An MHD simulation study of the Kelvin-Helmholtz instability at the Martian ionopause with a day-to-night density gradient

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1. Introduction

The Kelvin-Helmholtz (KH) instability at the magnetopause

✔Sibeck and Smith [1992]; Mozer et al. [1994]
Wave-like structures are detected at the Earth's magnetopause

✔Hasegawa et al. [2004]; Yan et al. [2014]
KH waves are detected at the Earth's magnetopause

✔ Miura et al. [1984]; Fujimoto and Terasawa [1994]
Transportation of momentum, energy and mixing of plasma

✔ Nykyri and Otto [2001]
KH vortex can be a trigger of magnetic reconnection

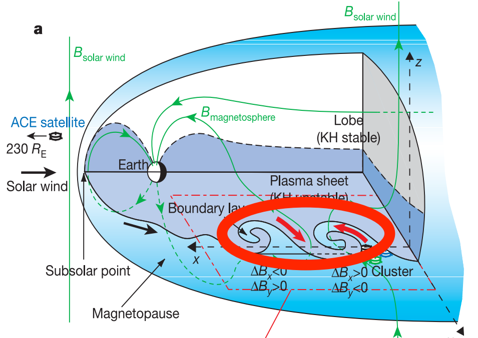


FIG.1. Interaction between the Earth's magnetopause and solar wind flow
[Hasegawa et al.,2004]

Expected roles of the KH instability at the ionopause

✔ Brace et al. [1982]; Wolff et al. [1980]
One of the major loss processes of ionospheric ions from an unmagnetized planet

✔ Wolff et al. [1980]; Cloutier et al. [1981]
The KH instability may generate magnetic flux ropes in the ionosphere.

➡ The KH instability can be an important process to understand the evolution of the Martian atmosphere through its history.

1. Introduction

The linear theory of the KH instability at the ionopause

✔ The linear growth rate of the KH instability with the most unstable case (**k** ⊥ **B**)

$$\gamma = \sqrt{k^2 \frac{\rho_1 \rho_2 (U_1 - U_2)^2}{(\rho_1 + \rho_2)^2}}$$

U : Velocity
ρ : Density
Suffix : 1 means sheath region, 2 means ionosphere region
(The finite thickness of the shear layer is ignored)

The linear growth rate depends on velocity shear and density jump.
To investigate the evolution of the KH instability, numerical studies are needed.

Previous study [Amerstorfer et al., 2010]

Authors have investigated the effect of the vertical density gradient using local MHD simulation

✔The maximum growth rate decreases with increasing the density ratio.
✔The wavelength of the fastest growing mode becomes large with increasing the density ratio.

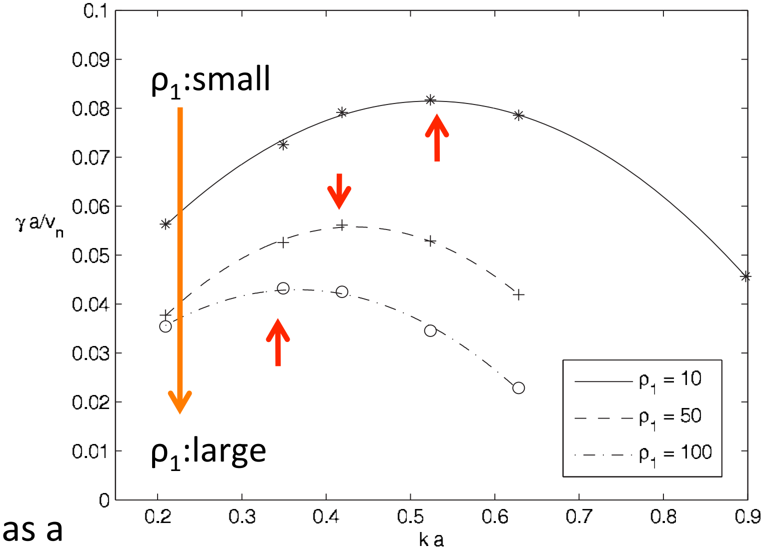


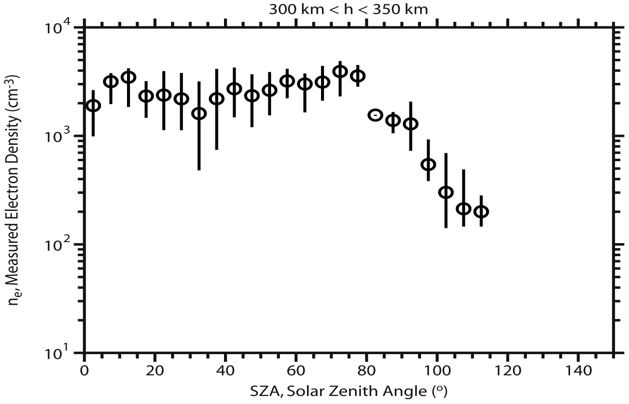
FIG 2. The normalized linear growth rate as a function of the normalized wave number.

1. Introduction

Problems of previous numerical studies

✔ Local periodic simulation
Actual KH vortex has not necessarily a periodic structure.

✔ Did not consider a day-to-night density gradient
The Martian ionosphere has a density gradient not only in the vertical direction but also in horizontal (day-to-night) direction. [Duru et al., 2008]



→FIG 3. The electron density profile as a function of the SZA.
(Altitude : 300km to 350 km)
[Duru et al., 2008]

Elements of a global model

local MHD ＋ aperiodic boundary
horizontal density gradient → Extended-local MHD

Purpose of this study

To investigate following two issues using non-local MHD simulations
✔ the asymmetrical evolution of the KH instability

✔ the effect of a day-to-night (horizontal) density gradient on the linear and nonlinear evolution of the KH instability

2. Model description and initial conditions

Governing equations

2D ideal MHD equations

✔ The conservation of mass

$$\frac{\partial}{\partial t}\rho + \nabla\cdot\left(\rho\vec{v}\right) = 0$$

✔ The conservation of momentum

$$\frac{\partial}{\partial t}\left(\rho\vec{v}\right) + \nabla\cdot\left(\rho\vec{v}\vec{v} + \Pi\overleftrightarrow{I} - \frac{\vec{B}\vec{B}}{\mu_0}\right) = 0$$

