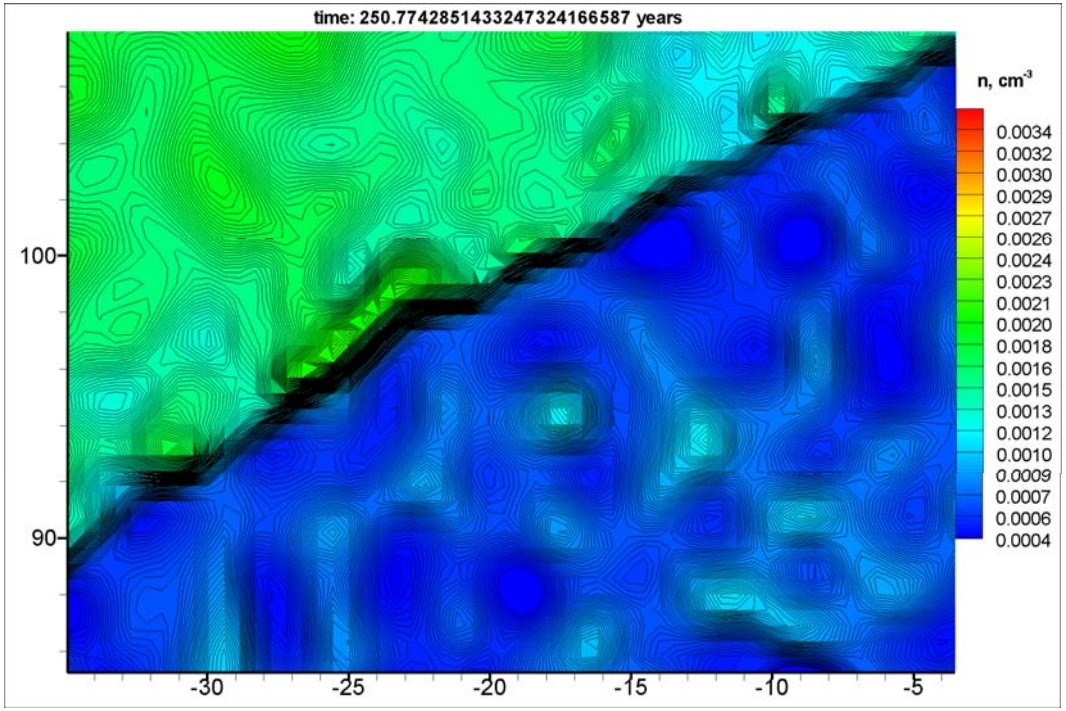
0.0012
0.0010
0.0009
0.0007
0.0006
0.0004
20
-85
-80
-75


time: 250.77428514332473241665 87 years
n, cm-3
0.0034
0.0032
0.0030
0.0029
0.0027
0.0026
0.0024
0.0023
0.0021
0.0020
0.0018
0.0016
0.0015
0.0013
0.0012
0.0010
0.0009
0.0007
0.0006
0.0004
80
-45
-40
-35


