Magnetic reconnection and plasma instabilities
in space and in the laboratory: similarities and differences

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SCIENTIFIC ROUND TABLE at the ITALIAN EMBASSY
in the RUSSIAN FEDERATION MOSCOW 20th - 22nd June 2011
PLASMAS IN ASTROPHYSICS AND IN THE LABORATORY:
THE IGNITOR CHALLENGE

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Overview

Instabilities are inherent to the dynamics of fully non equilibrium systems such as plasmas, and magnetic field line reconnection is ubiquitous both in space and laboratory plasmas and in plasma literature[1].

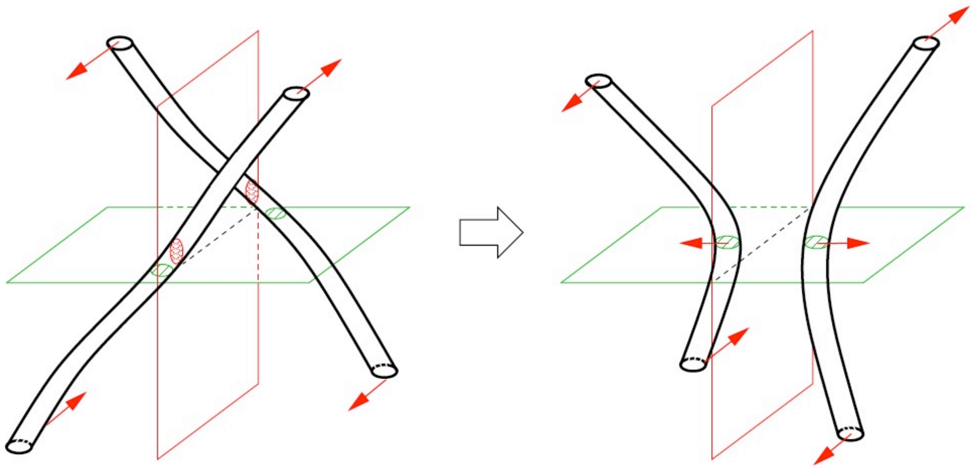


Figure 1: The reconnection cosmic strings. Slicing vertically, one sees a vortex-anti-vortex pair annihilate. Slicing horizontally, one sees two vortices scattering at right angles.

[1] and even outside plasma physics literature: *Reconnection of Non-Abelian Cosmic Strings*, Koji Hashimoto, David Tong, JCAP 0509 (2005) 004

This field of plasma physics investigation is so wide that what can be done sensibly here is simply to recall

- some of the different subjects of competence that are available in Italy[2],

- how they are made to play in the already existing Italian collaborations between space and laboratory physicists,

- which are the problems of our present interest,

- discuss how they could complement within the scope of the Ignitor project, and, most important, within an Italian-Russian[3] collaboration on Ignitor.

[2] based on the one-day workshop *PLASMI IN ASTROFISICA E IN LABORATORIO* held at CNR in Rome on May 18^{th} 2011

[3] Most of us have a long experience of extremely fruitful collaborations with Russian scientists

As noted in the subtitle, the framework within which plasma dynamics can be investigated in space and in the laboratory can be quite different

- in terms of spatial and temporal scales that can be resolved and in the degree of detail of the information available, both locally and globally,
- and, most important, in terms of boundary conditions: in the laboratory magnetic configurations tend to be strongly constrained by the external world[4].

Therefore physical mechanisms in space and in the laboratory may be similar, but the experimental questions posed and the investigation methods are different. This has made the two lines of research diverge somewhat from their initial close relationship, but represents a unique opportunity of viewing a given problem more deeply using different perspectives. Moreover, in recent years the study of relativistic plasmas in ultra-intense laser plasma interactions has opened up a new field of collaboration between plasma physics and high energy astrophysics.

[4]For example magnetic field lines Hamiltonians that are, in a loose sense, quasi integrable for laboratory configurations, which is rarely the case in space.

Burning plasmas

From a plasma physics point of view probably the most important and novel feature of a "burning plasma" is the presence of a fully non thermal population of magnetically confined fusion products with energies two orders of magnitude higher than that of the rest of the plasma.

The effect of these particles is twofold:

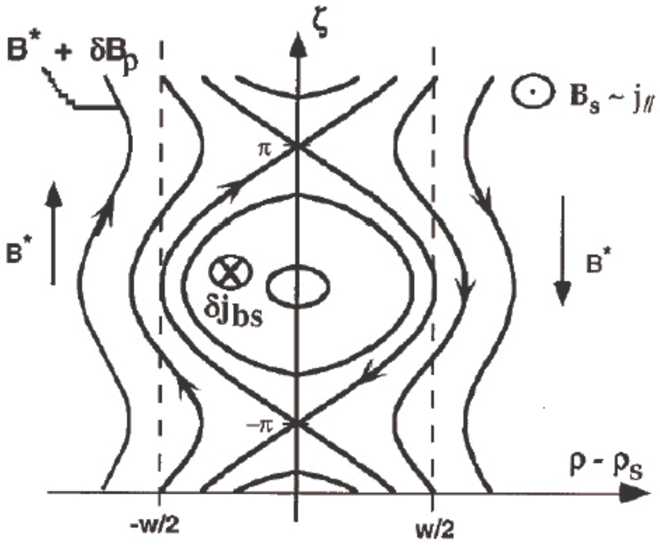
on one side they feed their energy to the plasma thus taking the place of the external heating sources or even allowing for ignition,

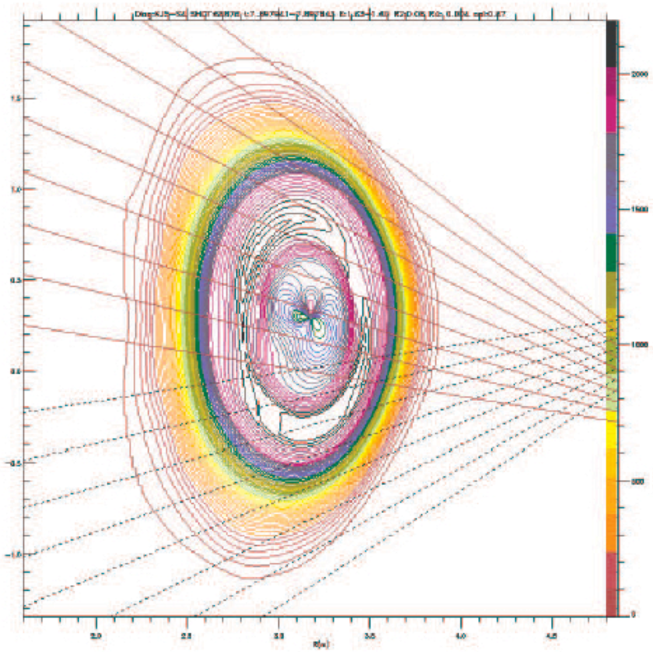
on the other side they can feed new instabilities[5], or even stabilize old ones[6] and in general can affect the plasma MHD behaviour, reconnection processes in particular, and the plasma particle, energy and momentum transport.