✔ The conservation of total energy

$$\frac{\partial}{\partial t}e + \nabla\cdot\left[\left(e+\Pi\right)\vec{v} - \frac{\left(\vec{B}\cdot\vec{v}\right)\vec{B}}{\mu_0}\right] = 0$$

✔ Induction of the magnetic field

$$\frac{\partial}{\partial t}\vec{B} + \nabla\cdot\left(\vec{v}\vec{B} - \vec{B}\vec{v}\right) = 0$$

◇Total energy $e = \frac{p}{\gamma - 1} + \frac{\rho\vec{v}^2}{2} + \frac{\vec{B}^2}{2\mu_0}$

◇Total pressure $\Pi = p + \frac{\vec{B}^2}{2\mu_0}$

Model description

Scheme

Time differencing ･･･ 3rd order TVD Runge-Kutta
Space differencing ･･･ 4th order semidiscrete scheme with UNO limiter

Simulation box length

Length of 1 grid : Δx = Δy = 1 km
Box size : [Case 1] (Lx, Ly) = (800, Ly)
※Ly depends on a wave number
[Case 2] & [Case 3] (Lx, Ly) = (800, 2000)
Simulation box is normalized with *a*
(*a* is a half of transition layer)

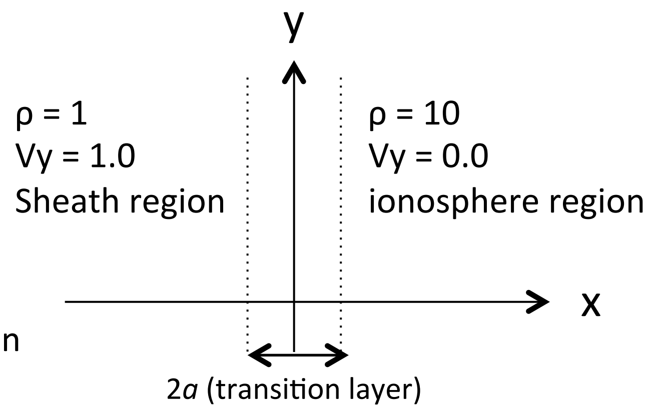


FIG.4. Sketch of the assumed configuration

2. Model description and initial conditions

Model description

Case 1 : local

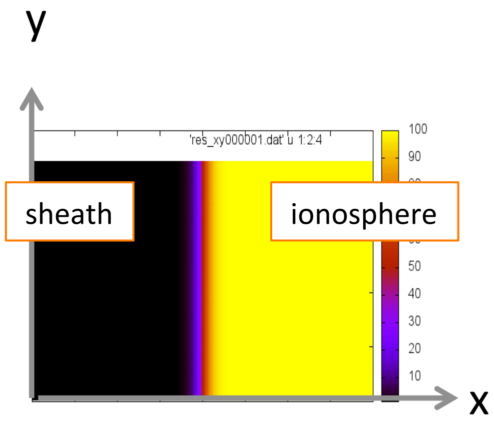
Periodic boundary

[x] Free

[y] Periodic

◆ Vertical density gradient

◆ The fastest growing mode only grows up



Case 2 : extended-local

Aperiodic boundary

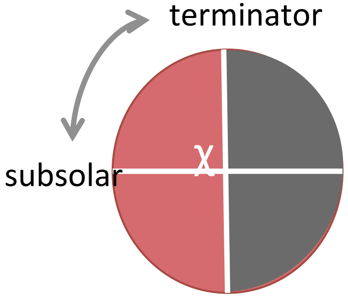
[x] Absorbing boundary

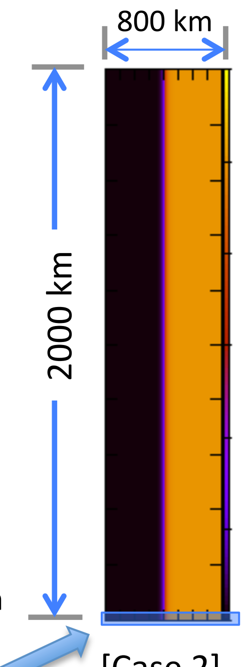
[y] upstream :Fixed

downstream : Free

/ no inflow boundary

◆ Vertical density gradient





The small perturbation is inserted from upstream boundary.

[Case 2]

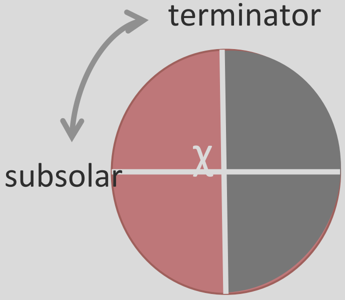
Case 3 : extended-local

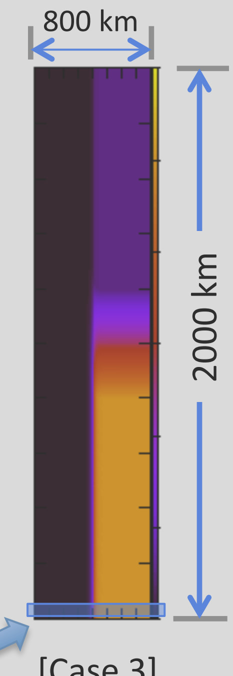
Aperiodic boundary

(same as [Case 2])

◆ Vertical and horizontal density gradient

(Horizontal density gradient is given by observation results)



