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FP7 SWIFF Project

Solar Wind - Magnetosphere Interaction: non linear dynamics driven by Kelvin-Helmholtz vortices

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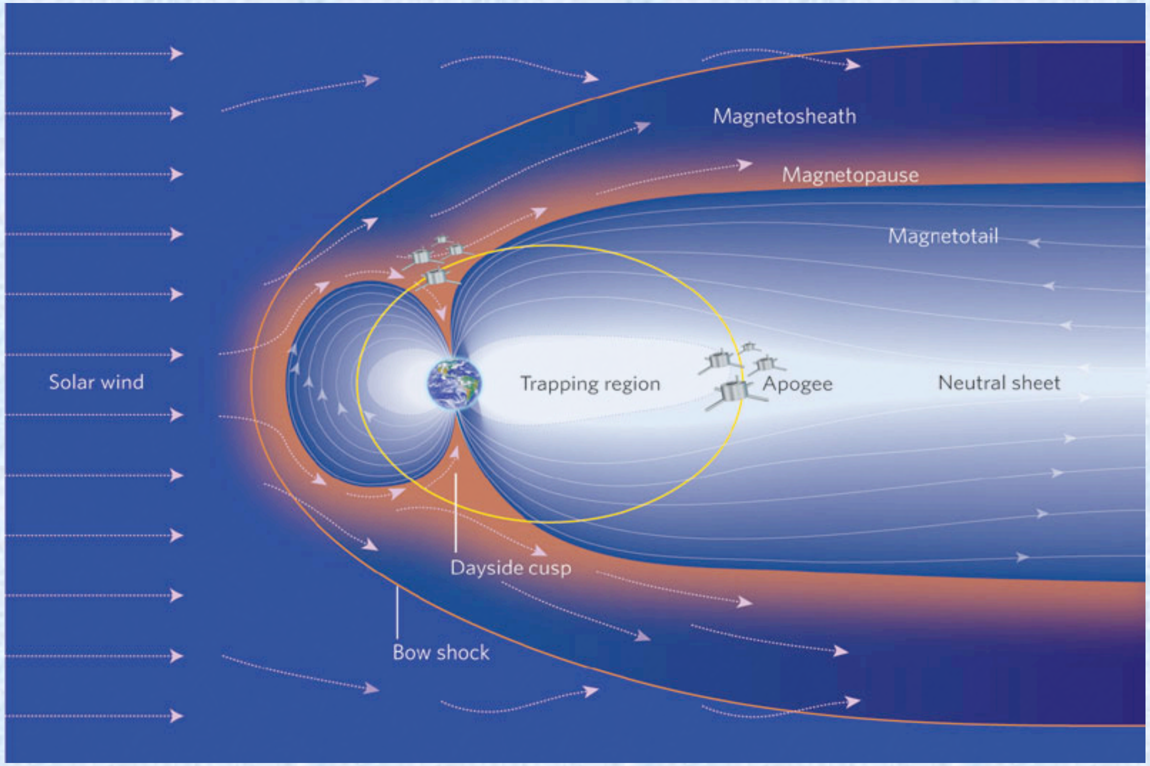
Vienna, WPI, 2011

THE PHYSICAL SYSTEM: SOLAR WIND – MAGNETOSPHERE

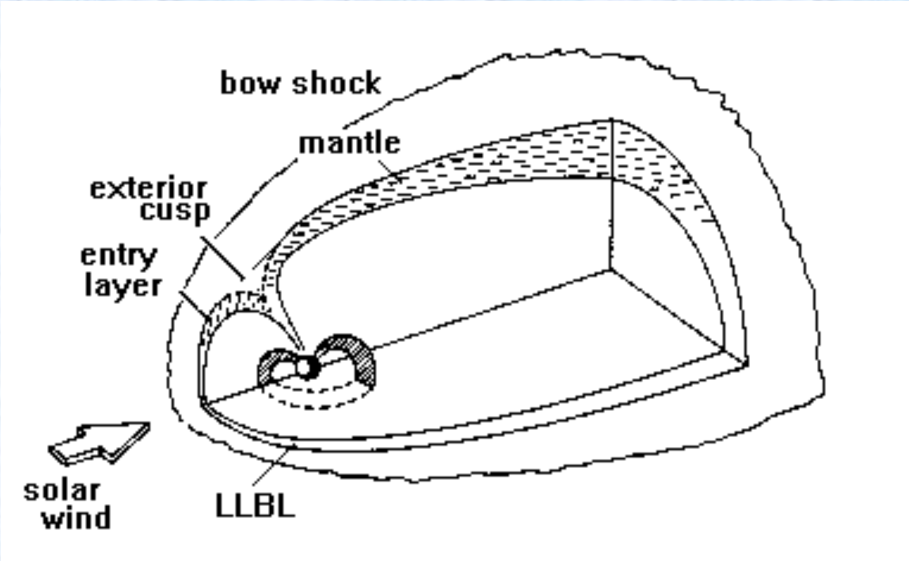
The connection between the solar wind and the Earth's magnetosphere is mediated through the *magnetosheath and magnetopause boundaries*.



The **great interest in the analysis of the processes** at play is:

i) Importance in the shaping and dynamics of the system

ii) A wealth of in-situ diagnostics of improving quality (electromagnetic profiles and particle distribution functions)



Question: how can we represent the 3D large scale field?

Is it a true equilibrium in the MHD sense?

Can satellite data help us ?

The system

The *solar wind-magnetosphere coupling* strongly depends on solar wind properties and their variability, as the density and velocity value or the ***Interplanetary Magnetic Field orientation***.

High-latitude reconnection in both hemispheres converts northward magnetosheath field lines into closed geomagnetic field lines allowing for the ***entry of the magnetosheath plasma into the magnetosphere*** [McFadden et al., 2008]

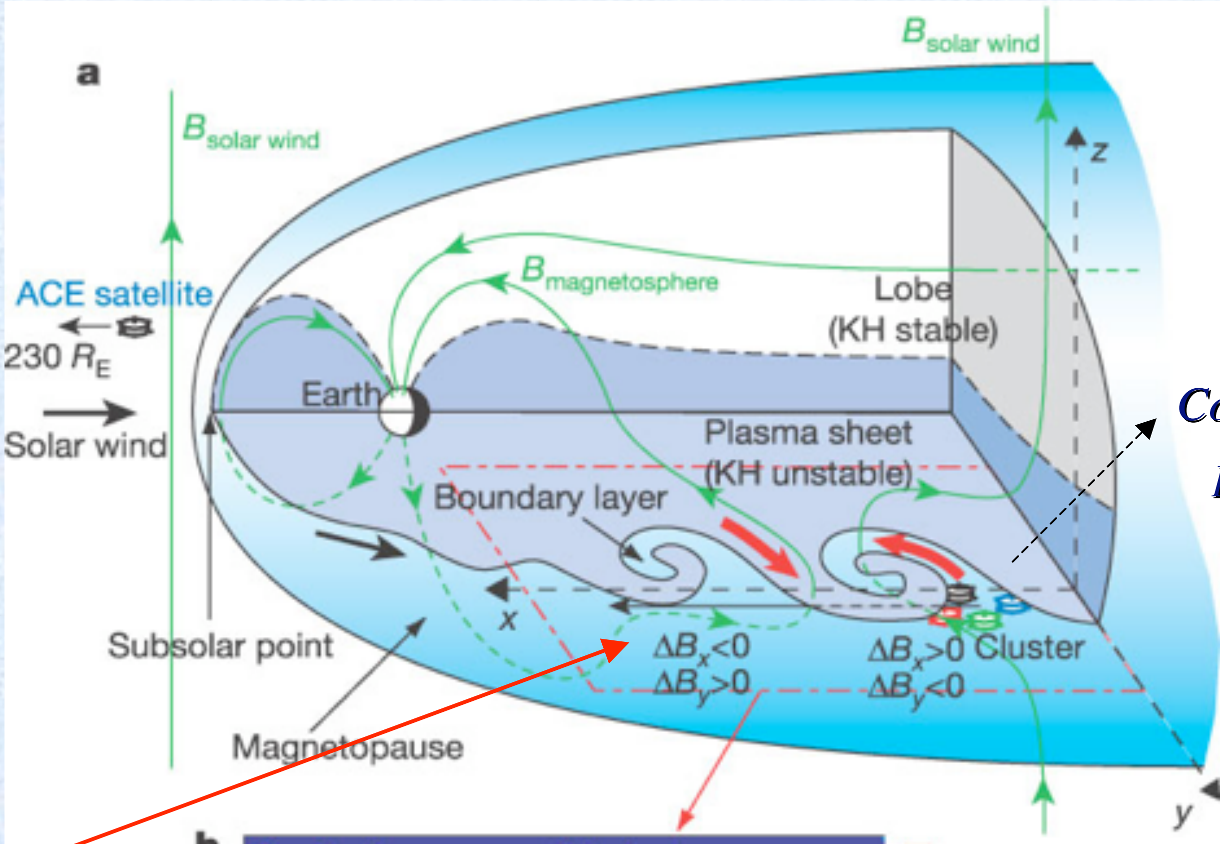
The system

At low latitude, when the IMF is mostly southward:
magnetic reconnection dominates the ***transport***

If reconnection at low latitude would be the only relevant phenomena for mixing, the northward periods (IMF and geomagnetic field parallel) should be relatively quiet -> flank regions dominated by the tenuous and hot plasma of the Earth plasma sheet

On the contrary: during northward periods the near-Earth plasma sheet becomes significantly denser and colder near the flanks suggesting an ***enhancement of the plasma transport*** across the magnetopause [Terasawa et al., Geophys. Res. Lett. 24, 935, 1997]

The ***Solar Wind* - *Earth's Magnetosphere* interaction** in regions where the velocity shear generates rolled-up vortices has been evidenced by *satellite in-situ measurements* [Fairfield et al., 2000; Hasegawa et al., 2004]



Complex non linear phenomenology induced by the K-H vortices

Quasi periodic perturbations often observed near the flank magnetopause

Mixing efficiency strongly increased !

The Kelvin - Helmholtz instability

It has been proposed[1,2] that the **shear flow** between the solar wind and the magnetosphere **drives** the formation of Kelvin - Helmholtz vortices that *tend to pair in the non-linear phase*.

This provides an efficient mechanism for the formation of a mixing layer

At low latitude the magnetic field is nearly perpendicular to the plane of the flow direction and of its transverse variation and does not inhibit the ***development of a "quasi-2D" Kelvin - Helmholtz instability***

[1] G. Belmont, G., Chanteur, in "Turbulence and Nonlinear Dynamics in MHD Flows", 1989

[2] A. Miura, Phys. Plasmas 4, 2871, 1997

KHI: Fast Growing Mode and vortex pairing

Net transport of momentum across the initial velocity shear occurs both when the Fast Growing Mode and its sub-harmonics (paired vortices) grow, and when the vortex pairing process takes place.

In a homogeneous density system,

the momentum transport caused by vortex pairing process is much larger than that due to the growth of the FGM[1]

thus leading to a faster relaxation of the velocity shear.

