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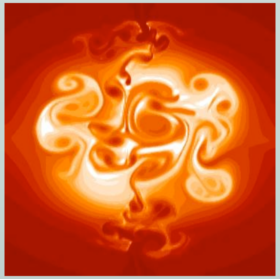


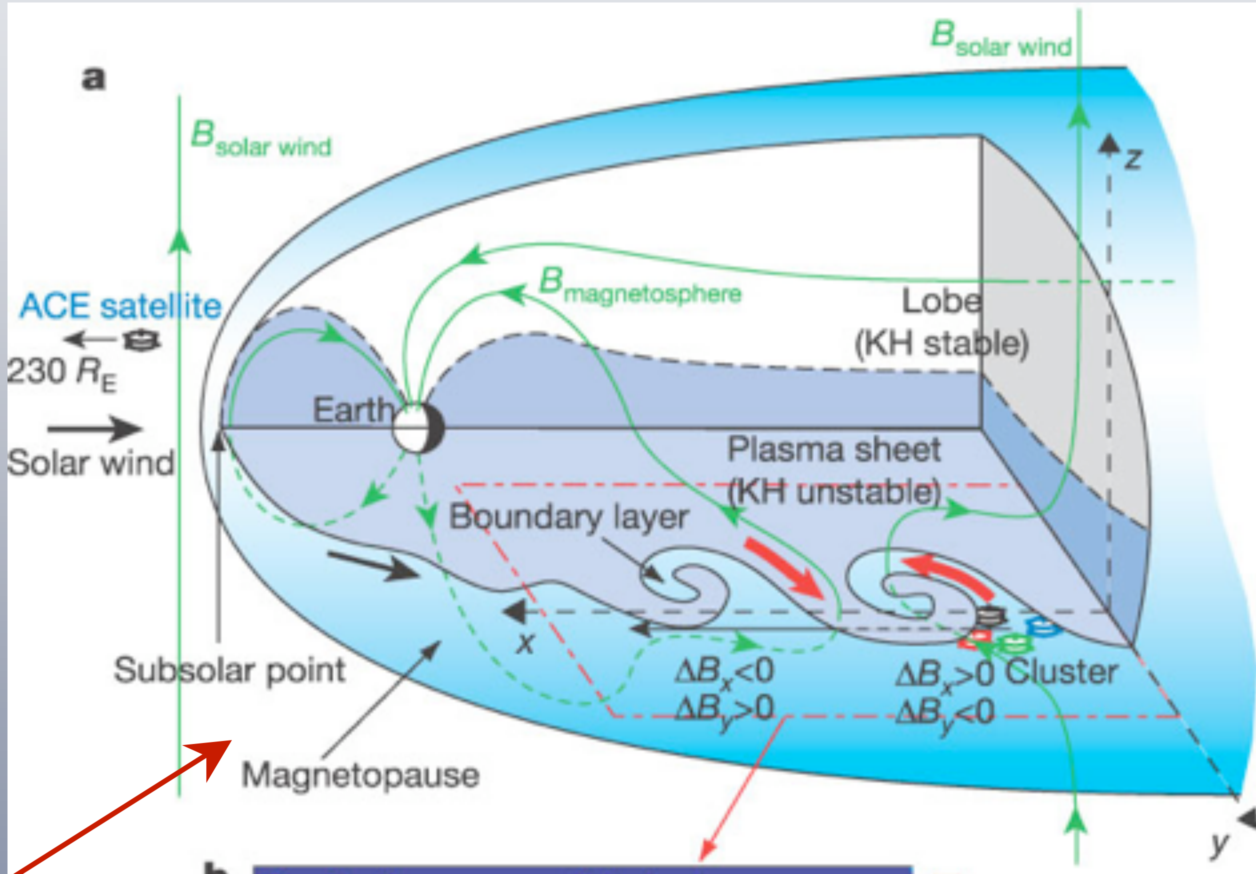
The role of the magnetic field in the interaction of the solar wind with a magnetosphere

Collaboration with M. Faganello & F. Pegoraro

Vienna, WPI, 2009

We consider the interaction of the solar wind with the magnetospheric plasma at low latitude and discuss the role of the magnetic field advected by the Kelvin - Helmholtz vortices generated by the sheared flow.

Several observations show that physical quantities observed along the flank magnetopause at low latitude are compatible with K-H vortex structures



H. Hasegawa *et al.*, Nature **430**, 755 (2004)
D.H. Fairfield et al., J. Geophys. Res. **105**, 21159 (2000).
A. Otto et al., J. Geophys. Res. **105**, 21175 (2000).

The ***Kelvin - Helmholtz instability*** has been shown

1) to play a crucial role in the interaction between the solar wind and the Earth's magnetosphere
2) to provide a mechanism by which the solar wind can enter the Earth's magnetosphere.

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

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

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

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

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).

Importance of magnetic field

In many astrophysical and laboratory systems with $\beta \approx 1$, the large scale plasma dynamics is governed by the interplay between plasma 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 **magnetic energy** corresponding to such an energetic jump is then capable of **affecting the large scale flow dynamics**.

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.

Along the flank magnetopause there is a magnetic field!

The magnetic field is nearly perpendicular to the flow, thus unable to inhibit the KH instability development, leading to the formation of large-scale ($L >> d_i$) MHD vortices. However, a small magnetic field component parallel to the solar wind direction is present.

This ”in-plane” magnetic field is advected by the rolling-up vortex dynamics and thus increasingly stretched and compressed, eventually leading to

Secondary Reconnection Instabilities.

