

Space weather and plasma simulation

Jörg Büchner, MP Ae Lindau

Collaborators:

B. Nikutowski and I. Silin, Lindau

A. Otto, Fairbanks

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Outline

- What is „Space Weather“: Manifestation, consequences, action at Earth and in space
- How does it work ? - Main scenarios of plasma heating and particle acceleration by artists's movies
- **MODELING AND SIMULATION APPROACHES:**
- Force free magnetic fields -> lowest order solar fields
- Ideal MHD -> large scale motion in the corona
- Resistive MHD -> reconnection in the transition region
- Kinetic simulation -> dissipation, structure formation
- State of the art global simulation and outlook

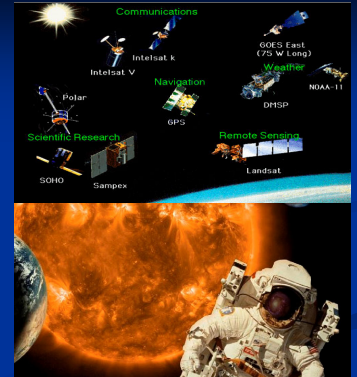
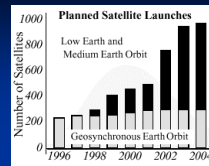
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Manifestation: Aurora



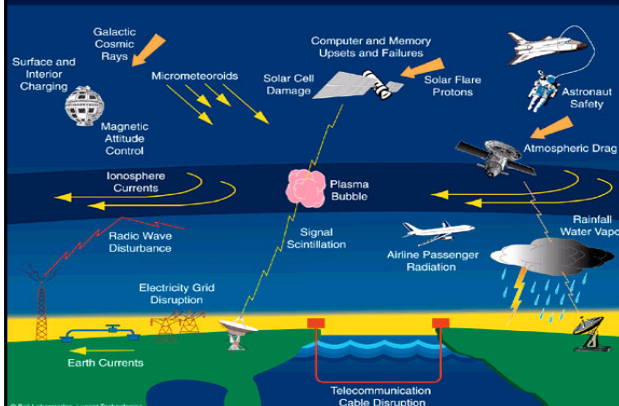
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Action in Space



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Space Weather: consequences



How does it work? Solar Wind and Magnetic Substorms



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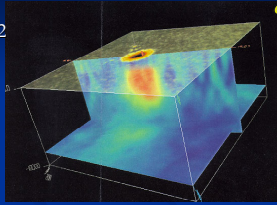
Source: motion of solar plasmas

Estimated energy fluxes:

Active regions	(0.5 -1) 104 W m ⁻²
Quiet regions	300 W m ⁻²
Coronal holes	800 W m ⁻²

Solar plasma convection:

- Dynamo effect -> magnetic fields
- Flows -> upward Poynting flux



$$\frac{\mathbf{E} \times \mathbf{B}}{\mu} \approx \frac{v B^2}{\mu} \approx 10^4 \text{ W} \cdot \text{m}^2$$

$$\mathbf{E} = -v \times \mathbf{B}; v = 0.1 \text{ km} \cdot \text{s}^{-1}; B = 100 \text{ G}$$

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Typical dimensionless parameters

If: L – Geometrical scale, n – Number density;

T_j – Temperature and B – Magnetic field, then:

Ion-gyro radius: $r_{gi} / L = (k_B T_i m_i)^{1/2} / (e B L)$

Mean-free path: $\lambda_{mfp} / L = 3 (2\pi)^{3/2} \frac{(k_B T_e \epsilon_0)^2}{n L e^4 \ln \Lambda}$

Magnetic Reynolds number $R_m = \mu_0 V L / \eta_e$

$E = v B \sim E_A = V_A B > E_D = \frac{e^3 n \ln \Lambda}{4 \pi \epsilon_0^2 k_B T_e}$ Dreicer-field

If $E_A > E_D$ collisions don't prevent runaway: collisionless!