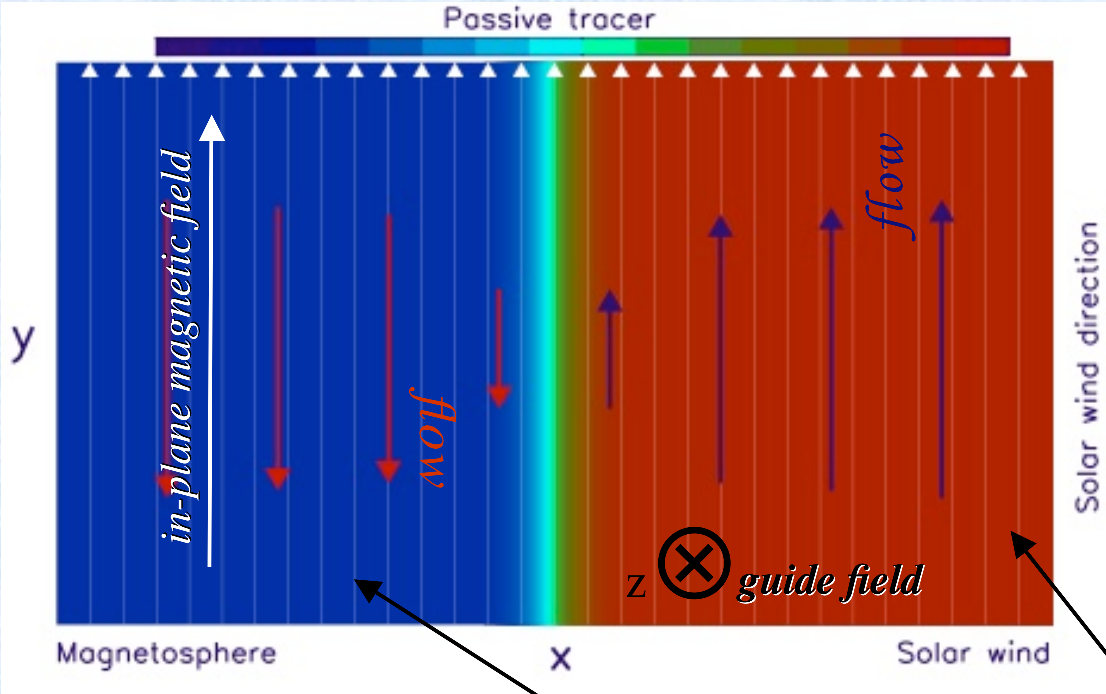
Vortex pairing is therefore expected to be an efficient process in the nearly two-dimensional external region of the magnetopause at low latitude[1]*.*

[1] A. Otto et al., J. Geophys. Res. 105, 21175 (2000)

Low Latitude Boundary layer: the model

The initial magnetic field is mainly perpendicular to the plane where the K-H instability develops and have no inversion points

The equilibrium velocity field in the ***commoving frame***.



$L_u \gg d_i$

$\mathbf{B}_{\text{in-plane}} \ll \mathbf{B}_{\perp}$

$$\mathbf{B} = B_0(x)\sin\theta\,\mathbf{e}_y + B_0(x)\cos\theta\,\mathbf{e}_z$$

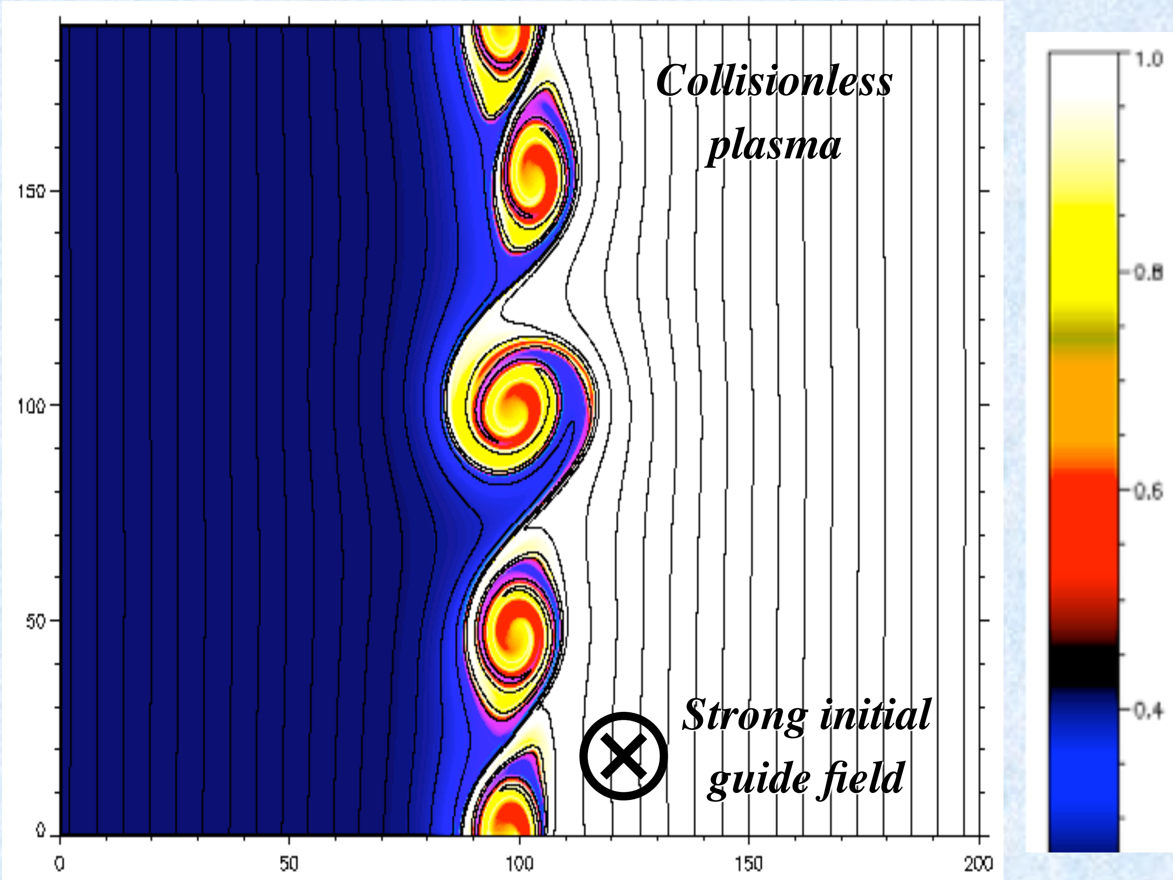
$\theta < 0.1 \Rightarrow$ K-H unstable !

The *magnetospheric* and *solar wind* plasmas are represented using red and blue **passive tracers**

Vortex chain generated by the KH instability

NL dynamics: competition between vortex pairing, Rayleigh-Taylor, Kelvin-Hemholtz, Reconnection

In-plane magnetic field advected by the rolled-up vortices and thus increasingly stretched and compressed



Sub-magneto-sonic regime dynamics dominated pairing and by secondary instabilities

Importance of magnetic field

In many astrophysical and laboratory systems with $\beta \approx 1$, the large scale dynamics is governed by the interplay between flow and magnetic field. At larger β, the flow becomes the main driver. However, even in this limit, magnetic fields can play a key role in the plasma dynamics by violating (locally) the ”ideal” Ohm law thus allowing the system to access ideally forbidden energetic states.

The process capable of violating the linking condition is known as

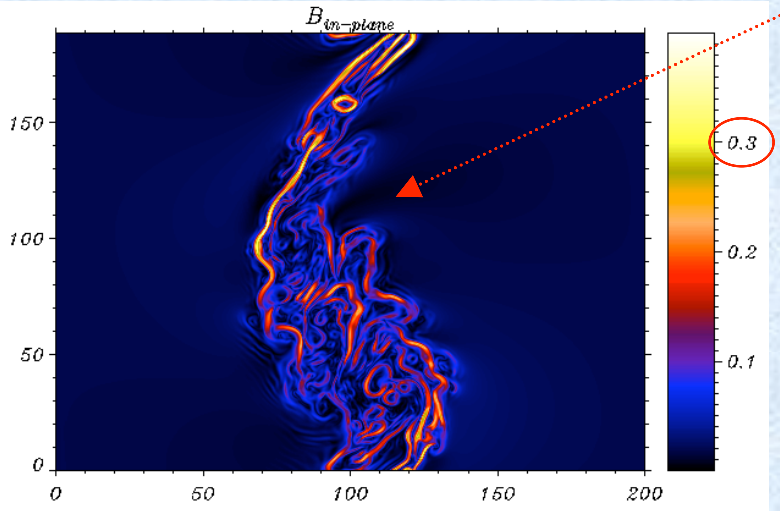
Magnetic Reconnection

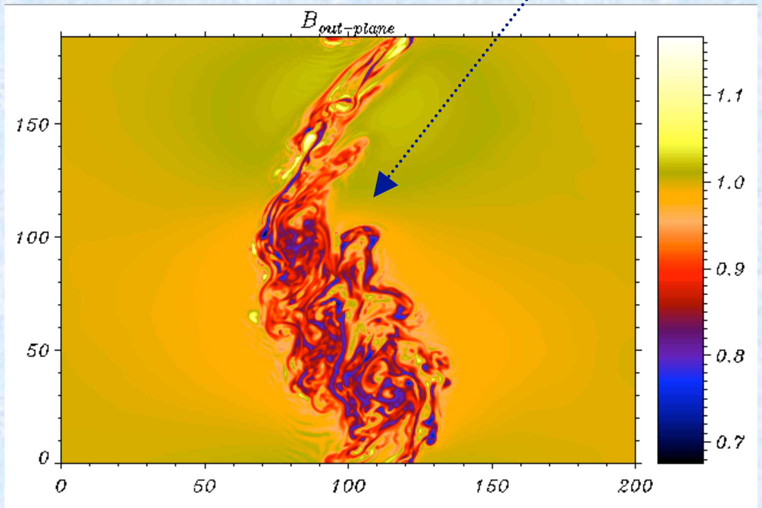
a fundamental plasma physics process being ***the only one capable of*** affecting the ***global energy balance of the system***, of interest in astrophysics, as well as of ***reorganizing the large scale magnetic topology***, a fundamental aspect in magnetic fusion and in theoretical plasma physics.

The role of
The dynamics

During northward periods $\mathbf{B}_{\text{in-plane}}$ is of the order of only a few percent with respect to $\mathbf{B}_{\text{out-of-plane}}$

2D simulation
NL REGIME





Initially **B** homogeneous: $\mathbf{B}_{\text{in-plane}} / \mathbf{B}_{\text{out-of-plane}} = 0.02$

Nevertheless the flow, driven by the **K-H** vortices, is able to **stretch and compress the magnetic field lines** and this in turn generates ***large magnetic fluctuations*** at the Magnetopause [**Otto and Fairfid, 2000**].

Moreover, the MHD KH vortices generate sub-MHD fluctuations at increasingly small scales where ideal constraints are violated thus **allowing the solar wind to enter the Earth's magnetosphere** [**Fujimoto et al., 1998**].