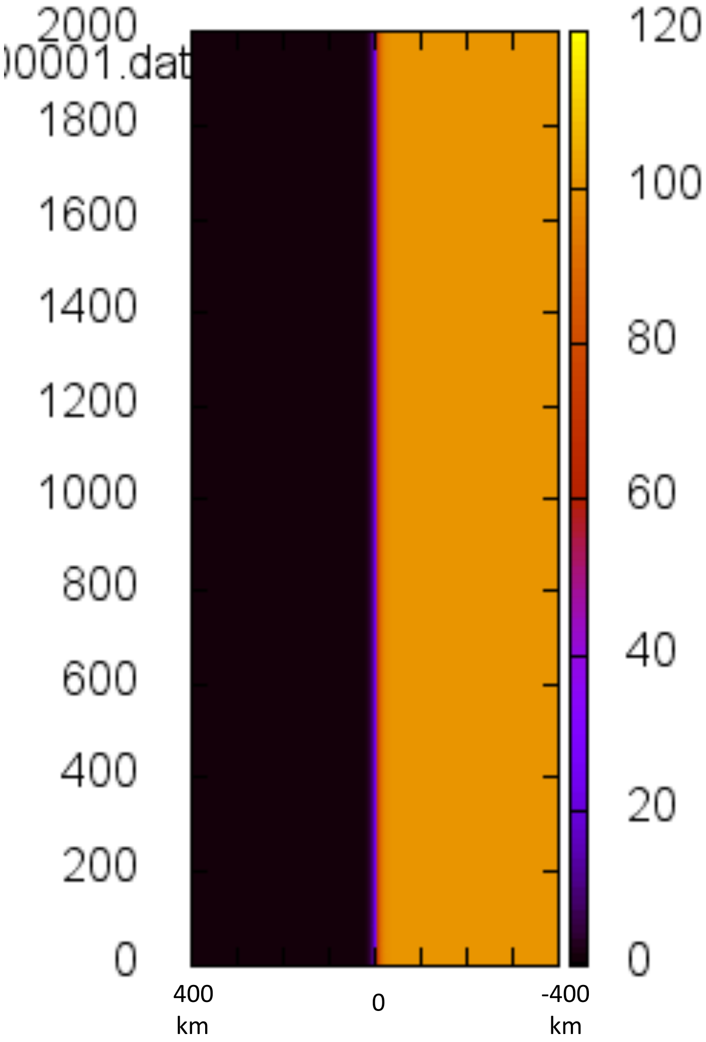


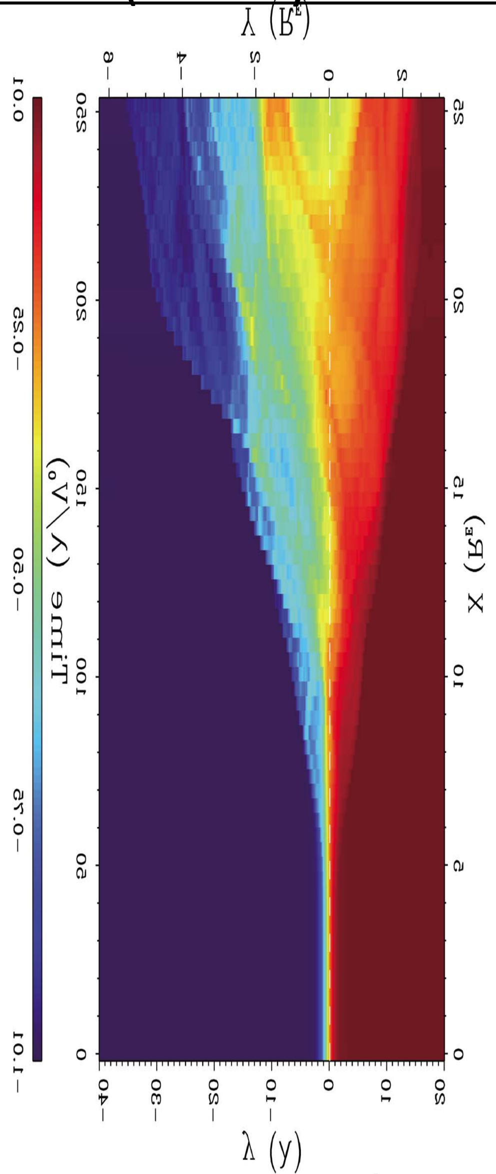
The small perturbation is inserted from upstream boundary.

[Case 3]

3. Results

[Case 2] Aperiodic & vertical density gradient (density ratio = 100)





[Matsumoto and Seki, 2010]