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Typical values

Parameter	Laboratory ¹	Magnetosphere ²	Solar Corona ³	Solar Interior ⁴
L (global scale)	10 ⁻¹ m	10 ⁷ m	10 ⁸ m	10 ⁸ m
n	10 ²⁰ m ⁻³	10 ⁵ m ⁻³	10 ¹⁵ m ⁻³	10 ²⁹ m ⁻³
T	10 ⁵ K	10 ⁷ K	10 ⁶ K	10 ⁶ K
B	10 ⁻¹ tesla	10 ⁻⁸ tesla	10 ⁻² tesla	10 ¹ tesla
$r_{ion-gyro} / L$	10 ⁻²	10 ⁻²	10 ⁻⁹	10 ⁻¹²
λ_{mfp} / L	10 ⁻¹	10 ⁹	10 ⁻⁴	10 ⁻¹⁶
R_m	> 1	$>> 1$	$>>> 1$	
E_D / E_A	10 ⁻¹	10 ⁻¹¹	10 ⁻⁷	10 ⁷

¹MRX at the Princeton Plasma Physics Laboratory

²Plasma sheet in the geomagnetic tail

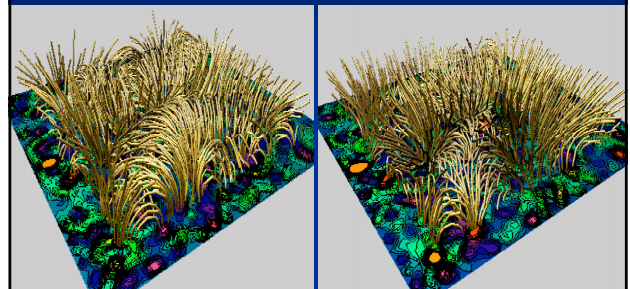
³Above an active region

⁴Base of the convection zone

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Force-free approximation

i.e. Currents flow only parallel to the magnetic field ->



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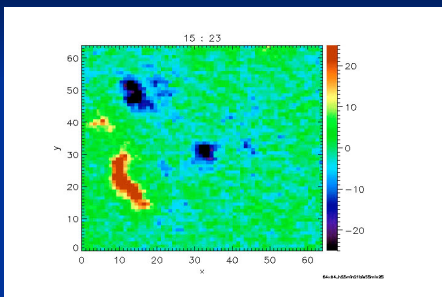
18.10.96

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Ideal MHD (magnetohydrodynamics)

- $\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$ -> „ideal“ magnetohydrodynamics, i.e. magnetic flux and plasma move together



SOHO-MDI photospheric B fields on 17./18.10.1996 60°, 23Mm

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Non-ideal MHD simulations

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{u} - \nu (\rho - \rho_0)$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} = -\nabla \cdot \rho \mathbf{u} \mathbf{u} - \frac{1}{2} \nabla p + \mathbf{j} \times \mathbf{B} - \mu \rho (\mathbf{u} - \mathbf{u}_0)$$

$$= -\nabla \cdot \left[\rho \mathbf{u} \mathbf{u} + \frac{1}{2} (p + B^2) \mathbf{1} - \mathbf{B} \mathbf{B} \right] - \mu \rho (\mathbf{u} - \mathbf{u}_0)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B} - \eta \mathbf{j})$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot p \mathbf{u} - (\gamma - 1) p \nabla \cdot \mathbf{u} + 2(\gamma - 1) \eta \mathbf{j}^2 - \kappa n k_B (T - T_0)$$