The model

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{U}) = 0$$

Quasi neutrality

$$\frac{\partial (nS_{e,i})}{\partial t} + \nabla \cdot (nS_{e,i}\mathbf{u}_{e,i}) = 0 \qquad S_{e,i} = P_{e,i} n^{-\gamma}$$

Isothermal or Adiabatic closure

$$\frac{\partial (n\mathbf{U})}{\partial t} + \nabla \cdot \left[n(\mathbf{u}_i\mathbf{u}_i + d_e^2 \mathbf{u}_e\mathbf{u}_e) + P\bar{\bar{\mathbf{I}}} - \mathbf{B}\mathbf{B} \right] = 0$$

$$(1 - d_e^2 \nabla^2)\mathbf{E} = -\mathbf{u}_e \times \mathbf{B} - \frac{1}{n}\nabla P_e$$

$$\partial B / \partial t = -\nabla \times E$$

$$B_0(x) = \left[B_{0,R}^2 + 2\left(P_{0,R} - P_0(x)\right) \right]^{1/2}$$

$P_o \equiv$ *total thermal pressure*

Problems: $\rho_i \sim d_i$ (~ 1000 *Km*) » $\rho_e \sim d_e$ » l_{coll} ; $\Pi_{I,j}$ terms important !

1. Kinetic model ? But how to initialize $U(x)\mathbf{e}_y$? Computationally heavy.
2. Fluid modelling of $\Pi_{I,j}$? But then $Q_{i,j,k}$? And $\beta > 1$?

We adopt as first a "**simple**" **fluid approach** with isothermal/adiabatic closure

Initial conditions

*Large-scale, **sheared velocity field** + constant magnetic field.*
Constant density (R-T excluded)

$\mathbf{M_S} = U_0 / C_S = 1.0$

Sub sonic regime
Quasi-perp. magnetized plasma

$\mathbf{M_{A,\perp}} = U_0 / V_{A,\perp} = \mathbf{1.0}$; $\mathbf{M_{A,\parallel}} = V_0 / U_{A,\parallel} = \mathbf{20.0}$

$U_0 = 1.0$; $L_x = 100$; $L_y = 30\pi$; $L_u = 3$; $L_n = 0$;

$$V_{eq} = \frac{V_0}{2} \tanh(x/L_{eq})\mathbf{e}_y$$

$$\mathbf{B} = B_0(x) \sin\theta\, \mathbf{e}_y + B_0(x) \cos\theta\, \mathbf{e}_z \qquad \theta = 0.05$$

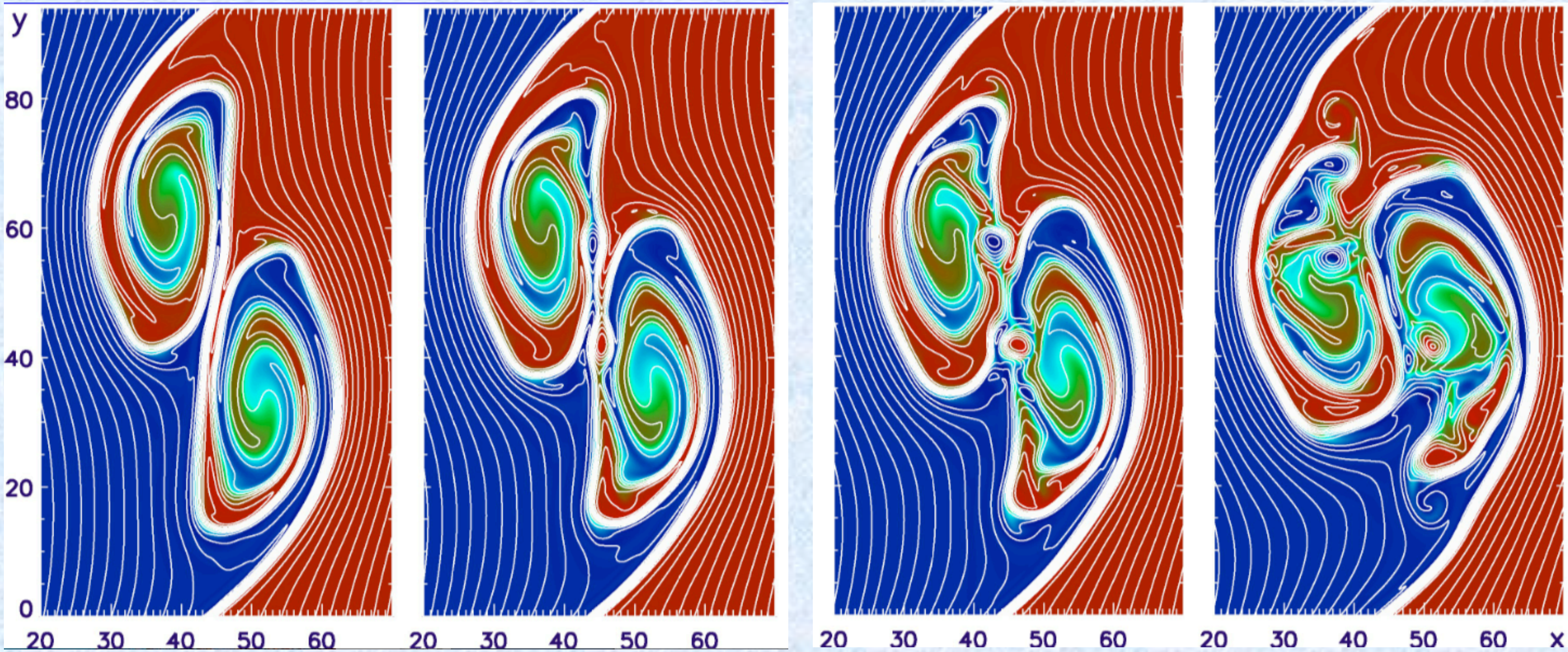
$[\,\vartheta < 0.1\,]$

Transparent boundary conditions[1] along x-axis

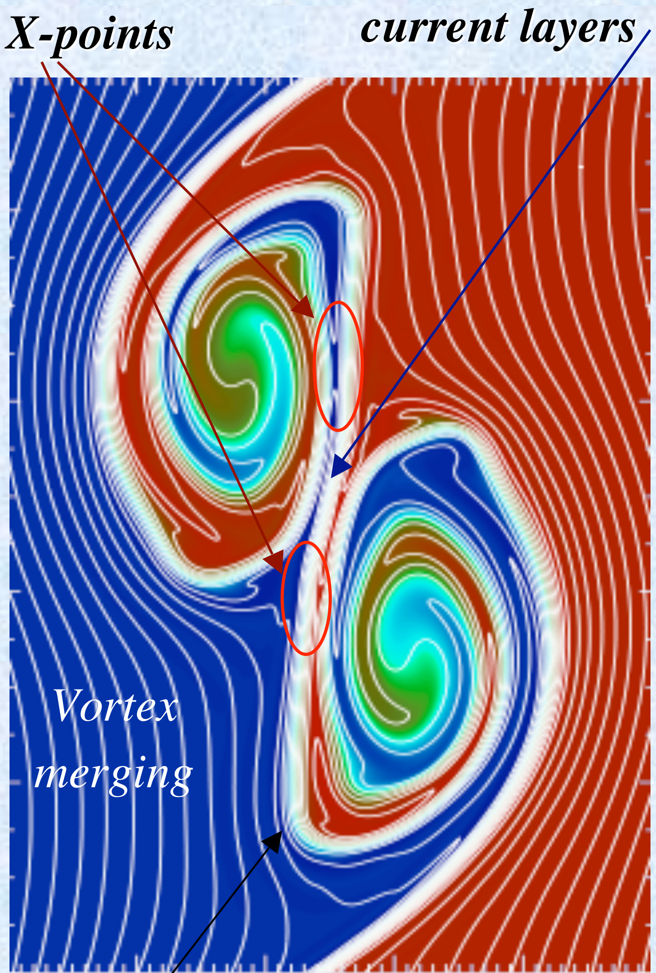
[1] K.W. Thompson, J. Comput. Phys. 68, 1 (1987)

System evolution

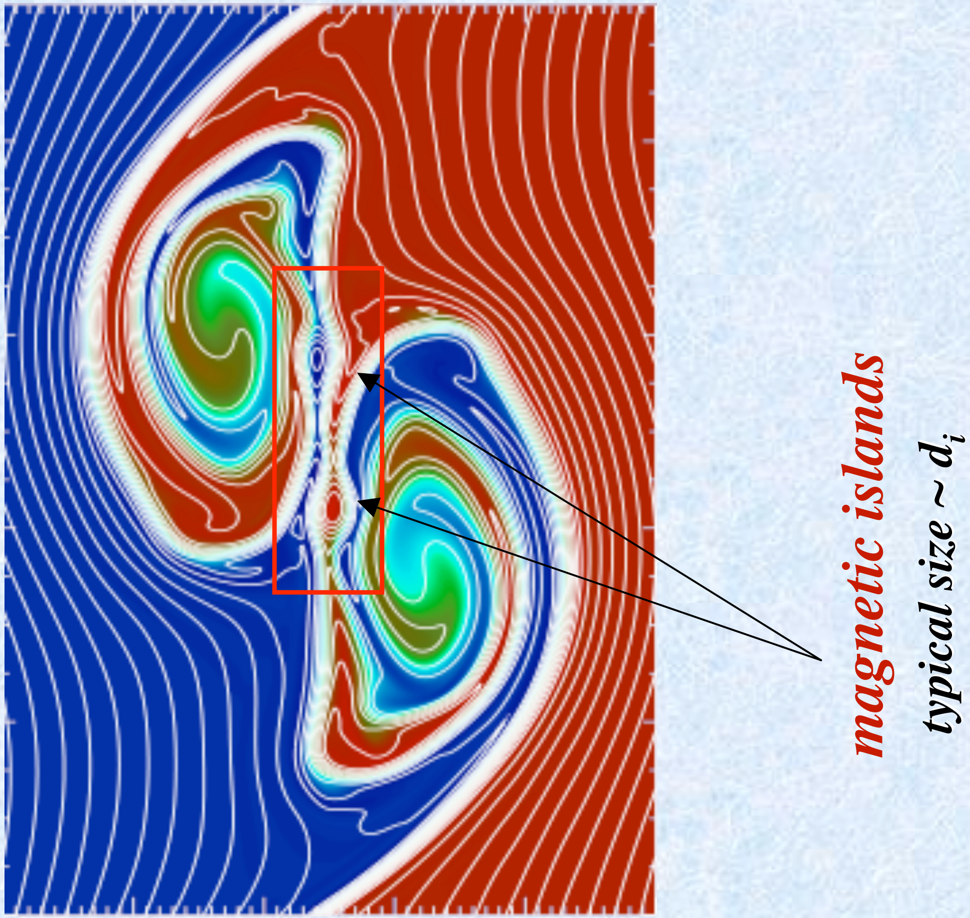
(plasma passive tracer and magnetic field lines)



Plasma passive tracer and magnetic field lines: formation of two vortices by the K-H instability