time: 250.77428514332473241665 87 years
n, cm-3
0.0034
0.0032
0.0030
0.0029
0.0027
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0.0023
0.0021
0.0020
0.0018
0.0016
0.0015
0.0013
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0.0004
100
90
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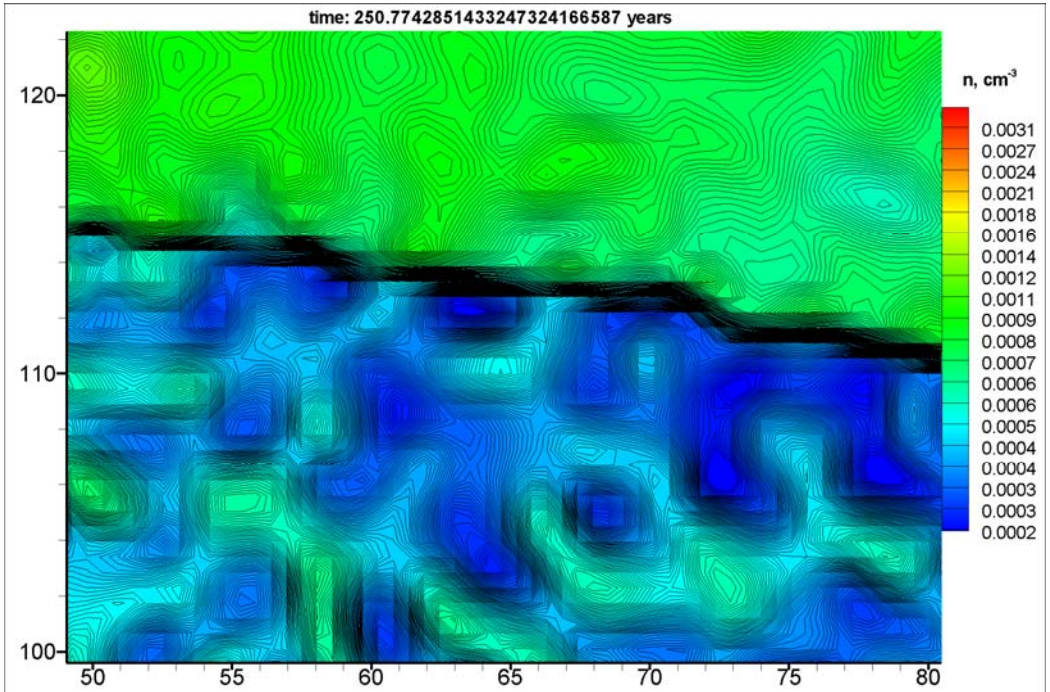
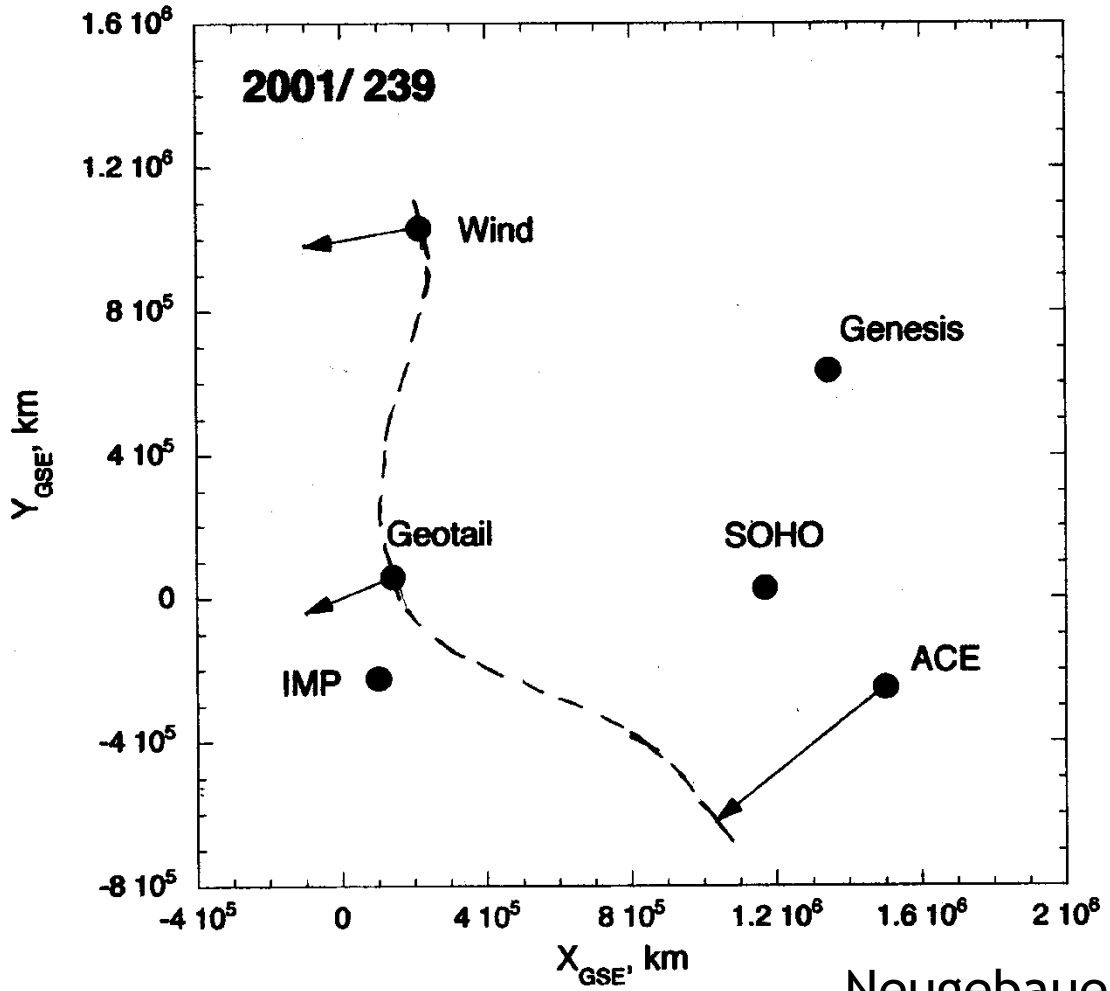
-20
-15
-10
-5


time: 250.77428514332473241665 87 years
n, cm-3
0.0031
0.0027
0.0024
0.0021
0.0018
0.0016
0.0014
0.0012
0.0011
0.0009
0.0008
0.0007
0.0006
0.0006
0.0005
0.0004
0.0004
0.0003
0.0003
0.0002
120
110
100
50
55
60
65
70
75
80