3. Results

[Case 2] Aperiodic & vertical density gradient

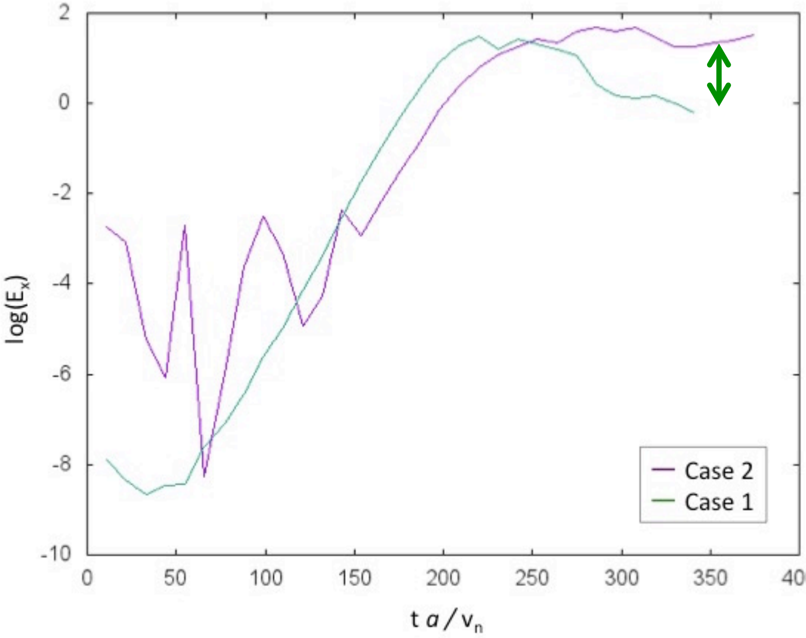
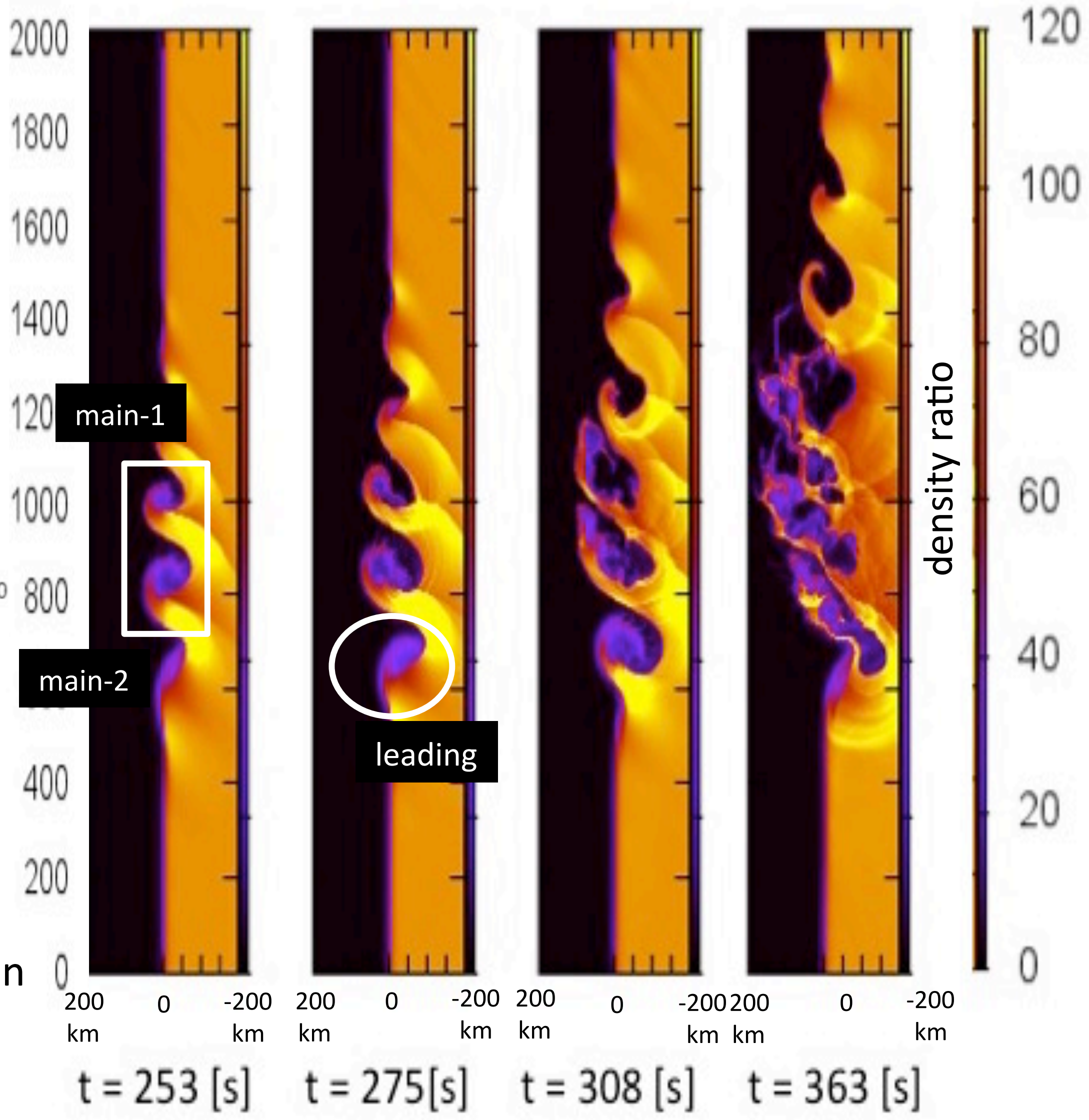


FIG 5. Time evolution of the logarithm of the peak vertical kinetic energy. (Ex = 1/2ρv_x^2)

✔The linear growth rate is almost same.

✔Kinetic energy increases during saturation phase because of the excitation of longer wavelength modes than the fastest growing mode [Baty et al., 2003].



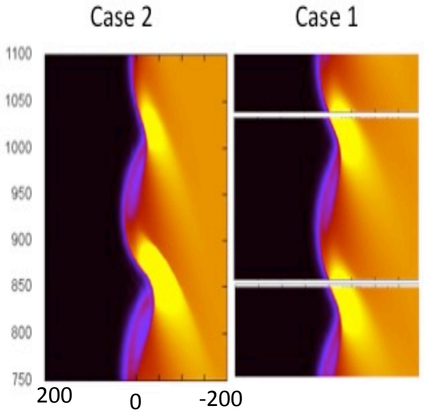
3. Results

[Case 2] Aperiodic & vertical density gradient

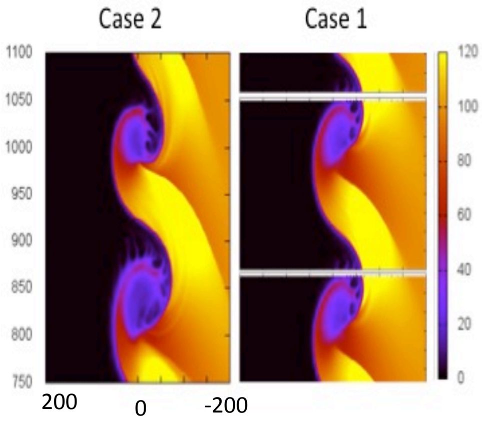
Comparing the evolution of the KH instability in Case 2 with that in Case 1.