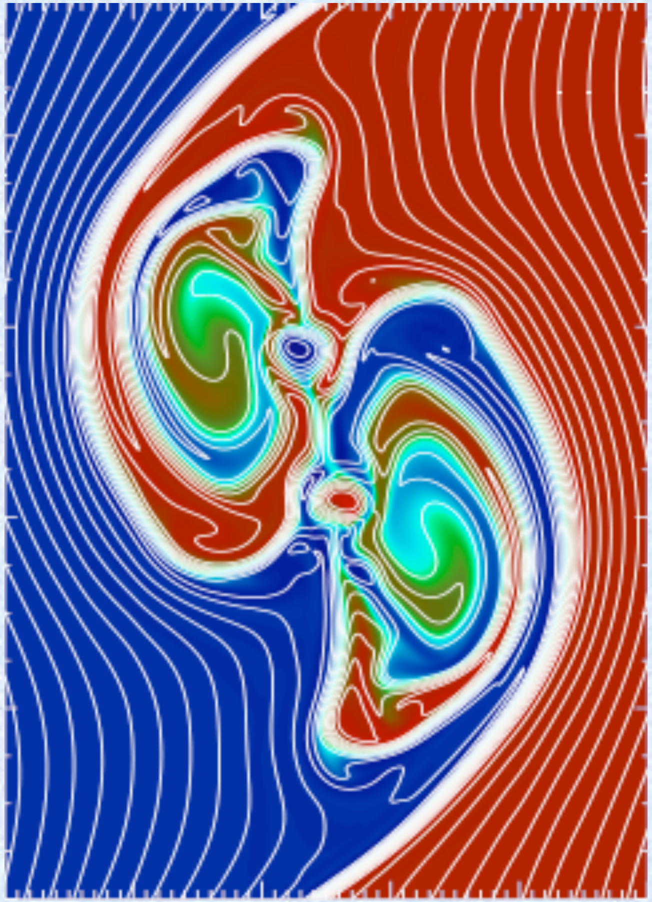
ribbon of nearly parallel, compressed magnetic lines.



Magnetic reconnection develops at the X-points

The inflow plasma velocity at the X-points is $\sim 0.1\ c_{A,\,local}$ (as expected for *fast magnetic reconnection*[*]) $\Rightarrow$ $\gamma \sim 0.1\ c_A / L_{B,\,local} \sim 0.15$ compatible with $d \ln E_z / dt$ at the X-point.

$\boxed{\gamma \sim 0.15}$



In the time interval of a few growth times the two vortices can only rotate by a few degrees

$\Downarrow$

The plasma displacement and the current rearrangement due to vortex rotation are

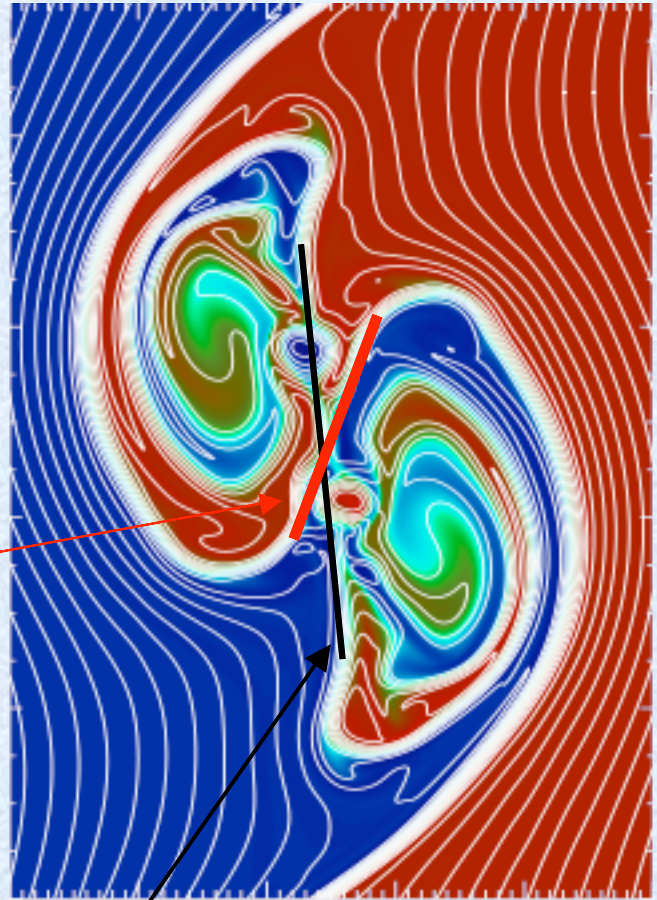
not sufficient rapid to interfere with the reconnection process.

$\Rightarrow$ ***"fast" reconnection***

[*]M.A. Shay *et al*., J. Geophys. Res. **103**, 9165 (1998)

Change inlarge scale magnetic field topology

The field line ribbon shrinks and finally opens up



*A **new ribbon** of field lines appears which no longer separates the red and the blue plasma regions*

old ribbon

Significant portions of the red plasma have been engulfed in the form of "blobs" into the blue plasma region and viceversa.

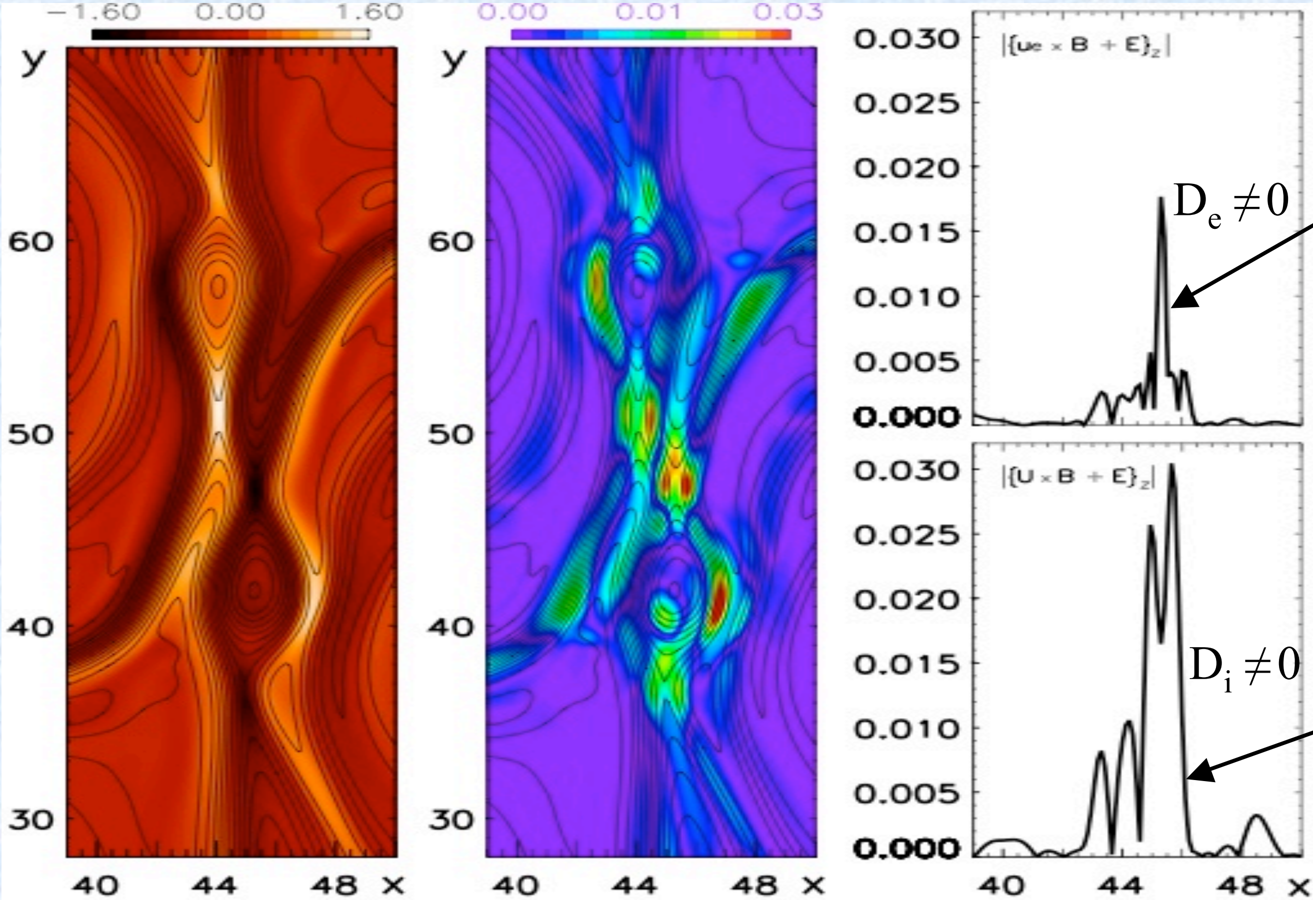
The Hall term

$L_u \gg d_i$ => *electrons and ions both initially magnetized*

In this region the Hall term is comparable to the UXB term

In the reconnection region $B_{in\text{-}plane}$ and B_{gf} are comparable !

Initially $B_{gf}/B_{in\text{-}plane}$ was more than a factor of ten.



~ several d_e

$D_e \neq 0$

$D_e = [\mathbf{u}_e \times \mathbf{B} + \mathbf{E}]_z$

$D_i \neq 0$

~ several d_i

J_z and Ψ between the pairing vortices.

Ion decoupling region $D_i \neq 0$ and Ψ lines.

$D_i = [\mathbf{u}_i \times \mathbf{B} + \mathbf{E}]_z$

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The value of the in-plane magnetic field inside the current sheet is strongly enhanced by the compressional motion of the vortices.