[5] fishbones, Toroidal Alfvèn Modes

[6] monster sawteeth

Spontaneous reconnection





- **Magnetic island appear on soft x-ray contours**

A major problem: Linear normal modes disappear in realistic conditions as diamagnetic and transport effects are included.

Figure 1: Courtesy of P Buratti Frascati Enea

Title: **THEORETICAL RESOLUTION OF MAGNETIC RECONNECTION IN HIGH ENERGY PLASMAS**

Sponsored in part by the U.S. Department of Energy.

DOI No: 10.1142/9789812778901_0007

Source: COLLECTIVE PHENOMENA IN MACROSCOPIC SYSTEMS (pp 59-74)

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Abstract: The formation of macroscopic reconnected magnetic structures (islands) have been observed in advanced experiments on weakly collisional, well confined plasmas while established theories of the drift-tearing modes, which depend strongly on the electron temperature gradient and can describe the formation of these structures, had predicted practically inaccessible excitation thresholds for them in these regimes. The relevant theoretical dilemma is resolved as mesoscopic modes that depend critically on the ratio of the transverse (to the magnetic field) to the longitudinal thermal conductivity $D_\perp^e/D_\parallel^e$, can produce large scale magnetic reconnection. These modes are envisioned to emerge from a background, which can be coherent, of collisionless microscopic reconnecting modes driven by the electron temperature gradient, that create a sequence of adjacent strings of magnetic islands and increase considerably the ratio $D_\perp^e/D_\parallel^e$ over its classical value. The mesoscopic reconnecting mode is treated by a singular perturbation analysis involving three asymptotic regions involving the small parameters $(D_\perp^e/D_\parallel^e)^{1/4}$ and $\varepsilon_*^{1/4}$, where $\varepsilon_* \equiv D_m D_A$, D_m is the magnetic diffusion coefficient, $D_A \sim v_A^2 r_{Te}/(D_B k_\perp)$, $r_{Te} \equiv (-d \ln T_e/dr)^{-1}$, $K_\perp$ is the transverse mode number, $v_A^2 = B^2/(4\pi n m_i)$ and $D_B = cT_e/(eB)$.