Main-1 vortex

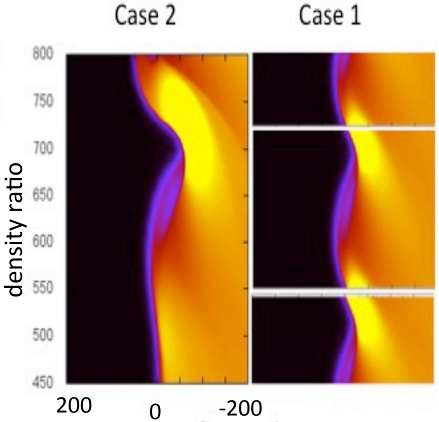
Leading vortex



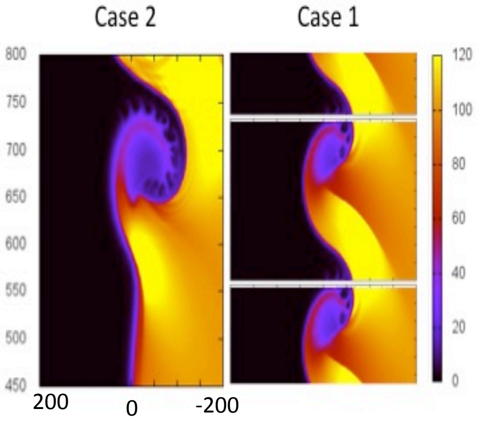
Start point



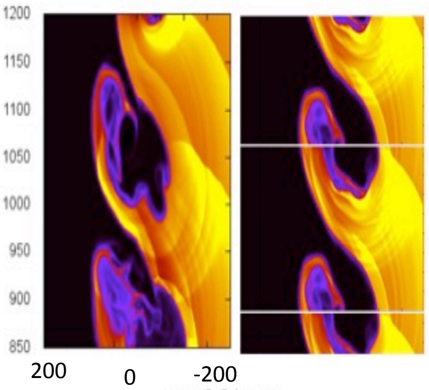
33 [s] later



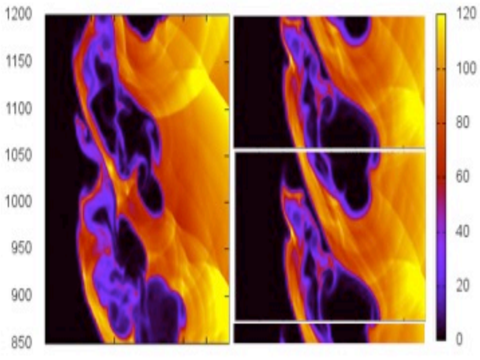
Start point



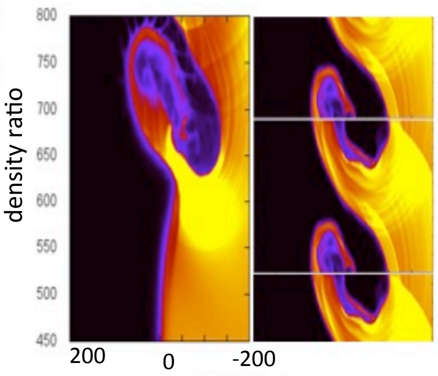
33 [s] later



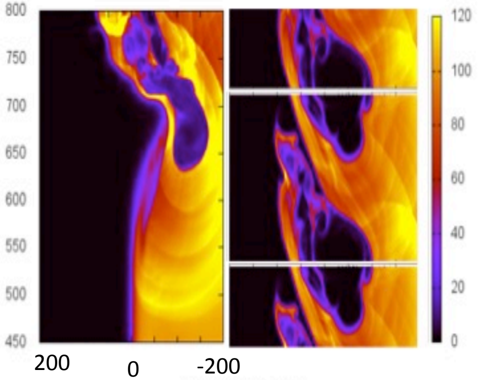
77 [s] later



110 [s] later



77 [s] later



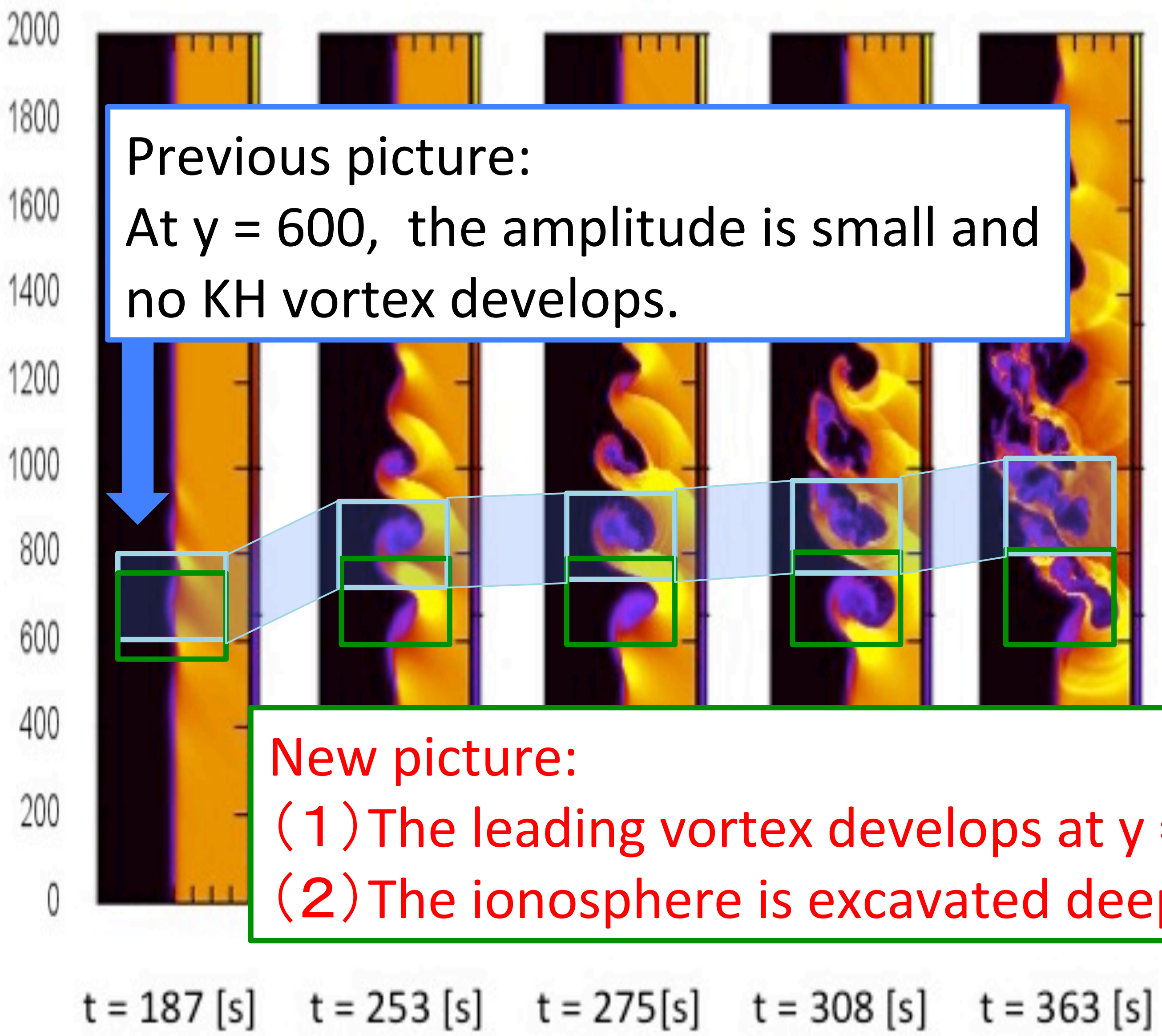
110 [s] later

Mostly same evolution