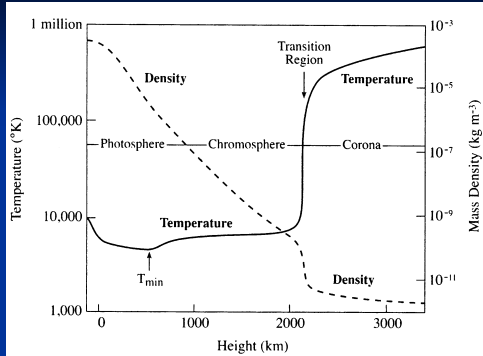
with $\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{j}$

$$\nabla \times \mathbf{B} = \mathbf{j}$$

$$\nu_{in} = n \sigma_n v_{th}$$

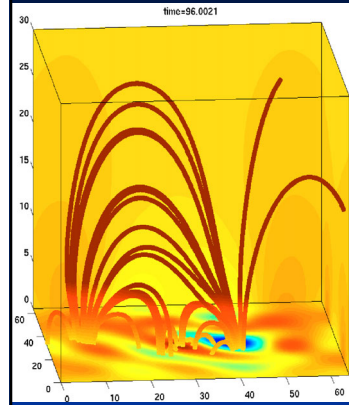
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Non-ideal MHD simulations



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MHD - simulations: example



Eruptive magnetic Reconnection directly in the transition region

*The question remains open: what is the nature of dissipation?
-> plasmakinetic investigation necessary*

Next order - smaller - scales

Electron equation of motion ("Ohm's law"):

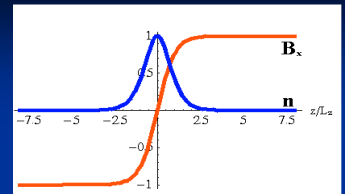
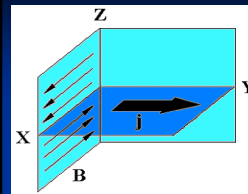
$$\frac{4\pi}{\omega_{pe}^2} \frac{d\vec{J}}{dt} = \vec{E} + \frac{1}{c} \vec{v}_i \times \vec{B} - \frac{1}{nec} \vec{J} \times \vec{B} + \frac{1}{ne} \nabla p_e - \eta \vec{J}$$

c/ω_{pe} c/ω_{pi} ρ_e <- Scales
 Electron inertia Whistler waves kinetic Alfvén waves <- Effects

- Below c/ω_{pi} electrons and ions decouple, i.e. electrons are magnetized, ions not -> Plasma- Hall- Effect
- Below c/ω_{pe} : Electrons demagnetized as well

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Crucial point: current sheets



$$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c} \vec{j}$$

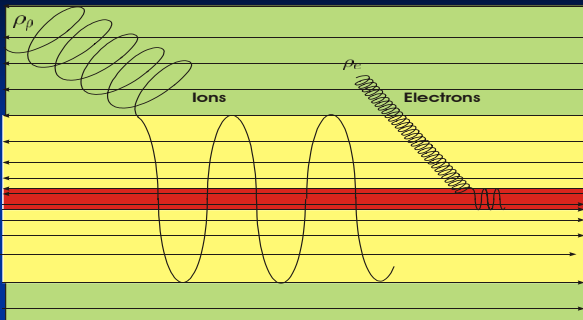
$$\frac{\partial B_x}{\partial z} = \frac{4\pi}{c} j_y$$

$$j_y = j_0 * 1 / \cosh^2(z/L)$$

$$B_x = B_0 * \tanh(z/L)$$

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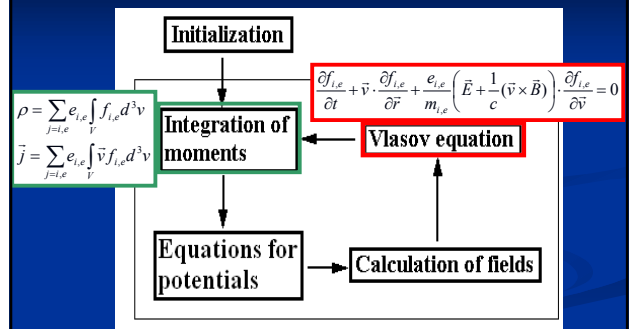
Hall currents in current sheets