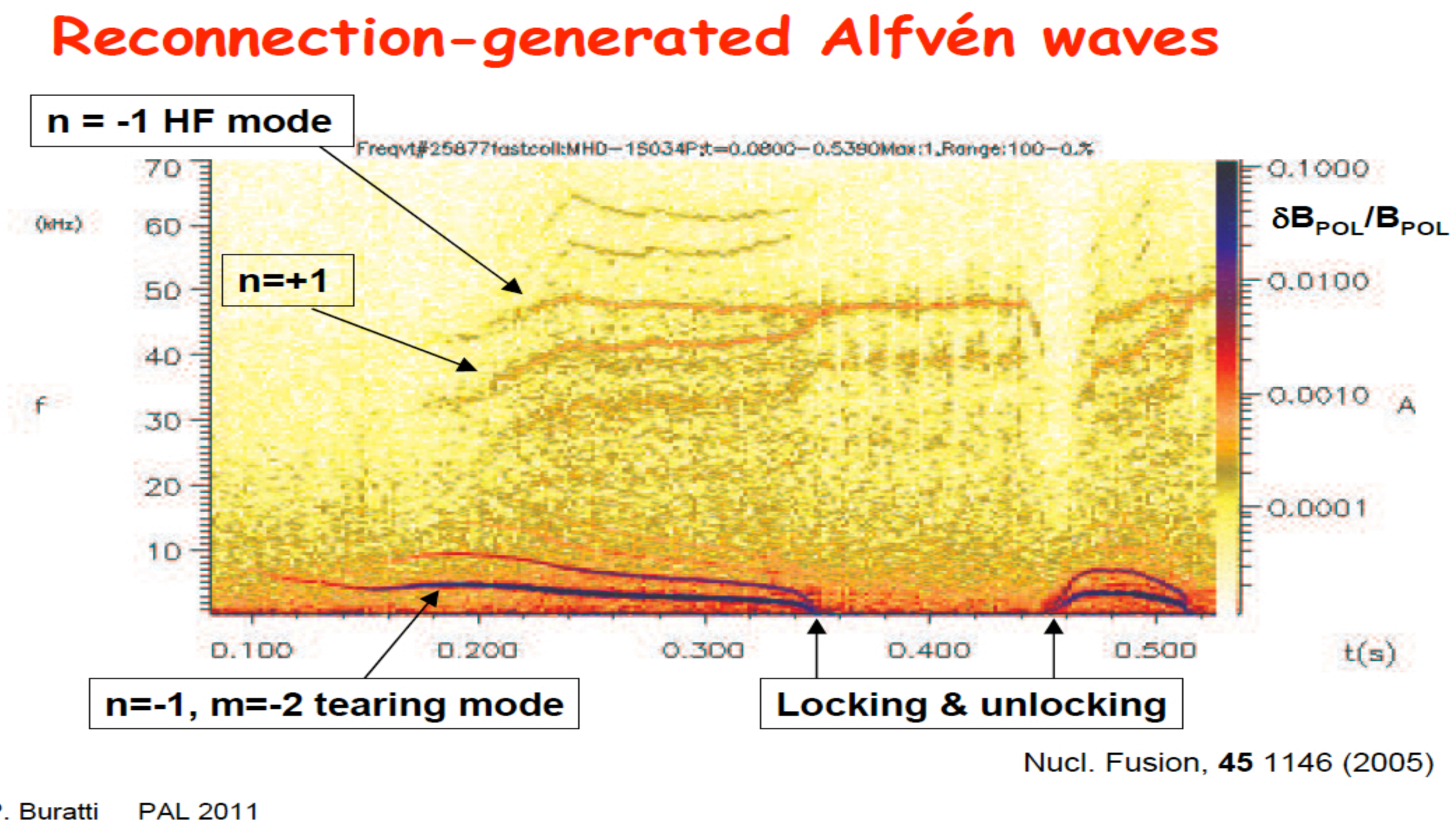

Figure 2: Courtesy of P Buratti Frascati Enea

PRL 105, 095002 (2010) PHYSICAL REVIEW LETTERS week ending 27 AUGUST 2010

Continuous Spectrum of Shear Alfvén Waves within Magnetic Islands

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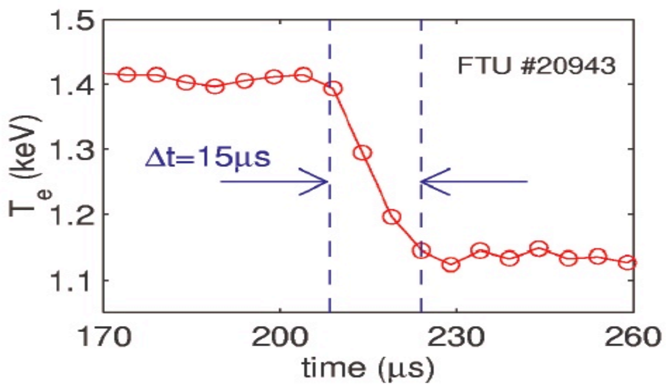
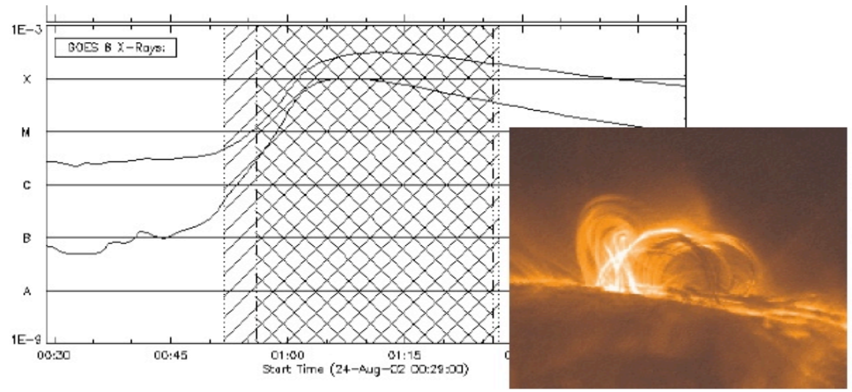
The radial structure of the shear Alfvén wave continuous spectrum is calculated inside the separatrix of a magnetic island. We find that, within a magnetic island, there is a continuous spectrum very similar to that of tokamak plasmas, where a generalized safety factor q can be defined and a wide frequency gap is formed, analogous to the ellipticity induced Alfvén eigenmode gap in tokamaks. This is due to the strong eccentricity of the island cross section. In this gap, a magnetic-island induced Alfvén eigenmode (MIAE) can exist as a bound state, essentially free of continuum damping, which can be resonantly excited by energetic particles and interact nonlinearly with the magnetic island. Because of the frequency dependence of the shear Alfvén wave continuum on the magnetic-island size, the possibility of utilizing MIAE frequency scalings as a novel magnetic-island diagnostic is also discussed.

DOI: 10.1103/PhysRevLett.105.095002 PACS numbers: 52.55.Tn, 52.35.Bj

Fast reconnection ($\tau << S^{1/2}\,\tau_{\text{Alfvén}}$)





Tokamak internal collapse

- **Δt = 15 μs**
- **Sweet-Parker time ≈ 1 ms**

PPCF **45** (2003) L9–L16

Solar flare **(TRACE X3.1 24 Aug. 02)**

- **Δt = 25'**
- **Sweet-Parker time ≈ weeks**

The main problems are the rapid time scale and the sudden onset at nearly unchanged macroscopic plasma parameters.