Completely different.
The leading vortex excavated deeply.

3. Results

[Case 2] Aperiodic & vertical density gradient



Previous picture:
At y = 600, the amplitude is small and no KH vortex develops.

New picture:
（1）The leading vortex develops at y = 600.
（2）The ionosphere is excavated deeply.

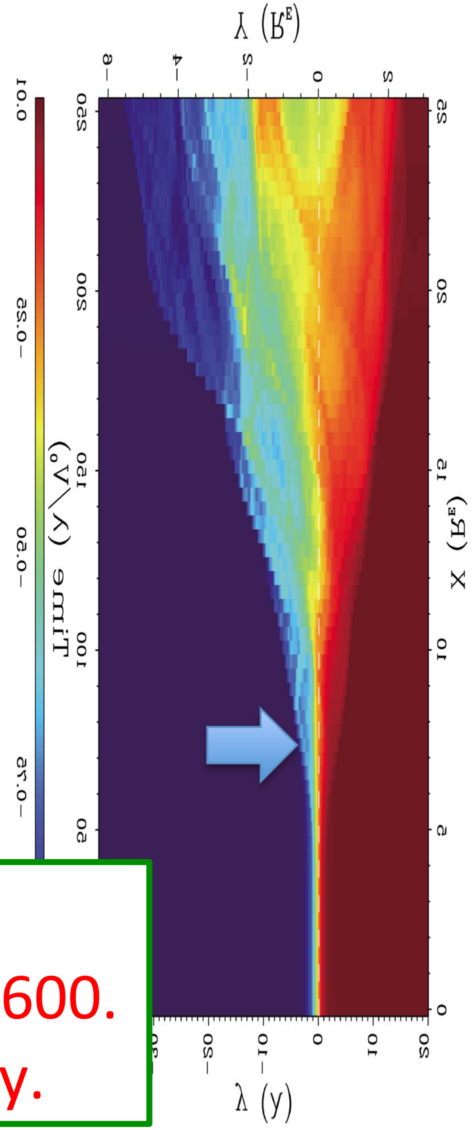
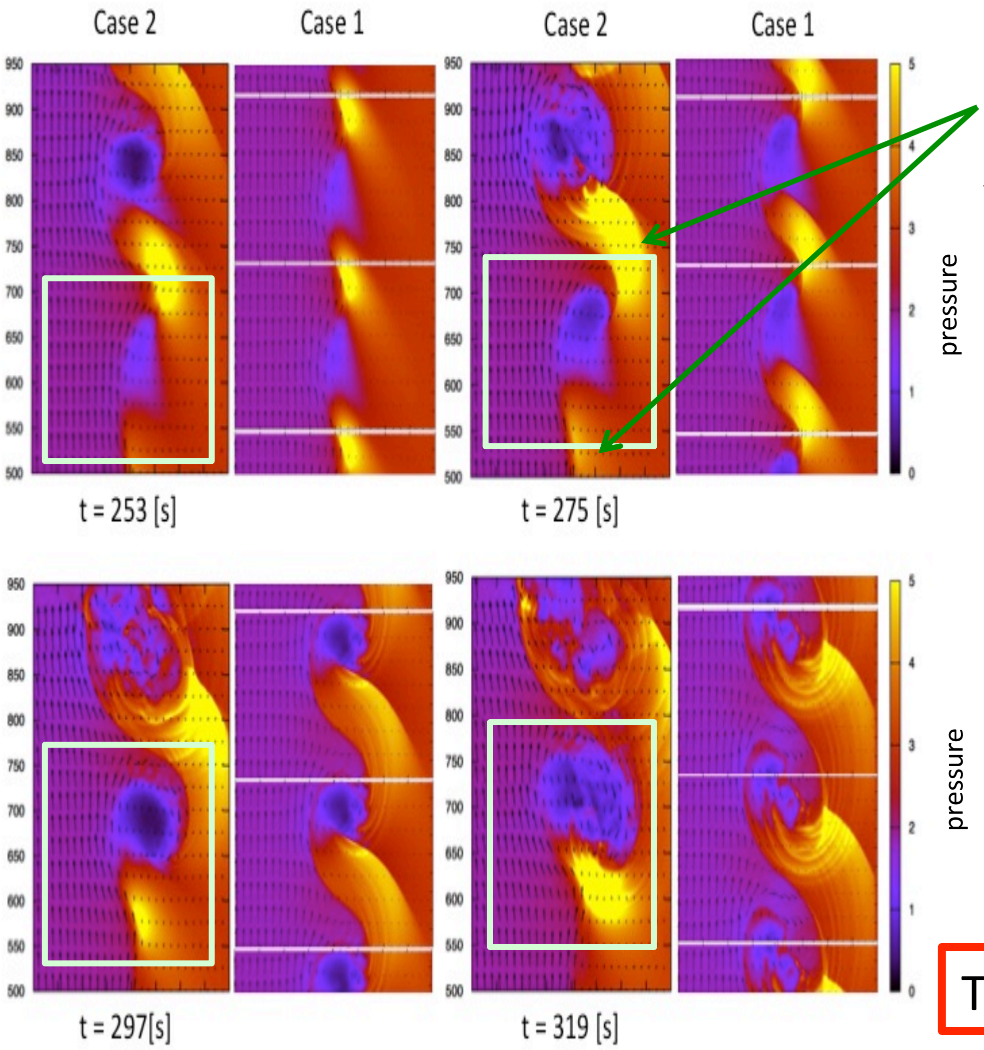


FIG 6. The time history of the average profile of the mixing rate [Matsumoto and Seki, 2010].