(Thin current sheet with $\rho_{io} \sim > L$)

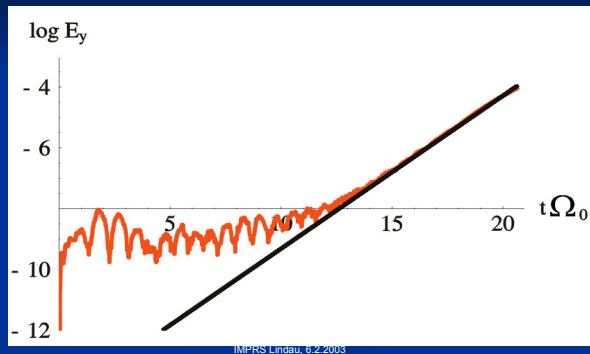
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Vlasov-code kinetic Simulation

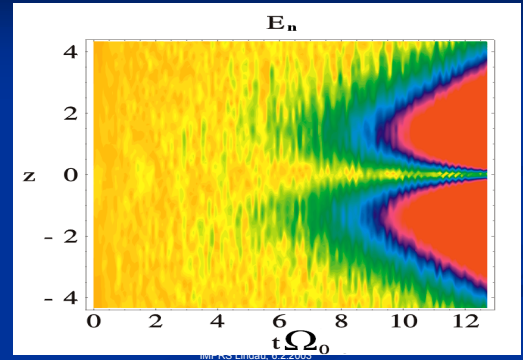


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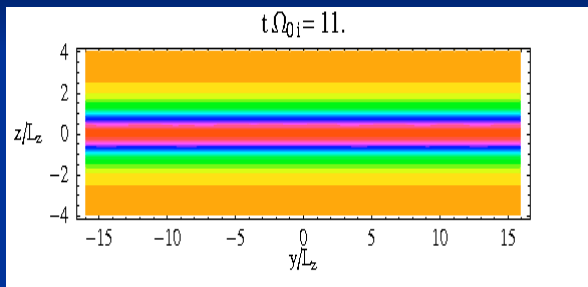
From microscopic fluctuations and turbulence to global instability: **TIME**



From microscopic fluctuations and turbulence to global instability: **SPACE**



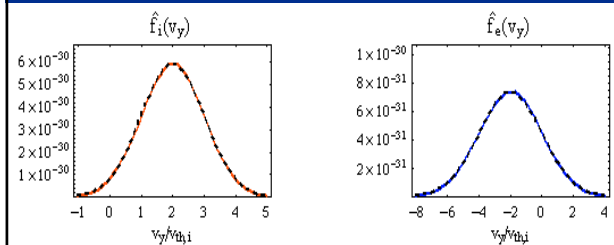
Current sheet decay: from microscopic fluctuations to global instability



Microscopic dissipation

Ion distribution in the current direction

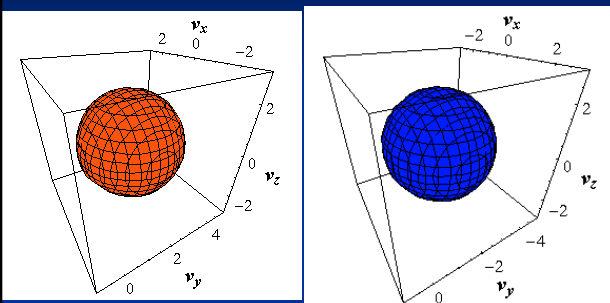
Electron distribution in the current direction



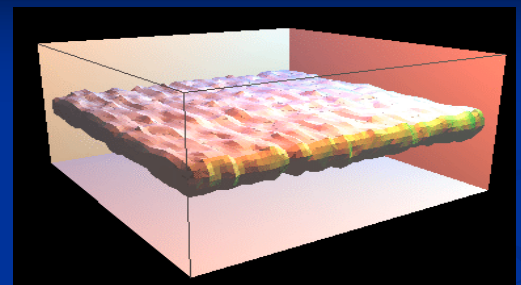
Ions drive waves ☐ plateau - formation ☐ electron-heating