Initial conditions

Large-scale, sheared velocity field + ***density variations*** *;*

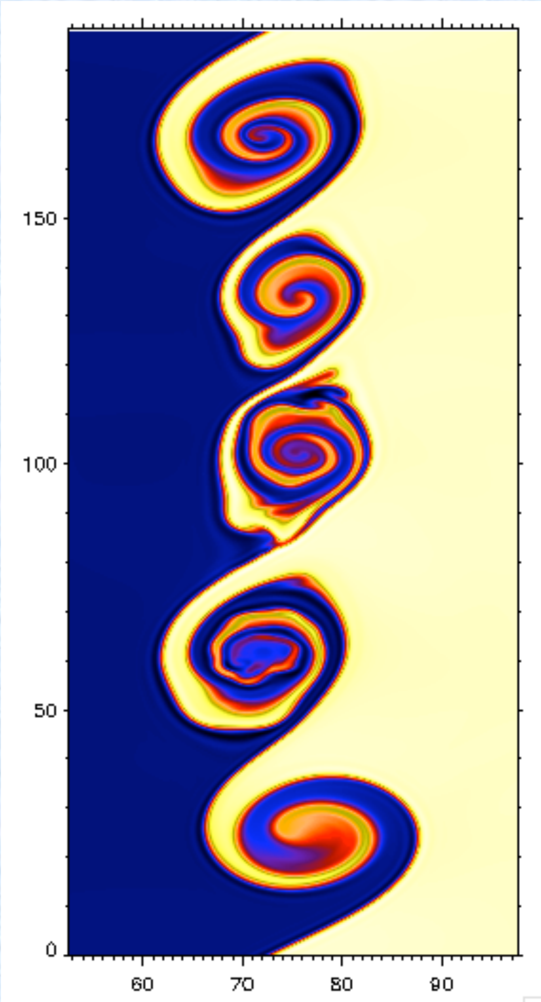
Purely perpendicular magnetic field : Reconnection excluded

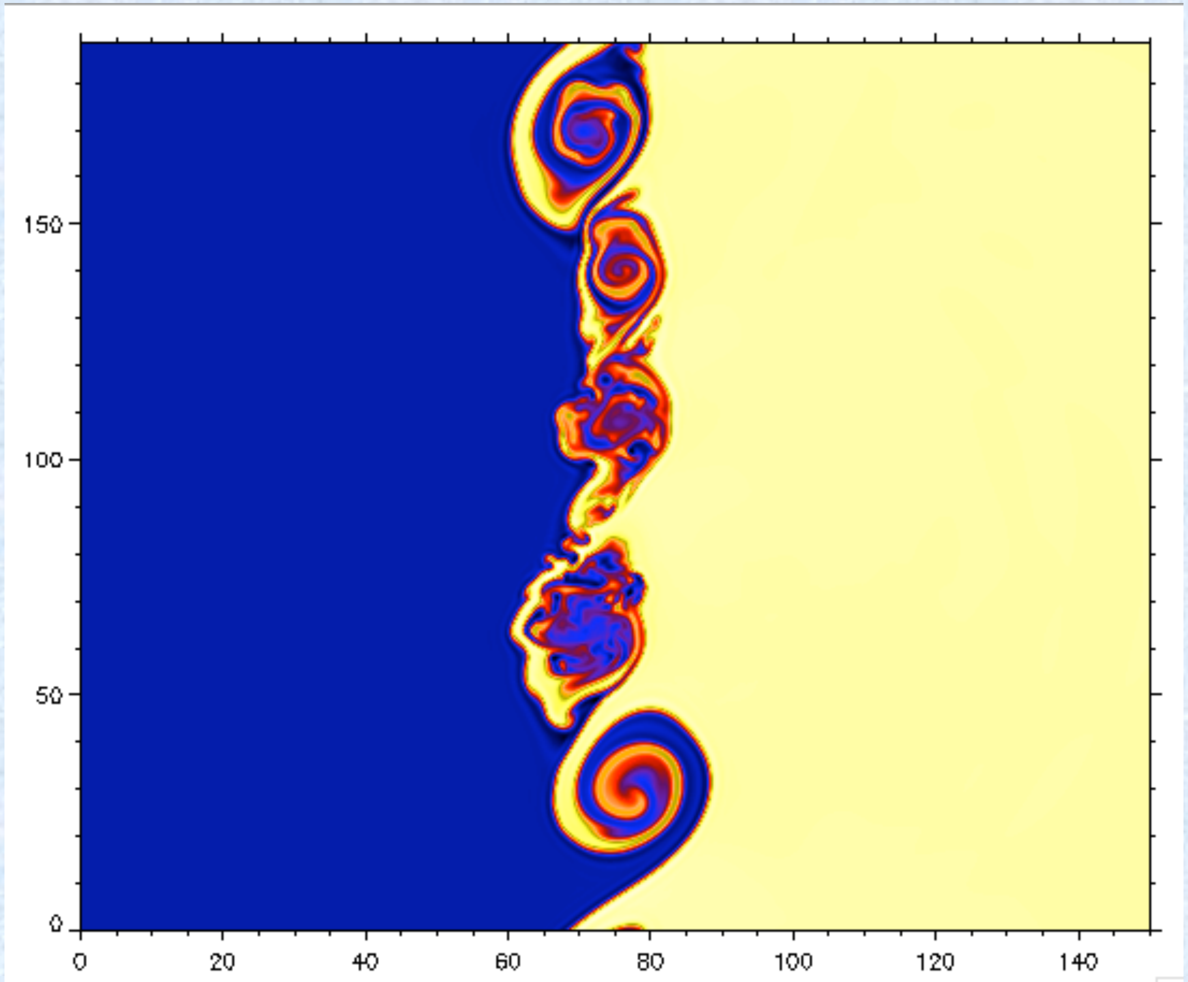
$$V_{eq} = \frac{V_0}{2} \tanh(x/L_{eq}) \mathbf{e}_y$$

According to the satellite observations, ***the plasma density increases*** from the Magnetosphere to the Magnetosheath while the temperature decreases in the same direction.

$$n(x) = n_0 - \frac{\Delta n}{2} [(1 - \tanh(x/L_{eq})]$$

Secondary KH and RT instabilities at play

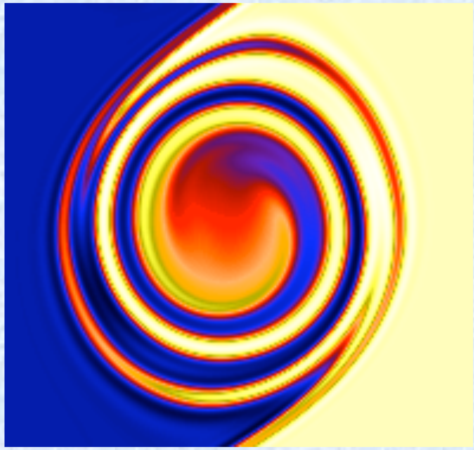




Secondary Rayleigh-Taylor Instability

The **density variation** between the two plasmas strongly modifies the non-linear evolution of the K-H instability possibly leading to the onset of turbulence[1,2].

The ***centrifugal acceleration*** of the rotating K-H vortices acts as an "**effective**" **gravity** force on the plasma.



spiralling arms of alternating right and left density

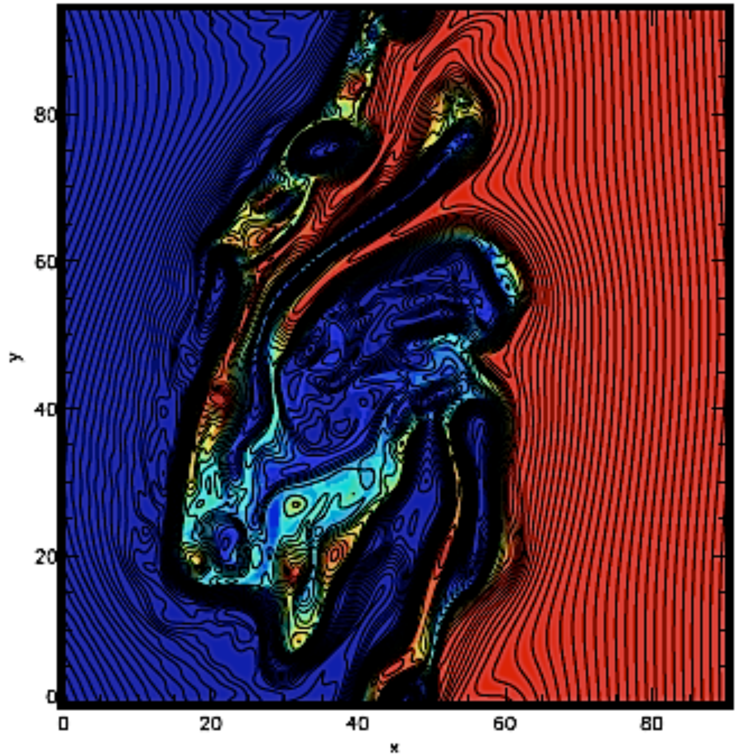
If the density variation is large enough, the **Rayleigh-Taylor** instability can grow along the vortex arms.

[1] W.D. Smyth, J. Fluid Mech. 497, 67 (2003).

[2] Y. Matsumoto et al., Geophys. Res. Lett. 31, 2807 (2004)

Secondary Rayleigh-Taylor (KH) Instability

How quickly the vortex becomes turbulent is crucial since the turbulence caused by the onset of the R-T secondary instability may destroy the structure of the vortices before they coalesce and may thus be the major cause of the increase in the width of the layer with increasing velocity and density inhomogeneity.



Tenerani et al., Plasma Phys. Contr. Fusion (2010)

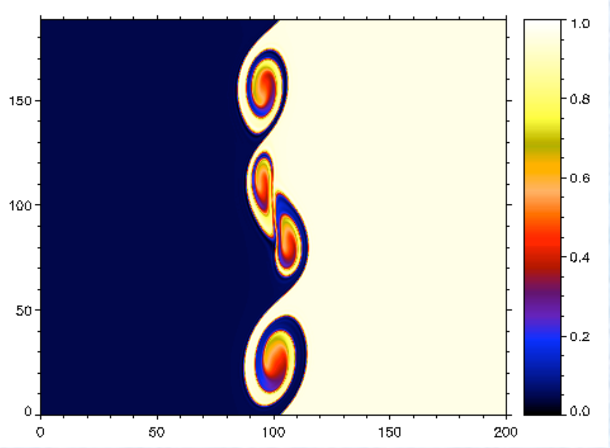
$V_0 = 1.0$; $D_n = 0.8$

$L_u = L_n = 3, \; L_x = 90, \; L_y = 30\pi;$

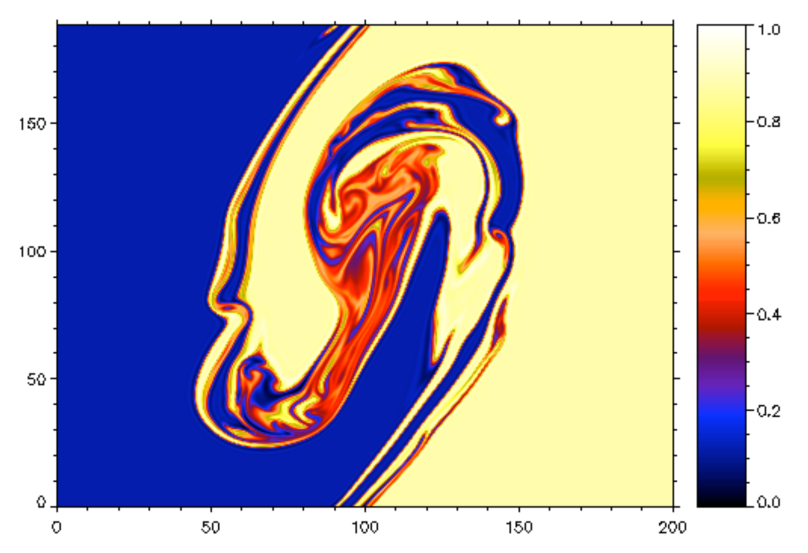
$M_S = U_0 / C_S = 1.0; \; M_A = U_0 / C_A$