4. Discussion

Comparison : Case 1 vs. Case 2

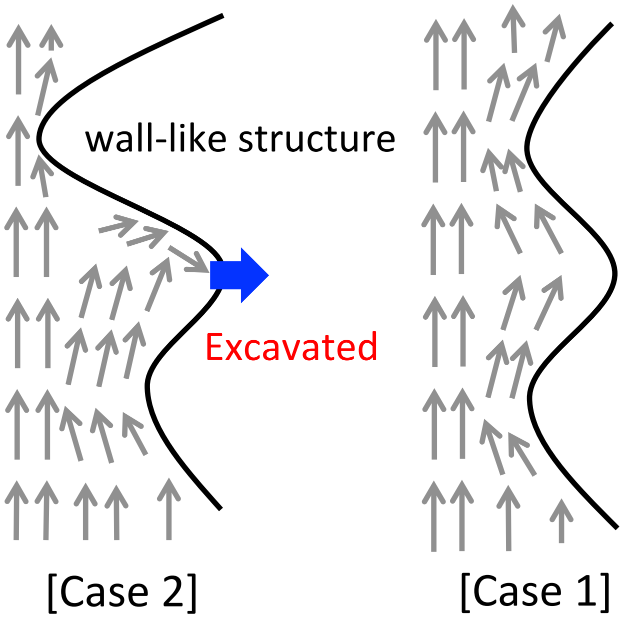
It has been thought that the mixing area gradually increases with the growth of the KH vortices. However, the leading vortex excavated ionosphere deeply during the linear growth phase.



✔ The asymmetry in the structure of both sides of the vortex.

✔ The structure in downstream of the vortex behaves wall against the sheath flow.

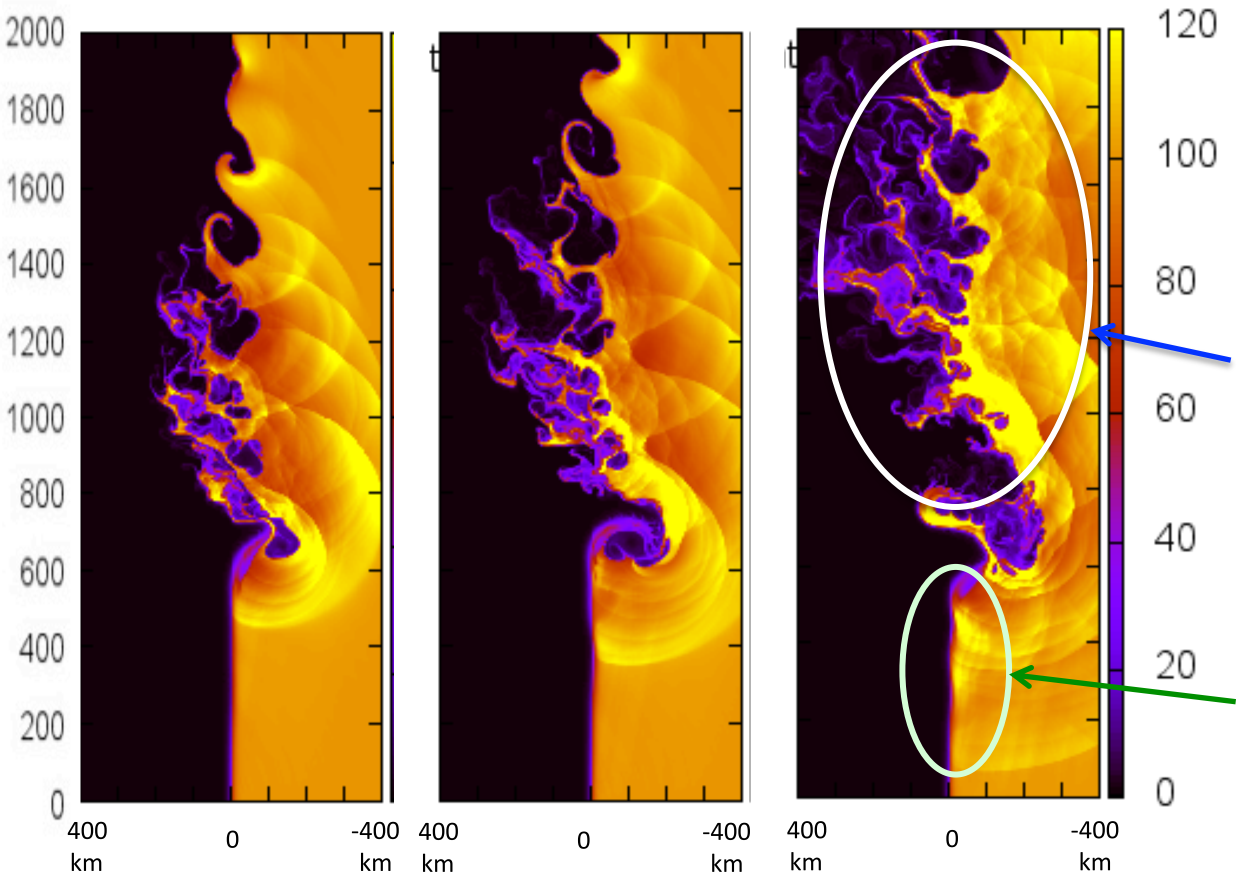
➡ The sheath flow will be stagnated



This excavation enhances mixing of ions

4. Discussion

The later stage of the KH evolution



t = 374 t = 418 t = 550

The later stage of the KH evolution

✔leading vortices arise one after another.
→ionosphere is excavated 200km.