Current reduction -> dissipation

Ion distribution function Electron distribution function

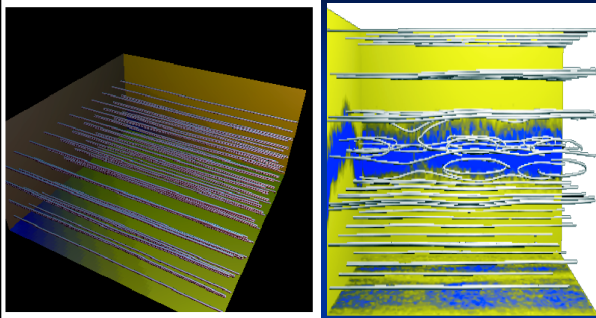


3D current instability



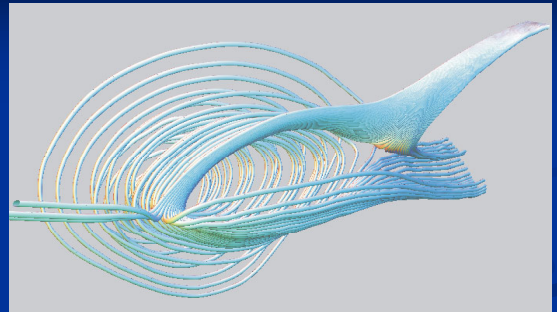
Plasma density wave

Transition to reconnection



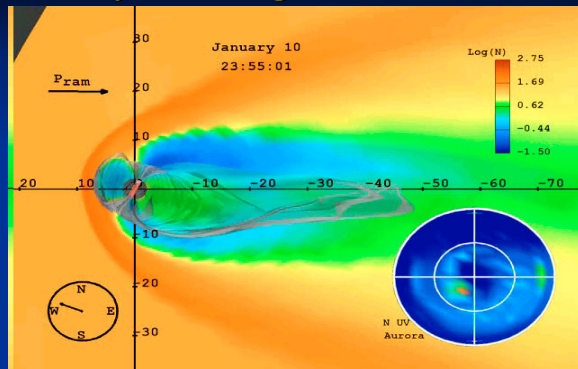
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3D magnetic reconnection



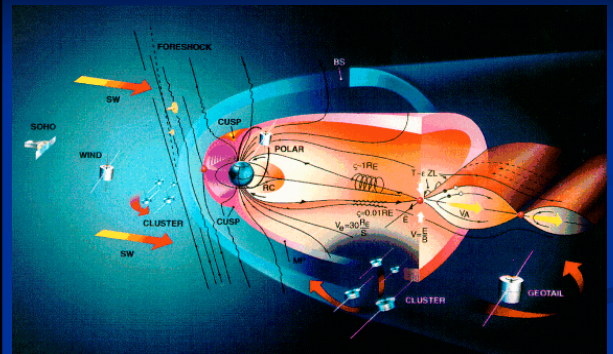
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State of the art: global MHD models



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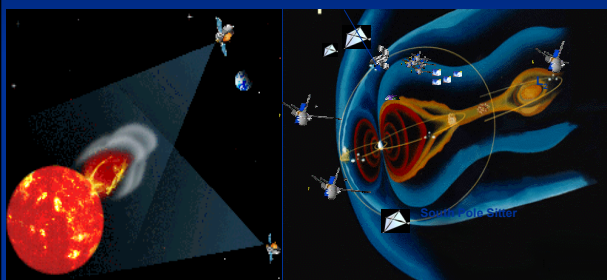
Multiscale processes in complex system -> plasma simulations necessary



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Comparison with observations

- International program „Living With a Star“ (ILWS)
- Missions 2006-08: SUNRISE, STEREO, MMS, SDO ...



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