Secondary Fluid (R-T) Instability **(not discussed in the following!)**

It exist also a **density variation** between the two plasmas that can strongly modifies the non-linear evolution of the K-H instability and that can lead to the onset of turbulence[1,2].

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

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

Indeed the centrifugal acceleration of the rotating K-H vortex acts as an "effective" gravity force on the plasma. If the density variation is large enough, the **Rayleigh-Taylor** instability can grow along the vortex arms.

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.

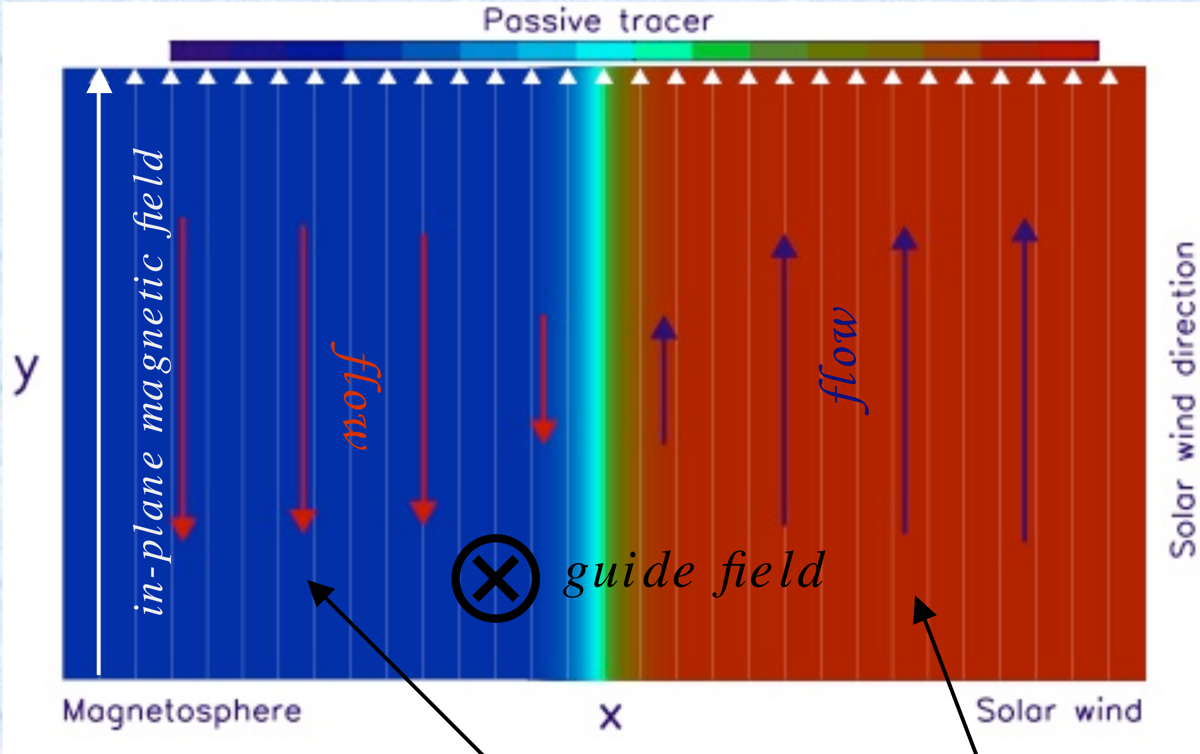
M. Faganello, F. Califano, F. Pegoraro, Phys. Rev. Lett. **100**, 015001 2008

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. The equilibrium magnetic field is nearly perpendicular to this plane.

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



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

The initial density is taken to be constant, i.e. <u>we do not include secondary R-T instability effects</u>

(see Phys. Rev. Lett. **100**, 015001 2008)

Rolled-up vortices, generated by the K-H instability and entering in the non-linear stage, could then evolve following

- *an inverse cascade process*
- *developing secondary fluid instabilities*
- ***Flow Induced Reconnection***

If $c_{A,\ \text{in-plane}}$ is sufficiently weak with respect to ΔU, the K-H instability generates **fully rolled-up vortices advecting the magnetic field lines in a complex configuration**, causing the formation of current layers (along the inversion curves of $\mathbf{B}_{\text{in-plane}}$).

1) **Homogeneous** *in-plane* magnetic field
2) **Sheared** *in-plane* magnetic field

Results discussed in the following published on
Phys. Rev. Lett. **101**, 105001 (2008) and Phys. Rev. Lett. **101**, 175003 (2008)

The model

Quasineutral plasma:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{U}) = 0; \quad \frac{\partial P_{i,e}}{\partial t} + \nabla \cdot (P_{i,e}\mathbf{U}) = 0$$

$$\frac{\partial (n\mathbf{U})}{\partial t} + \nabla \cdot \left[\frac{n}{1+d_e^2}(\mathbf{u_i u_i} + d_e^2 \mathbf{u_e u_e}) + \frac{1}{1+d_e^2}(P_{_T}\bar{\bar{\mathbf{I}}} - \mathbf{BB}) \right] = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\left(1 + d_e^2 \nabla^2\right) \mathbf{E} = -\mathbf{u_e} \times \mathbf{B} - d_e^2 \left\{ \mathbf{u_i} \times \mathbf{B} + \frac{1}{n} \nabla \cdot \left[n \left(\mathbf{u_i u_i} - \mathbf{u_e u_e} \right) \right] \right\}$$

$\mathbf{U} = \mathbf{u_i} + d_e^2 \mathbf{u_e}; \quad P_{_T} = P_i + P_e + B^2/2; \quad d_e^2 = m_e/m_i.$
$\nabla P_e/n$ does not contribute to $\nabla \times \mathbf{E}$.