Vortex pairing

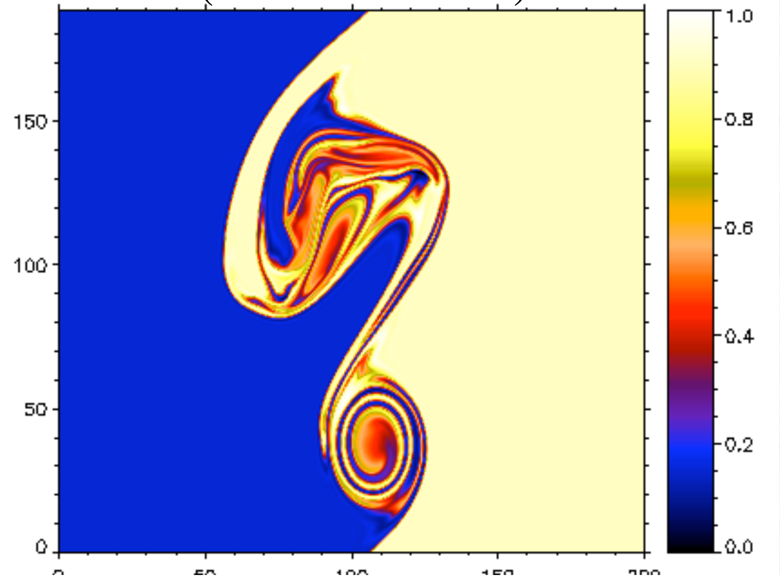
formation of
four vortices



vortices merging



Vortex interaction
(inverse cascade)



$V_0 = 2.0$; $\Delta_n = 0.5$;

$B_0 = 1$ ($B_{in\text{-}plane} = 0.0$)

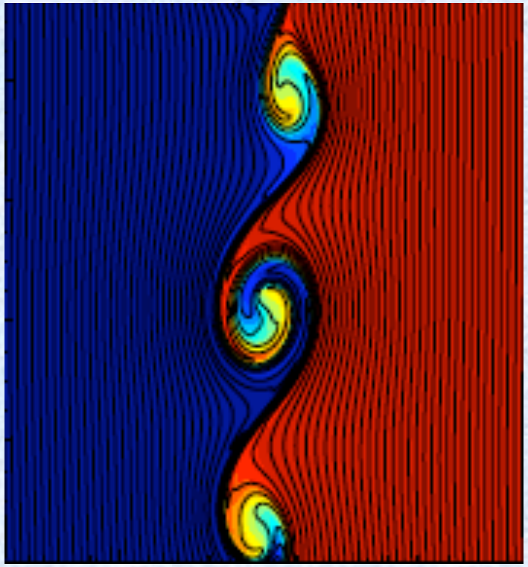
$L_u = L_n = 3,\ \ L_x = 200,\ L_y = 60\pi;$

Mixing layer

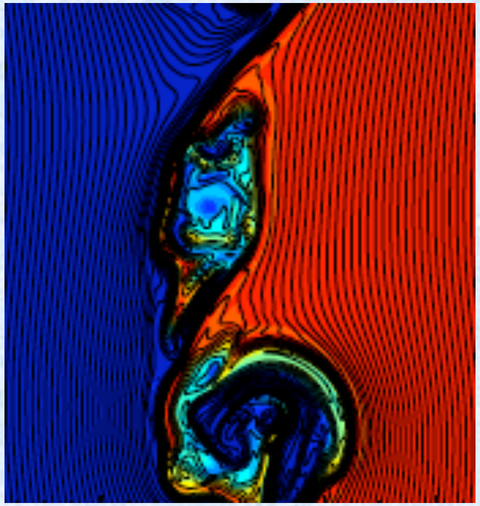
Strong density jump, $\Delta n = 0.8$

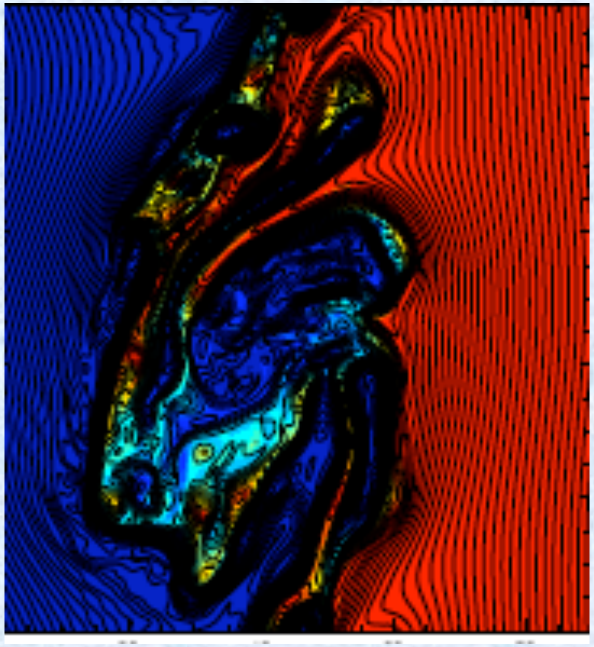
formation of a turbulent layer

KHI



Development of the R-T instabilities in the vortex arms





M. Faganello. F. Califano. F. Pegoraro. Phys. Rev. Lett. 100. 015001 2008

Onset of the secondary instability

We consider each vortex separately and to be stationary

We model the vortex as an "equilibrium”. Inside two nearby vortex arms: n_1, u_1 more dense ; n_2, u_2 less dense $\Longrightarrow$ density and velocity values off *two superposed fluid plasmas* in a slab geometry.

*The two plasma slabs are subjected to an "**effective**" **gravity** which corresponds to the centripetal acceleration arising from the arms curvature*

$\ell_u \;\; \ell_n \equiv$ scale length of the velocity and density gradient between the two arms; $\lambda \equiv$ wave length along the vortex arm associated to the observed R-T.

Typical values: $\ell_u \sim \ell_n \sim 1$; $1 \leq \lambda \leq 10$ (dimensionless)

The R-T growth rate is compatible with simulations

We model the system by a step-like configuration since the R-T instability is not affected by the finite value of the length ℓ_n , at least when $\lambda \geq \ell_n$

$$\gamma_{RT} \approx [\, g_{eff}\, k(\alpha_1 - \alpha_2)]^{1/2}$$

where $\alpha_1 = \rho_1/(\rho_1+\rho_2)$, $\alpha_2 = \rho_2/(\rho_1+\rho_2)$

$g_{eff} \approx 0.1$ estimated using the Ω_{vortex} and r_{arms}

For $\lambda = 10, 4, 1$ we get $\boxed{\gamma_{RT} = 0.2,\ 0.3,\ 0.6}$

The K-H growth rate is not compatible with simulations

K-H modes are heavily affected by the finite value of the shear-length ℓ_u

According to [1] we estimate the influence of the finite velocity shear layer on the secondary K-H instability that could develop in the vortex arms, as

$$\boxed{\gamma_{KH,max} \approx 0.2\ \Delta U/\ 2\,\ell_u \approx 0.06}$$

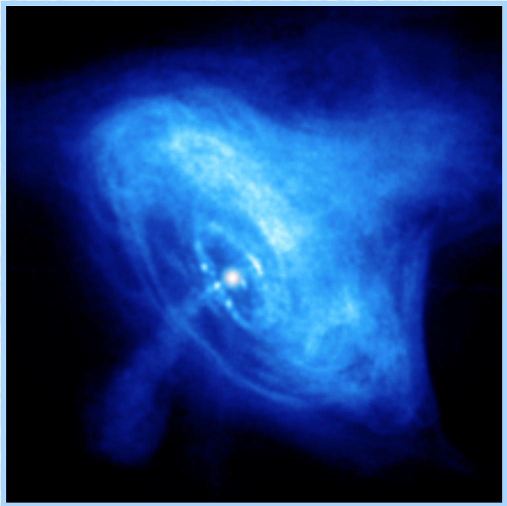
In conclusion, the R-T instability dominates

[1] A. Miura *et al.*, J. Geophys. Res. 87, 7431 (1982)

The Magneto-Rotational Instability is negligible

We observe that the variation of the angular velocity inside the vortex is not large enough to excite the Magneto-Rotational Instability[1].

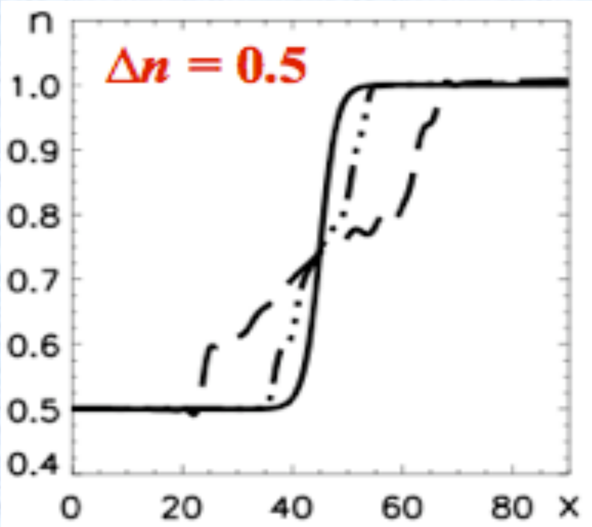
This suggests that this instability, which involves perturbations that depend on the *z*-coordinate is not important for the non-linear evolution of the KH vortex in a transverse magnetic field configuration and allows us to consider perturbations with $\boxed{\partial/\partial z = 0.}$



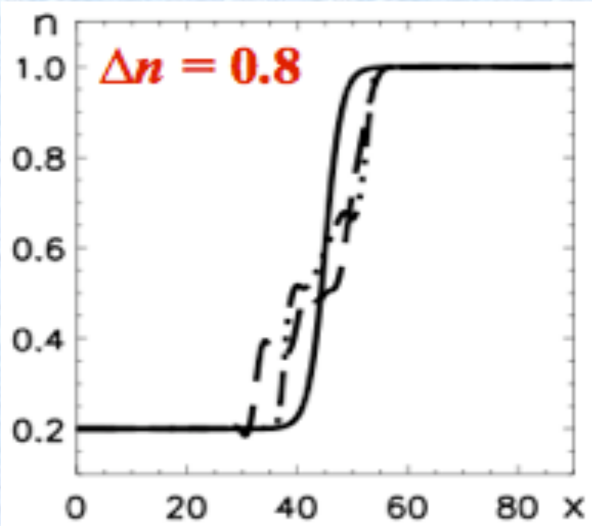
***MRI** important in accretion disks*
(transport of angular momentum, amplifying fields, generation of turbulence…)

[1]E.P. Velikhov, Sov. Phys. JETP 9, 995 (1959)

The competition between the vortex pairing process and the development of a turbulent layer has important consequences from an **observational** point of view and can affect the transport properties of the system.