P. Buratti PAL 2011

Figure 3: Courtesy of P Buratti Frascati Enea

Hamiltonian fluid models

- **Structures associated to invariants**

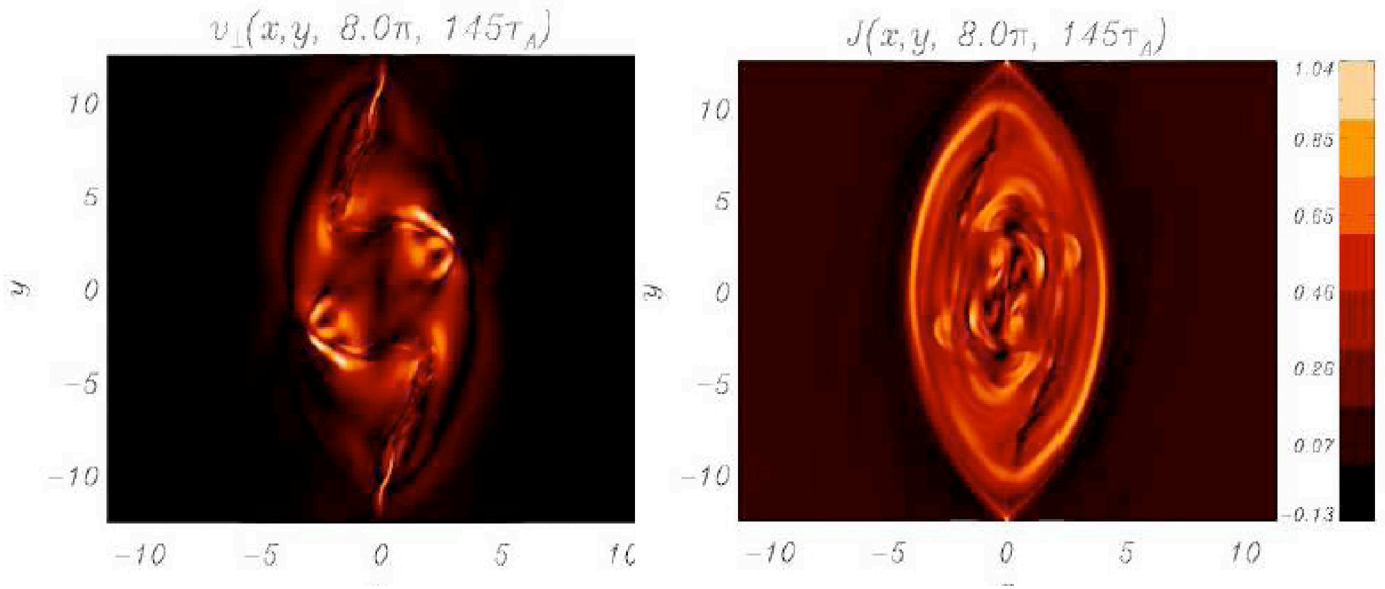


Figure 4: Turin Polytechnic, Pisa

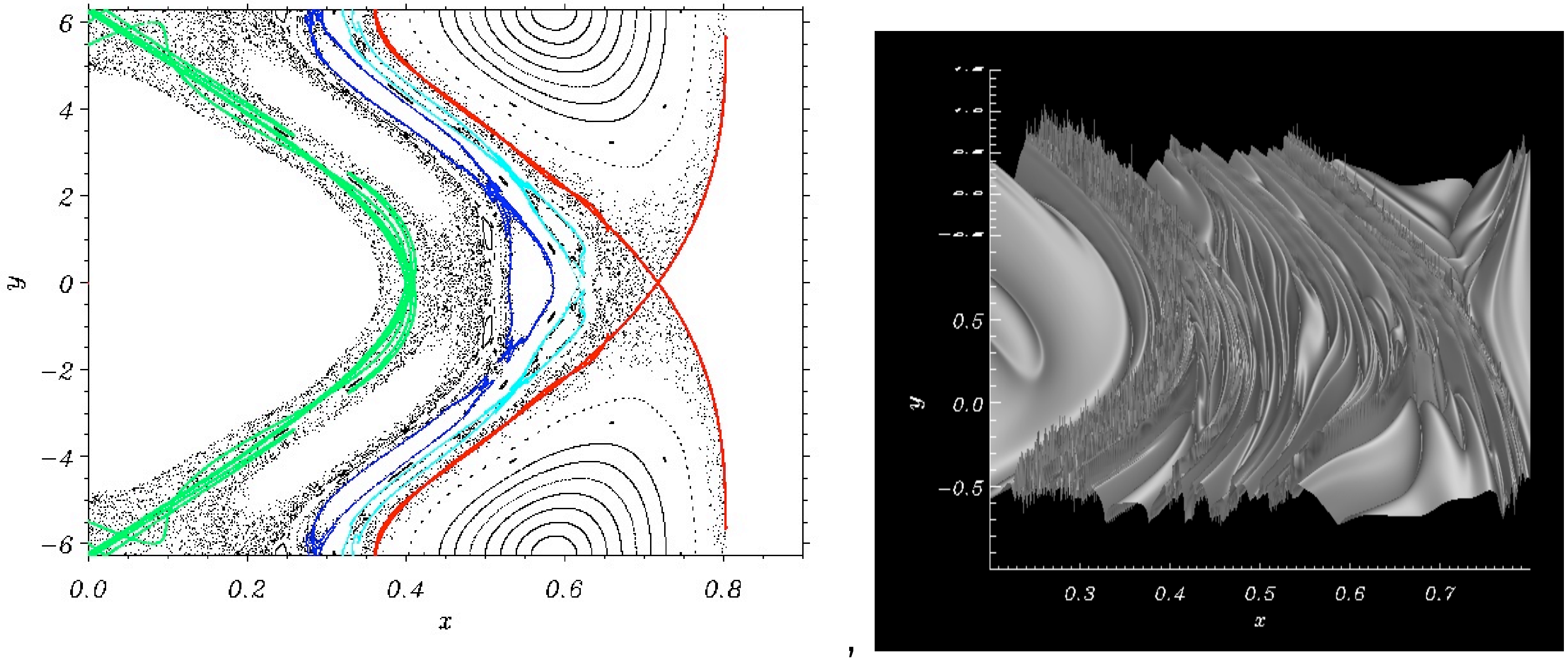


Figure 5: Lagrangian structures and ridges

PRL **105,** 215006 (2010) PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2010

Effects of Anisotropic Thermal Conductivity in Magnetohydrodynamics Simulations of a Reversed-Field Pinch

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(Received 13 July 2010; published 17 November 2010)

A compressible magnetohydrodynamics simulation of the reversed-field pinch is performed including anisotropic thermal conductivity. When the thermal conductivity is much larger in the direction parallel to the magnetic field than in the perpendicular direction, magnetic field lines become isothermal. As a consequence, as long as magnetic surfaces exist, a temperature distribution is observed displaying a hotter confined region, while an almost uniform temperature is produced when the magnetic field lines become chaotic. To include this effect in the numerical simulation, we use a multiple-time-scale analysis, which allows us to reproduce the effect of a large parallel thermal conductivity. The resulting temperature distribution is related to the existence of closed magnetic surfaces, as observed in experiments. The magnetic field is also affected by the presence of an anisotropic thermal conductivity.

DOI: 10.1103/PhysRevLett.105.215006 PACS numbers: 52.55.Hc

A reversed-field pinch (RFP) is a toroidal configuration for magnetic confinement of fusion plasmas. Differently from the tokamak, most of the magnetic field is generated by currents flowing in the plasma, through a dynamo effect produced by magnetohydrodynamic (MHD) instabilities [1–3]. In the past, a broad spectrum of instabilities was

The possibility of obtaining QSH states is important in order to achieve better confinement properties. In MH states the temperature is almost flat in the plasma core, while in QSH states strong temperature gradients appear and a hot structure is formed in coincidence with the magnetic island, indicating that a better thermal confinement is obtained in

Figure 6: Cosenza group

36th EPS 2009; M.Romé et al. : Wavelet Analysis of 2D Turbulence in a Non-neutral Plasma *4 of 4*

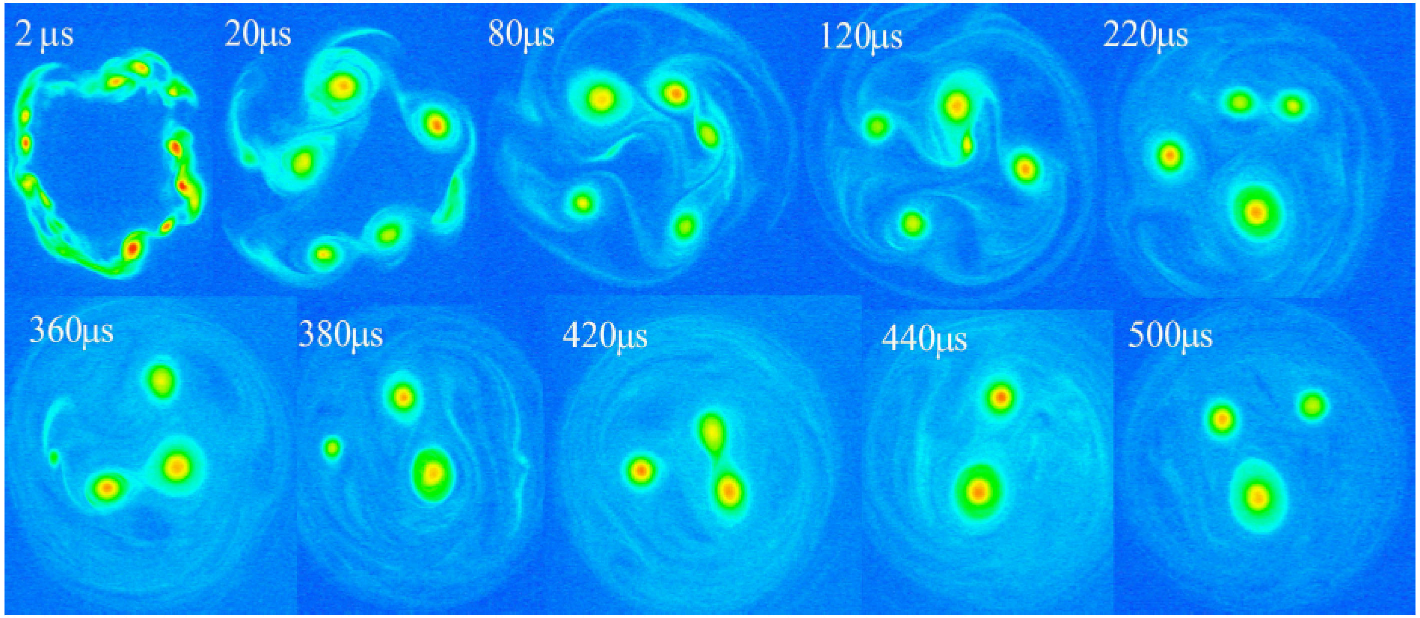

Figure 2: Time evolution of the plasma (the trapping time is indicated at the top left corner of each frame).