Shock Shape Calculated from Shock Speeds, Normals and Timing

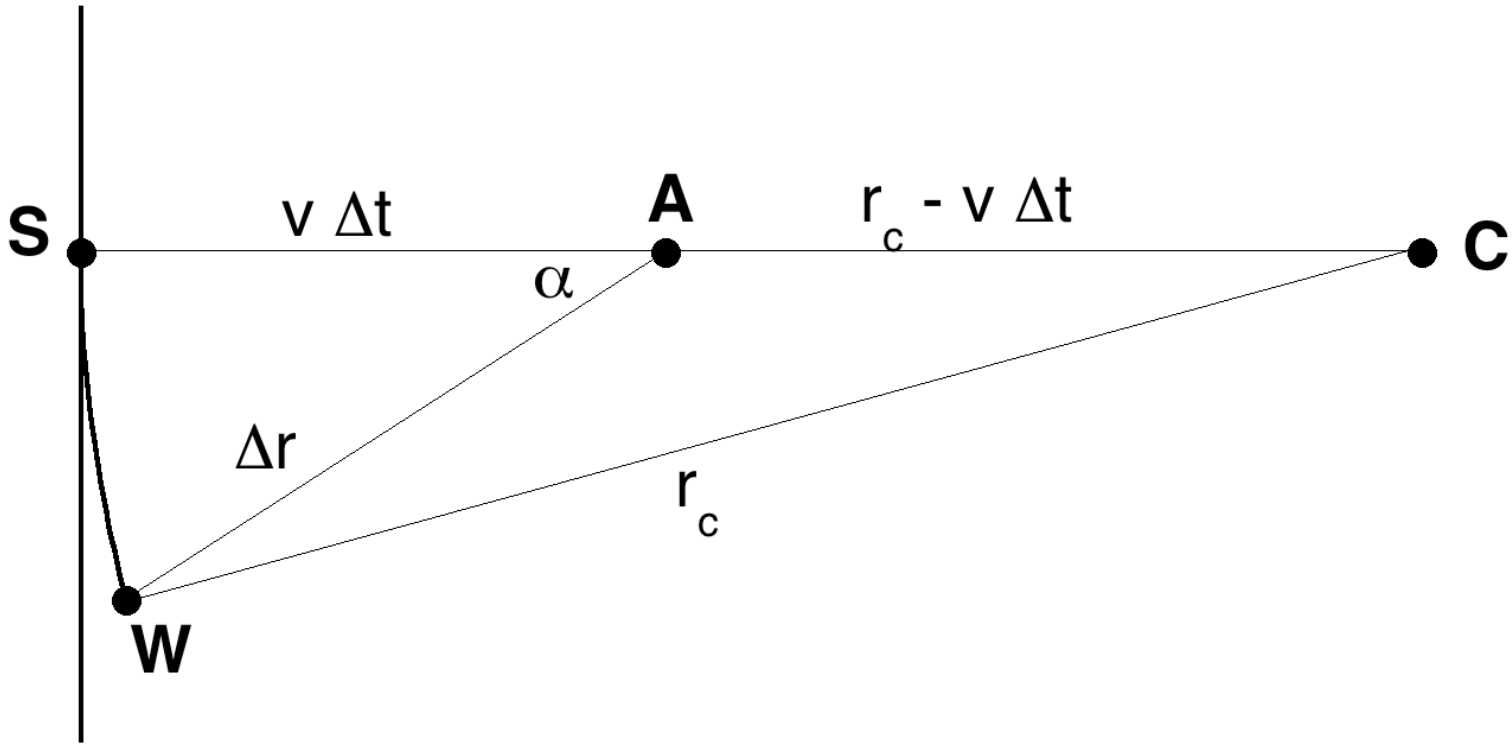


Wind/Geotail saw this shock nearly simultaneously

Obs. at ACE is used to predict shock location at the time of Wind/Geotail observation