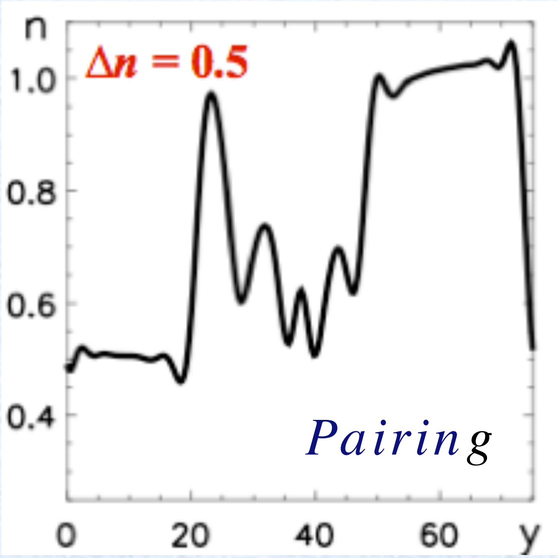
*"**Pairing**" : density profile inclined in the x-direction with a thickness directly related to the size of the vortex*



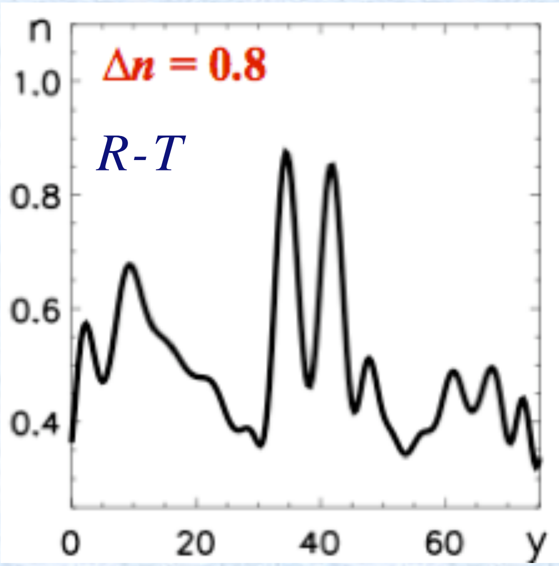
*"**Turbulence**": a plateau is formed in the central region of the sheared layer. Note an asymmetric evolution of the average density profile, indicating a diffusion of the plasma from the dense to the tenuous region with a mixing thickness comparable with the FGM vortex size.*

Mean density profile

Observational aspects



We observe well defined structures with typical length ~ L_y / 3 consisting of the well known[1,2] step-like configuration containing filament-like profiles in the central region of the vortex.



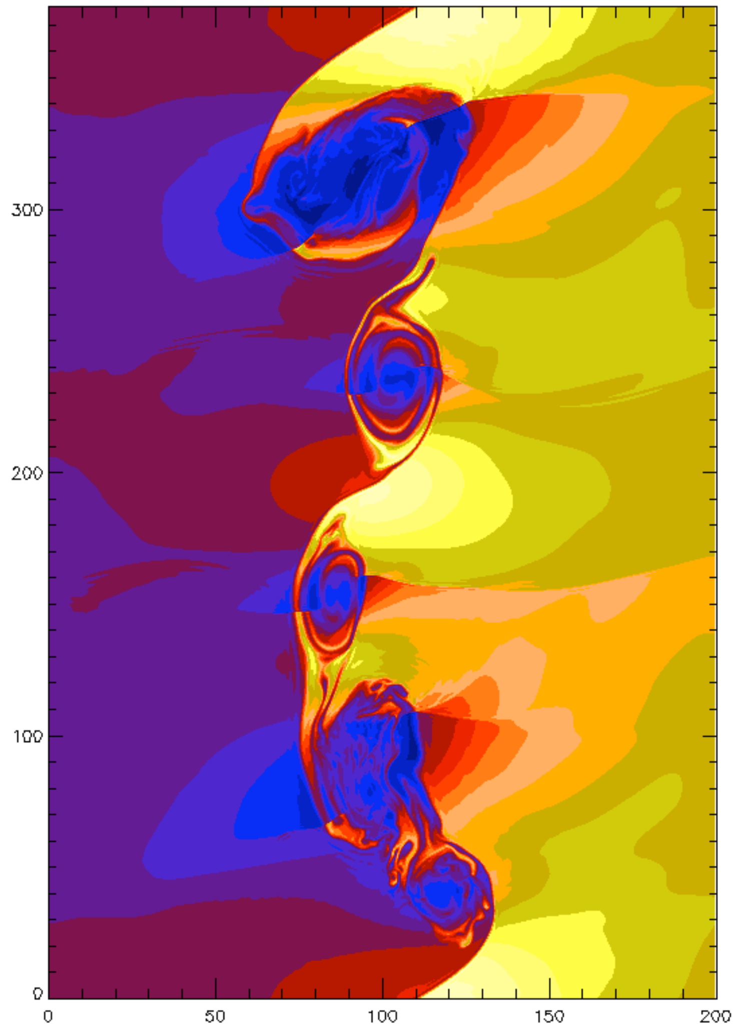
Alternating high and low density filaments that do not exhibit a well defined wave length related to the transition of the system to a "turbulent" state with the formation of a mixing layer

Plasma density profile along the solar wind

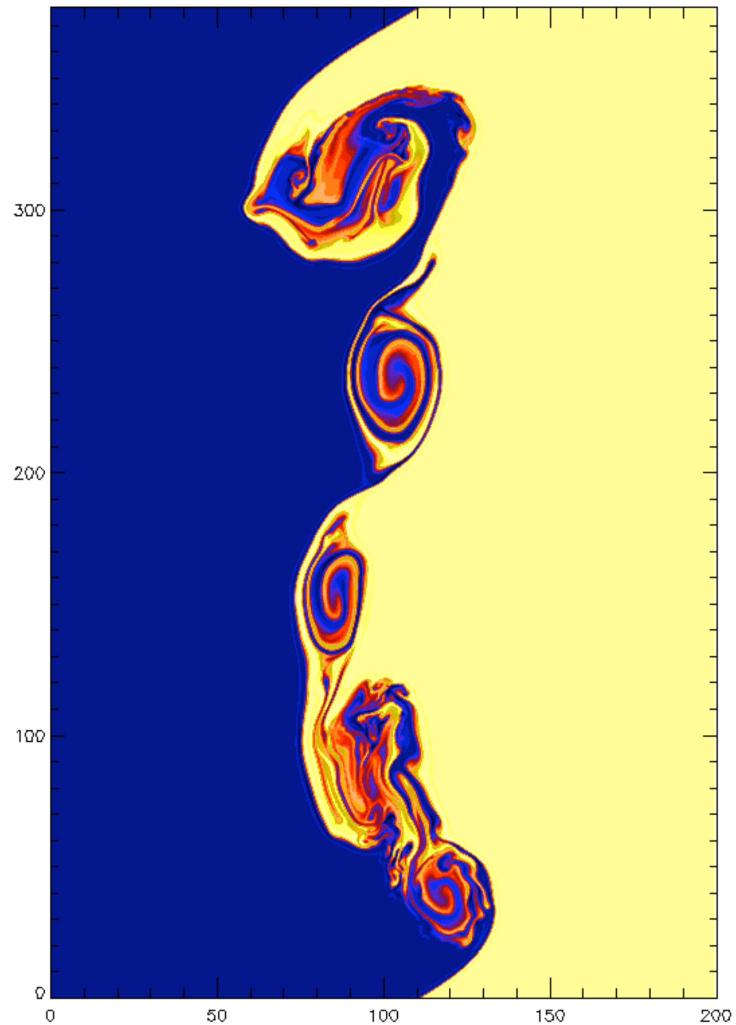
[1]H. Hasegawa *et al.*, Nature 430, 755 (2004)
[2]A. Otto et al., J. Geophys. Res. 105, 21175 (2000)

Larger flows, hydrodynamic regimes

$V_0 = 3$; $\Delta n = 0.5$, $B_{in\text{-}plane} = 0.02$;



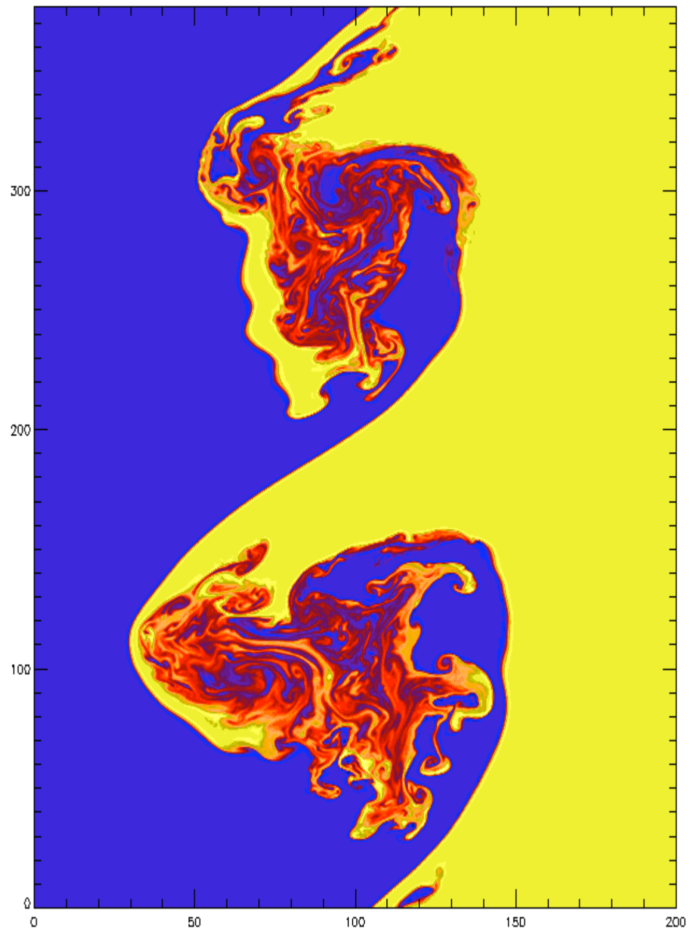
density



passive tracers

…larger flows, hydrodynamic regimes

Strong flow generates low density vortices.
***Mixing extremely efficient*.**



$$V_0 = 3.0\ ;\ \Delta_n = 0.5;$$

$$B_0 = 1\ (B_{in\text{-}plane} = 0.02)$$

$$L_u = L_n = 3,\ \ L_x = 200,\ L_y = 120\pi;$$

$$M_S = U_0 / C_S = 1.0;\ M_A = U_0 / C_A$$

From sub-sonic to super-magnetosonic regimes

The physical properties of the solar wind change when crossing the Earth's bow shock and moving tailward inside the magnetosheath where, according to the Rankine-Hugoniot relations, plasma density and temperature increases thus leading to subsonic velocities.

However, at larger distances the shocked solar wind regains a fraction of its initial speed as it flows past the magnetosphere[1] while the plasma temperature decreases more and more[2]. In particular, near the magnetopause flanks, the velocity of the magnetosheath plasma is increasingly accelerated as the distance from the Earth increases.

⇒ we can expect a transition to a supersonic regime for the KHI in the tail region of the magnetopause

[1]Fairfield et al., J. Geophys. Res., 105, 21.159 (2000)

[2]Spreiter et al., Planet. Space Sci., 14, 223 (1966)

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Super-magnetosonic regimes

We stuy this regime by ***increasing*** *V_0*

Transition towards m.s. Mach numbers ≥ 1:
the ***vortex*** *acts as an* ***obstacle*** *leading to*
formation of shocks structures
extending far from the transition region.

System dynamics: in this “strong” flow regime, rarefaction and compressional effects play a key role. In particular the vortices are now of low density thus *modifying the non linear dynamics* (pairing, secondary instabilities) observed in the "low” Mach number regime.

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Importance of the shocks

1) The shocks could provide an ***efficient mechanism for particle acceleration***.