Figure 7: Milan group Nonneutral plasmas

Collisionless Magnetic Reconnection in the Presence of a Sheared Velocity Field

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The linear theory of magnetic field lines reconnection in a two dimensional configuration in the presence of a (Kelvin-Helmholtz stable) sheared velocity field is investigated within a single fluid model where the onset of magnetic field line reconnection is made possible by the effect of electron inertia in the so called large Δ' regime.

PACS numbers: 52.35.Vd, 47.20.Ft

Figure 8: Pisa, Phys. Plasmas 17, 062102 (2010)

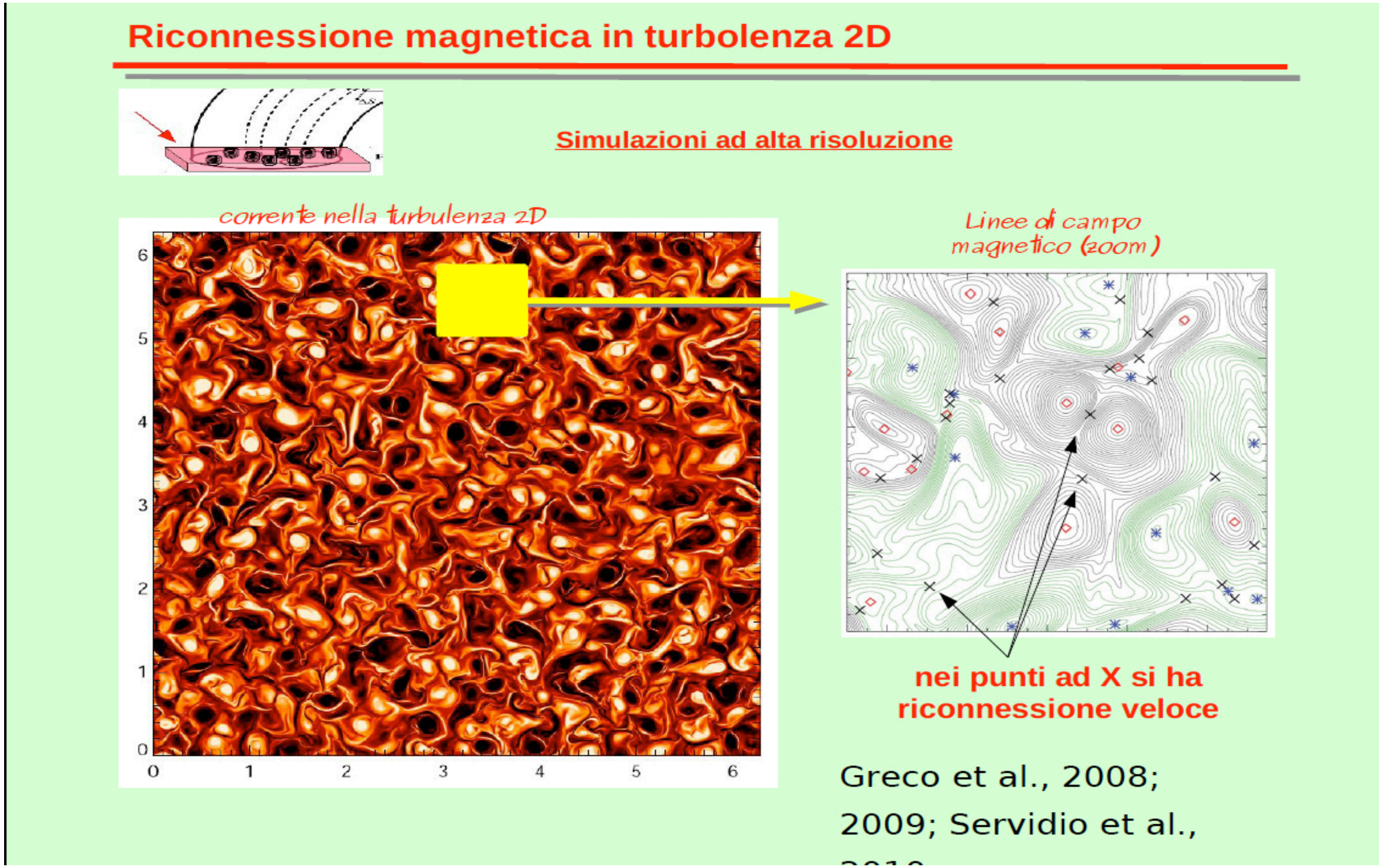

Figure 9: Cosenza group Reconnection in 2d turbulence

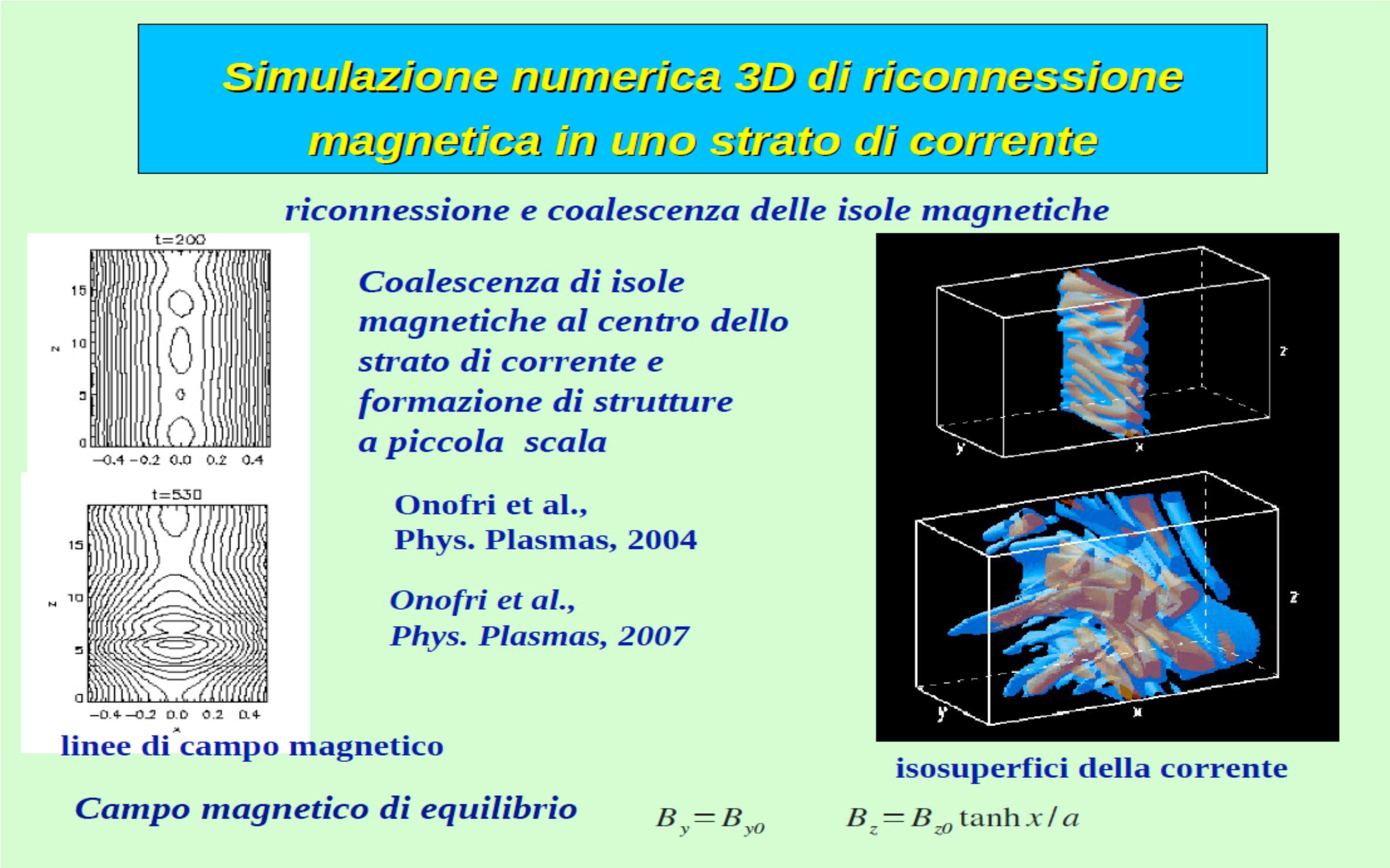

Figure 10: Cosenza group Reconnection in 3d current layers

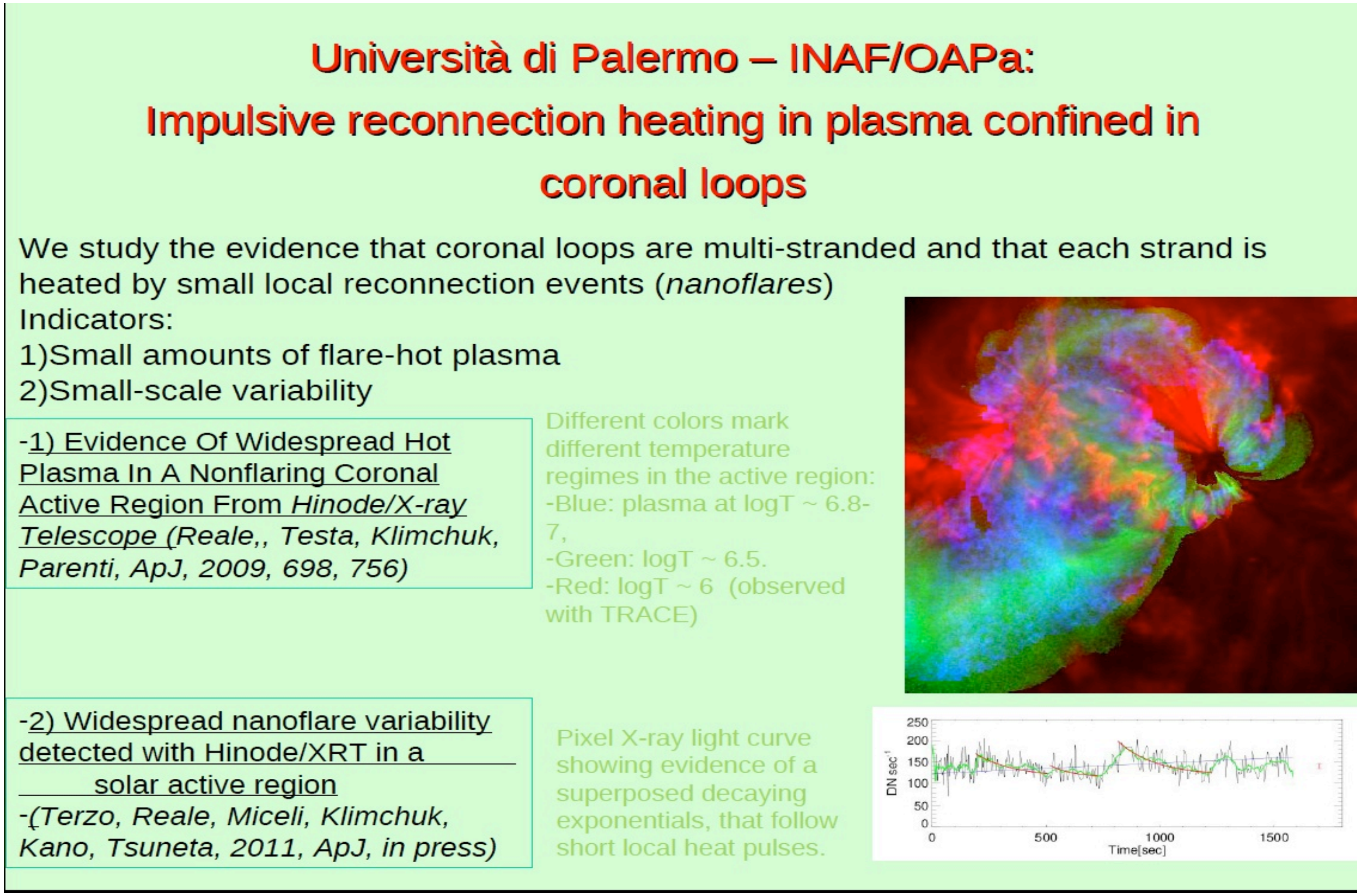

Figure 11: Palermo group

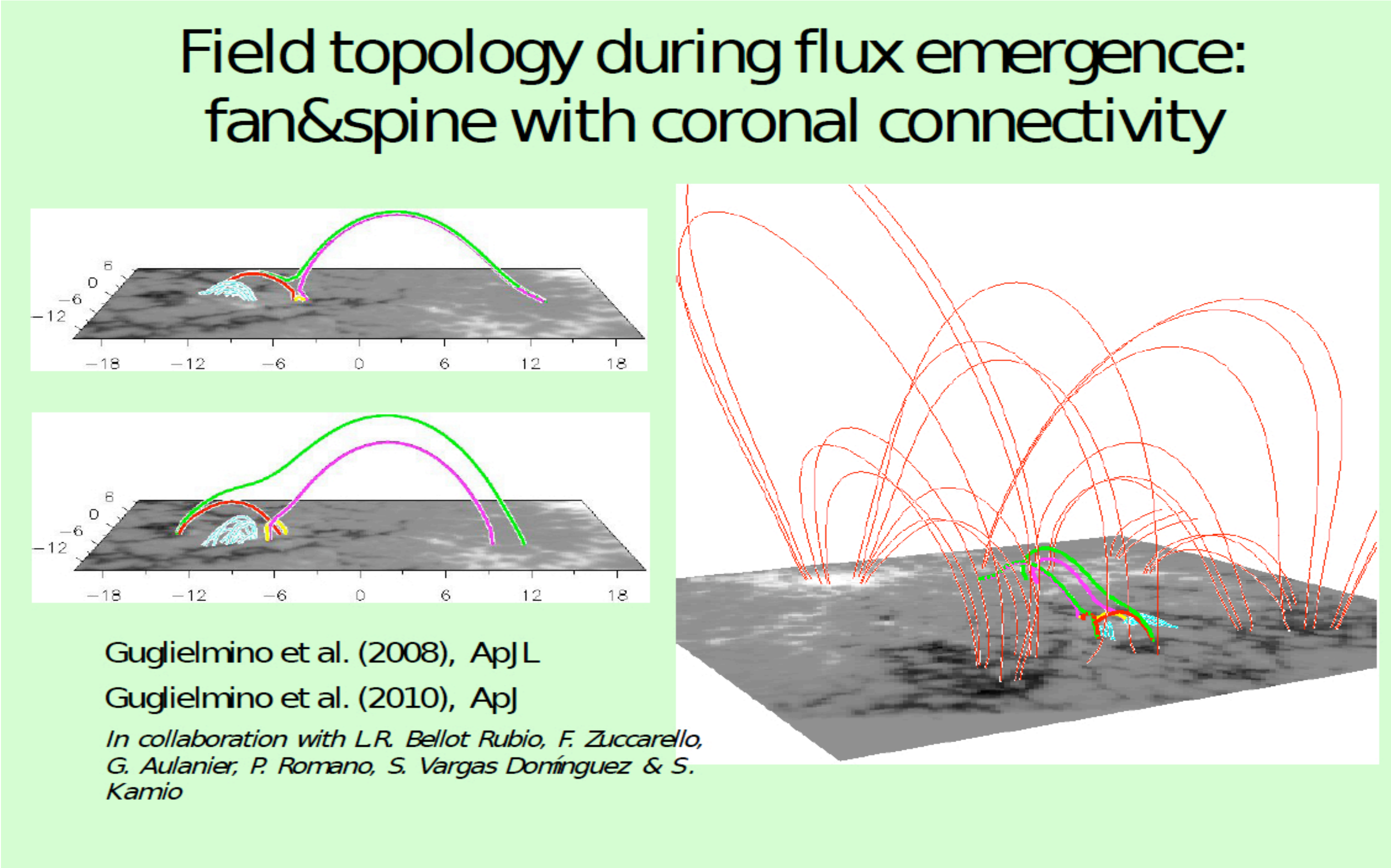

Figure 12: Catania group Reconnection in 2d turbulence