✔Large wave like structure may arise.
It is possible to arise a larger KH vortex.
Simulation domain is not enough.

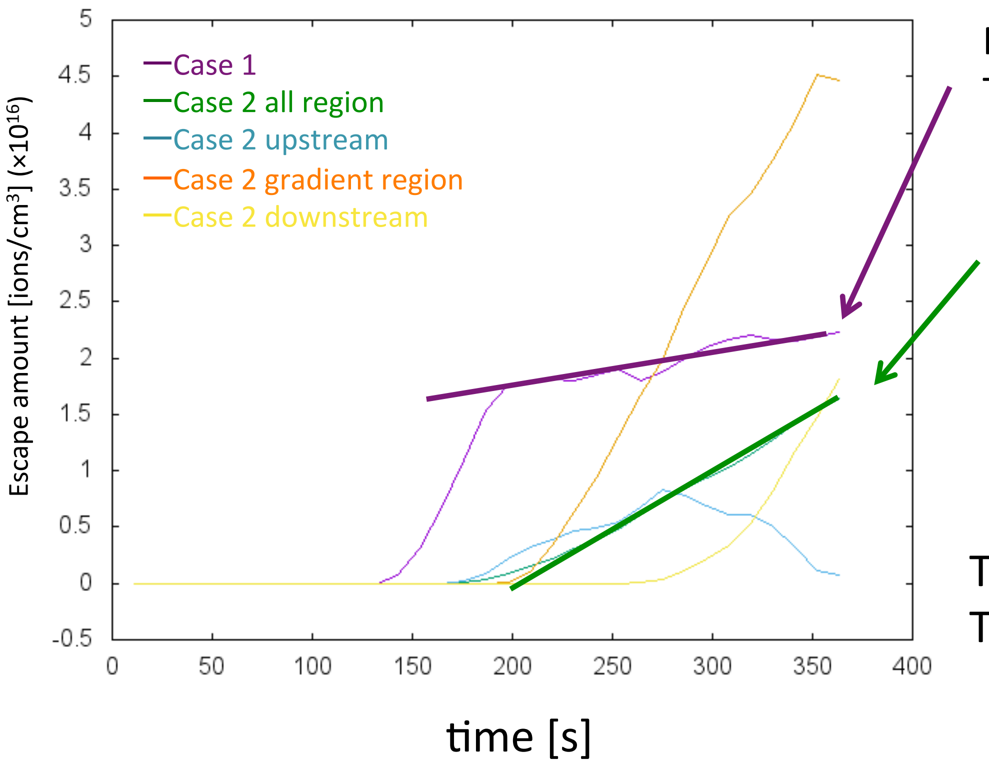
✔Compressibility makes upstream ionopause unstable.

We can see a wave-like structure more clearly in the case of ρ1=10, 50.
→We need a larger simulation box size and time steps in the case of ρ1=100

4. Discussion

loss rate [Case 1 vs. Case 2]

There are many assumptions to evaluate the ions loss efficiency.



Previous assumption :
The ion loss rate are evaluated using this slope.

The loss amount per unit of all region in Case 2 decreases but loss efficiency increases
(because we take an average of all sheath region)

The KH vortex develops one after another.
The slope of previous assumption is ‘transient’

The loss rate in Case 2 is about 3 times larger than that in Case 1.

We can evaluate the ion loss efficiency more directly using the aperiodic boundary condition.

5. Conclusions

The effect of an aperiodic boundary condition

✔ The asymmetry in the structure of both sides of each vortex.
- The ionosphere excavated 1.5 times deeper in Case 2 because of the stagnated sheath flow.
→ The excavation enhances mixing of ionospheric ions.
→ Elongated filaments may be 'tail rays' or 'filaments' observed in wakes of Venus and Mars.

✔ The peak energy of the KH waves increases during the nonlinear phase.
because of the excitation of longer wavelength modes.
→ Aperiodic boundary condition can provide a more realistic picture.

✔ The later stage of the KH evolution
We can see the larger wave-like structure in the later stage of the KH evolution.
It is possible to arise the larger KH vortex.

✔ Ion loss efficiency
We can evaluate the ion loss efficiency more directly using the aperiodic boundary condition.

The effect of the day-to-night density gradient

✔ The asymmetry in the structure of both sides of each vortex
✔ The two-way wave propagation

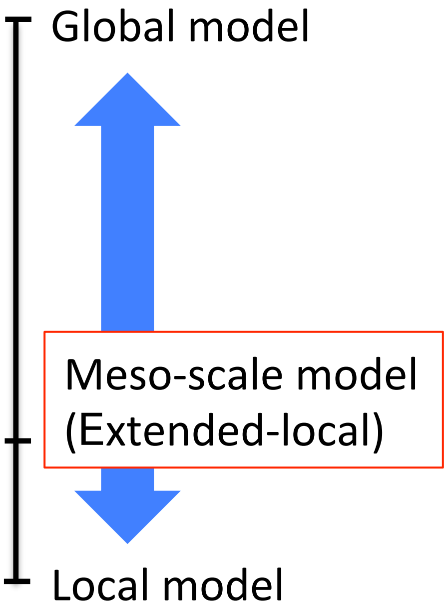
6. Future work

✔ The spatial scale

To investigate the later stage of the KH evolution and to compare simulation results with observation results, the spatial scale is not enough. We need to use a larger simulation box.

✔ Chemical reaction, gravity, etc.

To understand the evolution of the KH instability in more realistic configuration. Some other effects should be taken in consideration.



✔ There is a large gap between global MHD simulation and local MHD simulation

➡

✔ We would like to understand the later stage of the KH evolution and the effect of the asymmetry in the structure for global processes.

✔ We can compare observational results from MAVEN and simulation results

Appendix : the case of rho=10, 50