Usually the existence of super-thermal ions and electrons observed in the cold magnetosheath has been explained as a product of magnetic reconnection and/or a hot magnetospheric plasma injection[1,2]. The particle acceleration associated with the, vortex induced, shocks could instead provide a different explanation.

2) Periodic shock structures observed away from the magnetopause could provide an ***indirect signature of fully developed KH vortices*** at the magnetopause in supersonic conditions.

[1] Fujimoto et al., J. Geophys. Res. 103, 2297 (1998)

[2] Lavraud et al., J. Geophys. Res. 110, A062109 (2005)

Observations

The ***super-sonic regime*** has been recently considered[1] using spacecraft measurements around the Earth's Magnetopause during northward magnetic field periods. Typical values of the Magnetosheath sonic and ***magneto-sonic Mach numbers*** were $M_s^{sw} \approx 1.4, 1.9$ and $M_f^{sw} \approx 1.7, 2.0$, ($X_{GSM} \approx - 4\ R_E$, $X_{GSM} \approx - 13\ R_E$)

Previous investigations[2,3] of K-H vortices signatures at $X_{GSM} \approx - 14\ R_E$, have observed ***larger sonic and magneto-sonic Mach numbers***, namely $M_f^{sw} \approx 3.7$, $M_f^{sw} \approx 2.2$

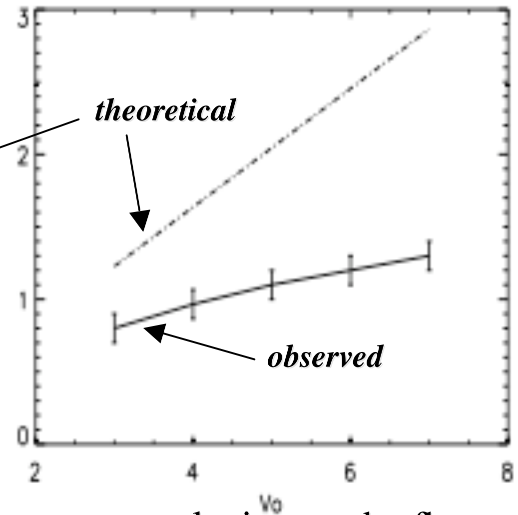
[1] Gnavi et al., J. Physics: Conf. Series 166, 012022 (2005)
[2] Fairfield et al., J. Geophys. Res. 105, 21.159 (2000)
[3] Hasegawa et al., Nature 430, 755 (2004)

Vortex propagation due to density variations

The most important effect with respect to the uniform density regime is that the vortices now propagate in the same direction of the flow where the plasma density is larger (but less than expected).

$$V^{vort}_{theor} = \frac{V_0}{2}(n_{0,R} - n_{0,L})/(n_{0,R} + n_{0,L})$$

(incompressible plasma with density discontinuity)



The vortex velocity vs. the flow velocity V_0 in the simulation reference frame)

Fast magneto-sonic Mach $M^{sw}_f = V^{sw}/c_f \; ; \quad c_f = (c_s^2 + c_A^2)^{1/2}$

Convective Mach number $M^{vort}_{f,L/R} = U_{L/R}/c_{f,L/R} \; ; \quad U_{L/R} = \|V_0/2 \mp V_{vort}\|$

Numerical simulations

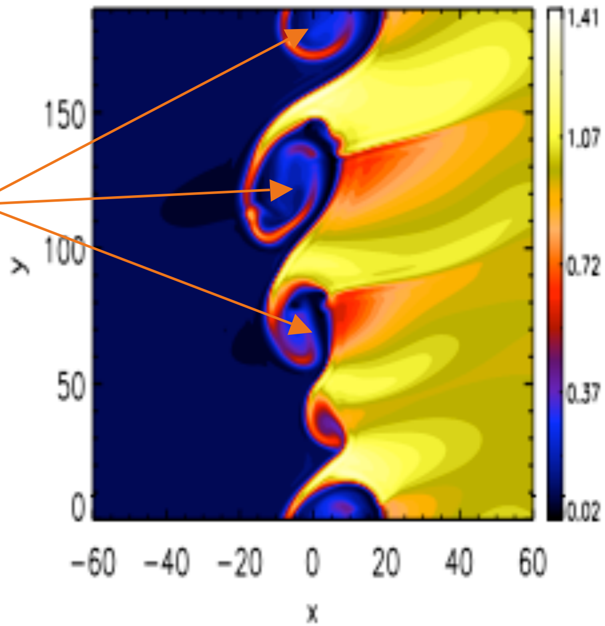
The transition occurs before reaching a Magnetosheath vortex Mach number equal to one

$M_{f,R}^{vort} \leq 1$
(non propagating ~ 1.5)

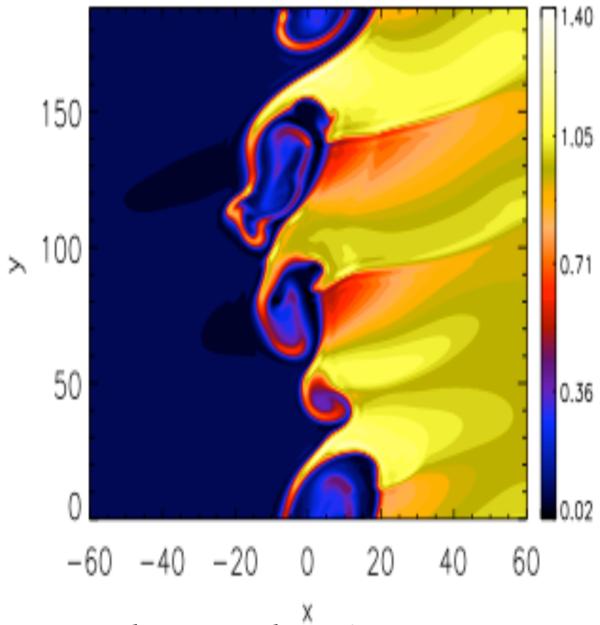
velocity fluctuations resulting from the KHI development and associated with the vortices enhance the value of the **"local" vortex Mach number**.

$M_{f,R}^{vort} \leq 1$

low density, nearly uniform vortices



plasma density, $V_0 = 5$



plasma density, $V_0 = 7$

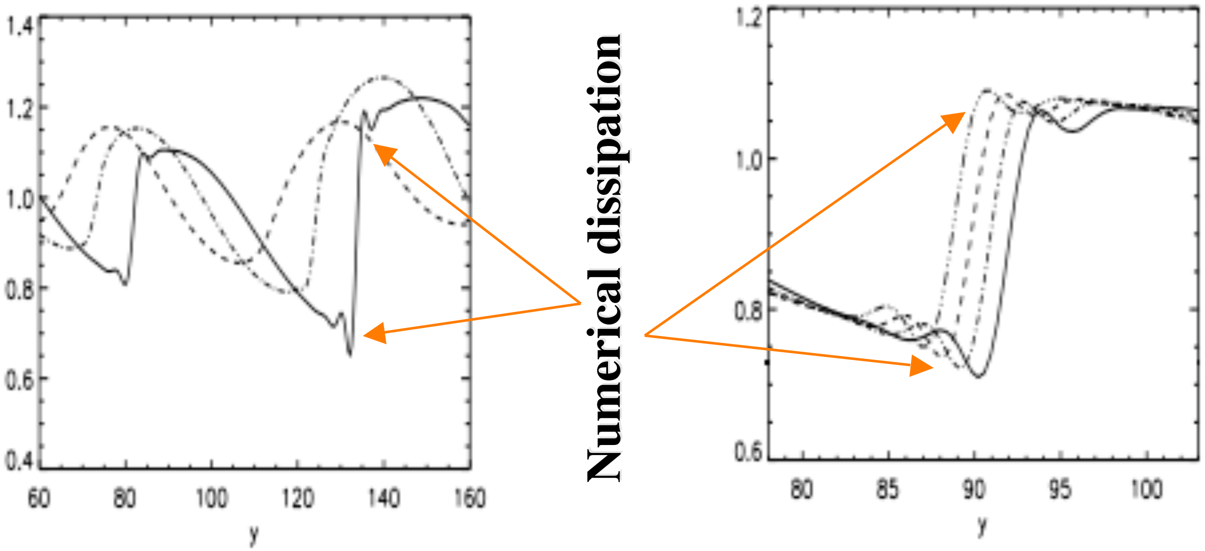
The shocks

The perpendicular magnetic fluctuations δB_z are practically superposed to the density fluctuations δn thus identifying the shock as a ***perpendicular magneto-sonic shock***, in agreement with the fact that it propagates, with respect to the magnetic field, at an angle $\pi/2 - \theta$ where $\theta < (m_e/m_i)^{1/2}$

Upstream (downstream) plasma velocity > (<) magnetosonic velocity

formally "collisionless shocks"

In the shock frame of reference, the **Rankine-Hugoniot** conditions for a fast magnetosonic shock are satisfied.



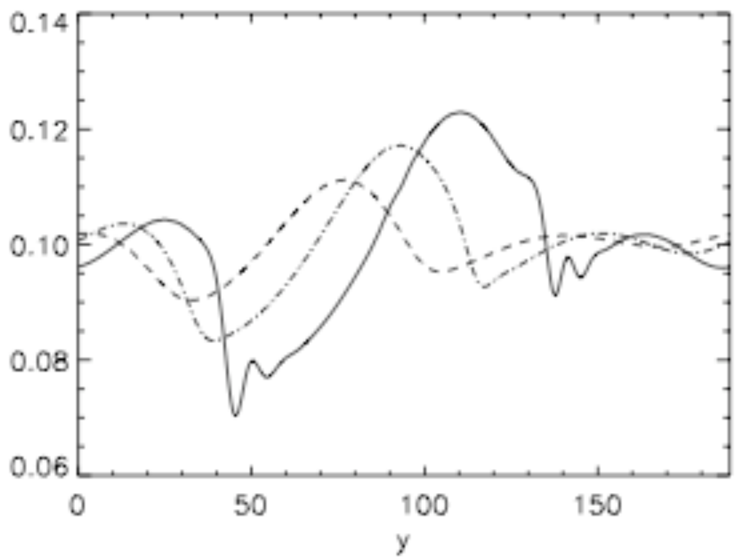
$$\mathbf{n_2 / n_1 \approx B_2 / B_1 \approx u_{y,1} / u_{y,2}}$$

oblique shocks

Dispersive effects: we decrease the angle between the direction of propagation of the shock and the magnetic field to $\theta = 0.3 \gg (m_e/m_i)^{1/2}$, leaving unchanged the other parameters. The dispersion relation reads

$$\frac{\omega^2}{k^2} = c_A^2(1 + k^2 d_i^2 \theta^2)$$

thickness $\ell_s \sim \theta d_i$



CONCLUSIONS

The Solar wind - Magnetosphere low latitude boundary layer:

i) Play a key role for the entry of solar wind plasma in the Magnetosphere

ii) It is a laboratory of excellence for basic processes in plasmas

iii) It is one of the best example of multi-scale plasma dynamics

Results

We have understood many key processes at play in the dynamics

Problems and future work

i) Need for satellite data analysis in the transition region: large scale fields

ii) Need of a 3D initial configuration (MHD equilibrium ?)

iii) Need of kinetic simulations