The Astrophysical Journal, 722:65-78, 2010 October 10
Preprint typeset using LaTeX style emulateapj v. 2/16/10
doi:10.1088/0004-637X/722/1/65

SHEAR PHOTOSPHERIC FORCING AND THE ORIGIN OF TURBULENCE IN CORONAL LOOPS

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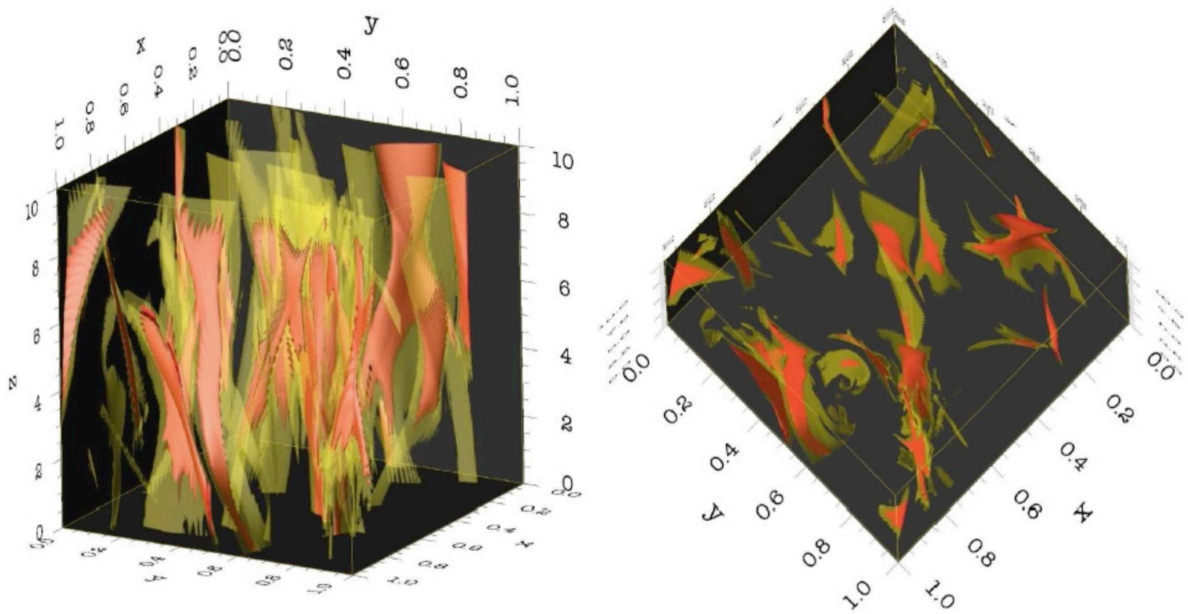
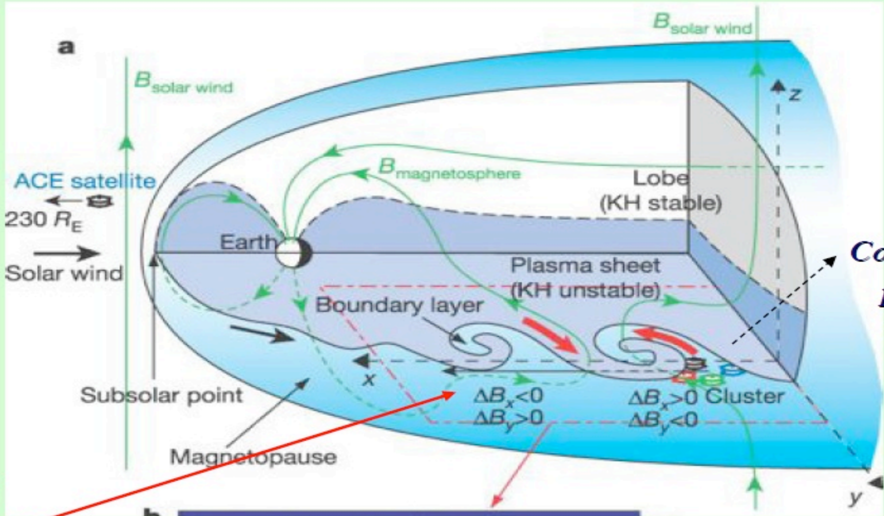


Figure 4. Side and top views of a snapshot of magnetic field-lines (*top row*) and current sheets (*bottom row*) at time $\tau \sim 550\,\tau_A$.