Neugebauer & Giacalone, 2007

Definition of 2-D Radius of Curvature



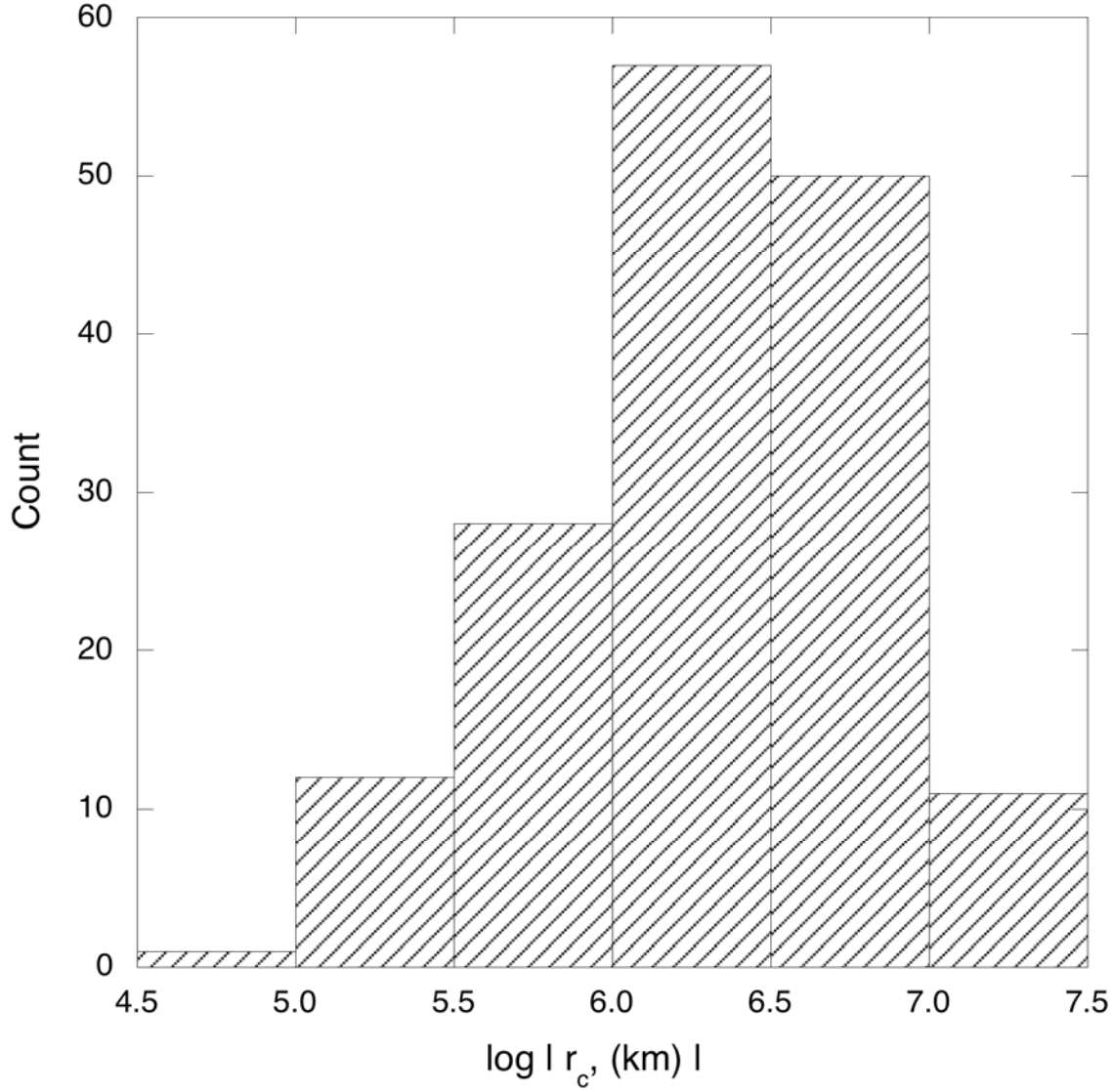
S is the location of the shock determined from observed speed (v) and direction at ACE

W is the location of another s/c that sees the shock a time Δt later

If the shock is planar, W would be on the vertical line – this was seldom the case. Can use simple geometry to get the radius of curvature

Distribution of shock radii of curvature

Neugebauer & Giacalone, 2007



CONCLUSIONS

- Need to understand the interaction of turbulence with shocks, motivated by Voyager observations downstream of the TS and models for particle acceleration at quasi-perpendicular shocks.
- Structure of shock modified – smoothing, non-R-H jumps (i.e., non-steady)
- Incompressible upstream fluctuations generates compressible fluctuations downstream, amplified density fluctuations, and vortical flow.
- Begun to study effect of varying Mach number, obliquity, and incidence of entropy fluctuations.
- Development of turbulence and vortical structure downstream due to mode coupling
- Magnetic fields generated downstream – implications for particle acceleration at perpendicular shocks interesting.
- Complications in numerically simulating interaction of fluctuations with shock wave are not trivial.