The problem: solar wind interaction with the magnetosphere at low latitude

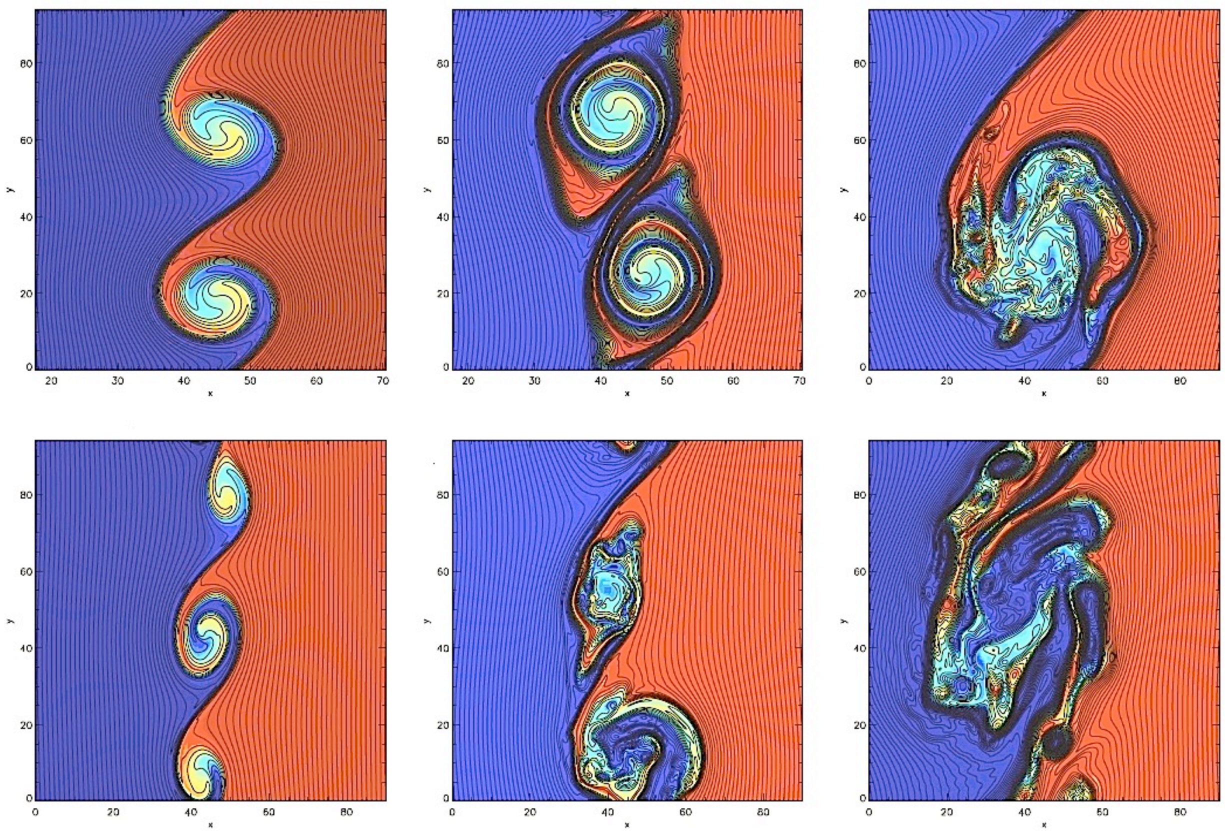
The ***Solar Wind*** **-** ***Earth's Magnetosphere*** **interaction** in regions where the velocity shear generates rolled-up vortices has been evidenced by *satellite in-situ measurements* [Fairfield et al., 2000; Hasegawa et al., 2004]



Quasi periodic perturbations often observed near the flank magnetopause

Complex non linear phenomenology induced by the K-H vortices

Mixing efficiency strongly increased !



Pisa group. Kelvin-Helmholtz, secondary instabilities and reconnection

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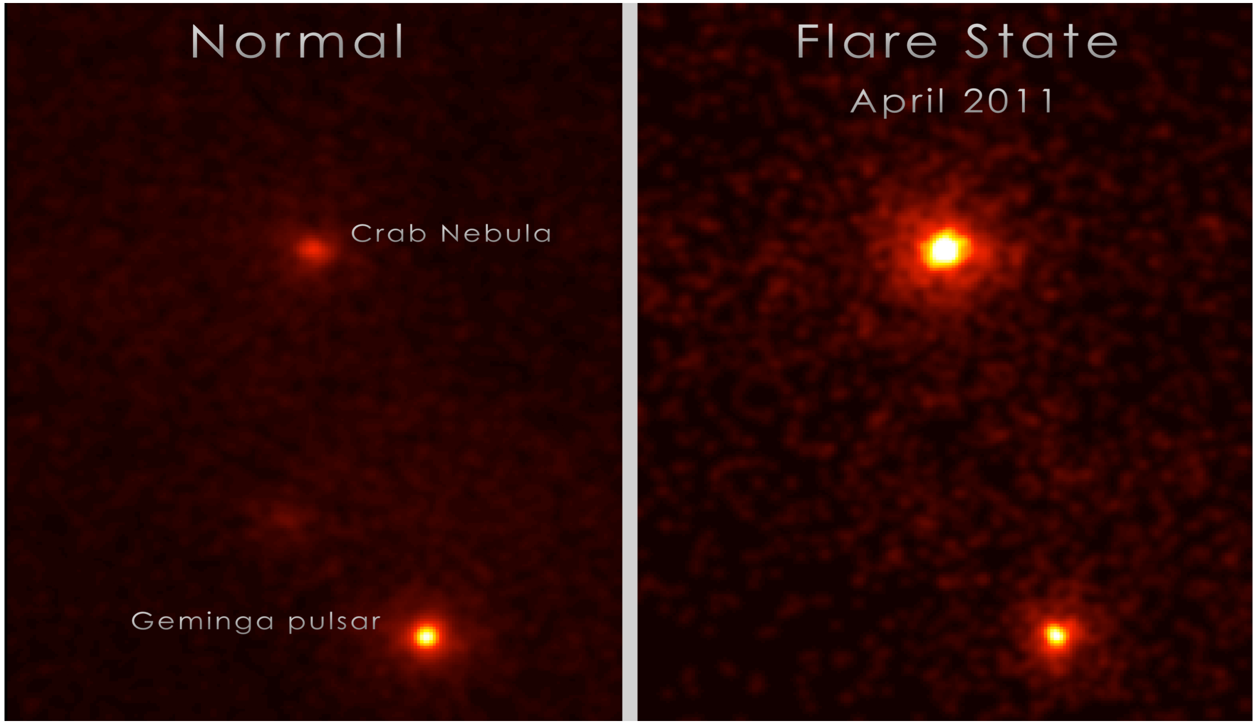

The Crab Nebula flaring up. Left: The region 20 days before the flare. Right: April 14, 2011. (NASA/DOE/Fermi LAT/R. Buehler)

THANKS FOR YOUR ATTENTION

Secondary shocks and instabilities on Kelvin Helmholtz vortices.