Space weather and plasma simulation

Jörg Büchner, MPAe Lindau

Collaborators:

B. Nikutowski and I.Silin, Lindau

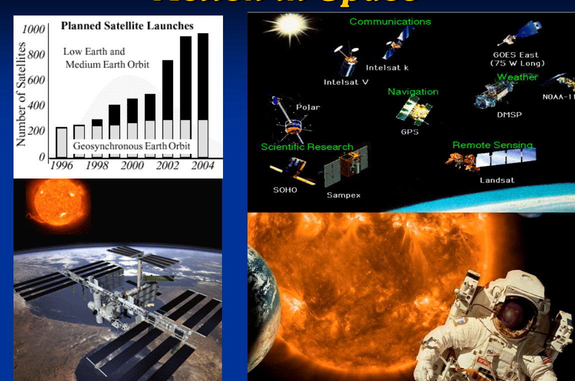
A. Otto, Fairbanks

Outline

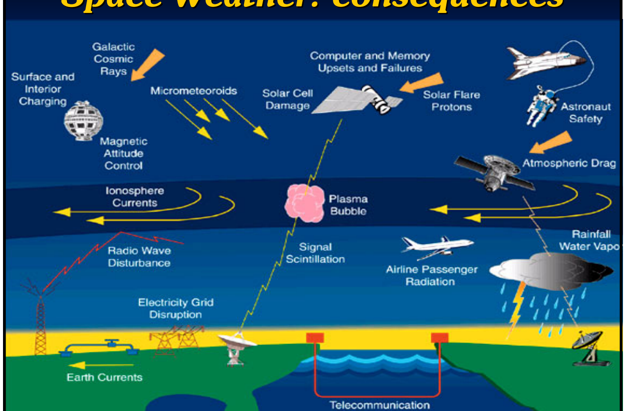
- What is „Space Weather": Manifestation, consequences, action at Earth and in space
- How does it work ? - Main scenarios of plasma heating and particle acceleration by artists's movies
- MODELING AND SIMULATION APPROACHES:
- Force free magnetic fields -> lowest order solar fields
- Ideal MHD -> large 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

Manifestation: Aurora

Action in Space



Space Weather: consequences

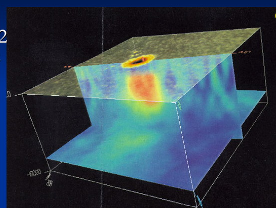


How does it work?
Solar Wind and Magnetic Substorms

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

$$\frac{\mathbf{E}\times\mathbf{B}}{\mu} \approx \frac{vB^2}{\mu} \approx 10^4 W\cdot m^2$$
$$E = -v\times B; v = 0.1\ km\cdot s^{-1}; B = 100\ G$$

Typical dimensionless parameters

If: L – Geometrical scale, n – Number density;
T_j – Temperature and B – Magnetic field, then:

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

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

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

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

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

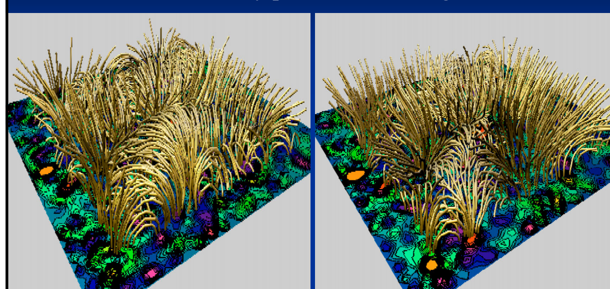
Typical values

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
$r_{ion\text{-}gyro} / L$	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}	

[1]MRX at the Princeton Plasma PhysicsLaboratory
[2]Plasma sheet in the geomagnetic tail
[3]Above an active region
[4]Base of the convection zon

Force-free approximation

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



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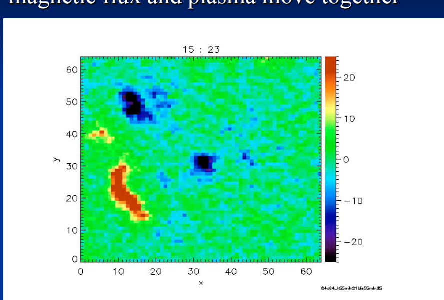
Ideal MHD (magnetohydrodynamics)

- E + v x B=0 -> „ideal" magnetohydrodynamics, i.e. magnetic flux and plasma move together



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

Non-ideal MHD simulations

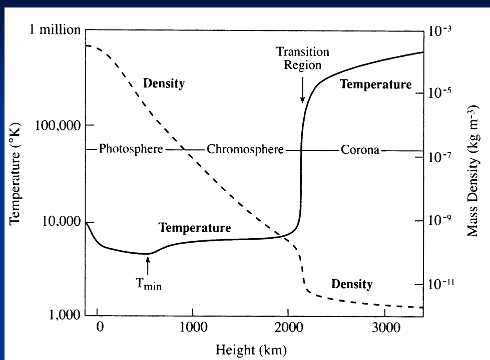
$$\frac{\partial \rho}{\partial t} = -\nabla\cdot\rho\mathbf{u} - \nu(\rho-\rho_0)$$
$$\frac{\partial \rho\mathbf{u}}{\partial t} = -\nabla\cdot\rho\mathbf{u}\mathbf{u} - \frac{1}{2}\nabla p + \mathbf{j}\times\mathbf{B} - \mu\rho(\mathbf{u}-\mathbf{u}_0)$$
$$= -\nabla\cdot\left[\rho\mathbf{u}\mathbf{u} + \frac{1}{2}\left(p+B^2\right)\underline{\underline{1}} - \mathbf{B}\mathbf{B}\right] - \mu\rho(\mathbf{u}-\mathbf{u}_0)$$
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B} - \eta\mathbf{j})$$
$$\frac{\partial p}{\partial t} = -\nabla\cdot p\mathbf{u} - (\gamma-1)p\nabla\cdot\mathbf{u} + 2(\gamma-1)\eta\mathbf{j}^2 - \kappa n k_B(T-T_0)$$

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

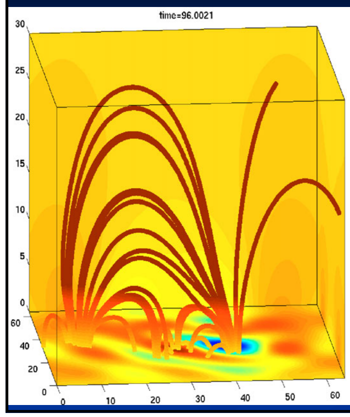
$\nabla\times\mathbf{B} = \mathbf{j}$

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

Non-ideal MHD simulations



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

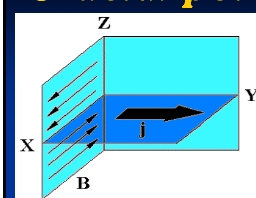
Electron equation of motion ("Ohm's law"):

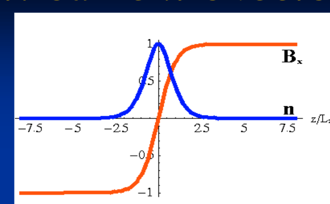
$$\frac{4\pi}{\omega_{pe}^2}\frac{d\vec{J}}{dt} = \boxed{\vec{E} + \frac{1}{c}\vec{v}_i \times \vec{B}} - \frac{1}{nec}\vec{J}\times\vec{B} + \frac{1}{ne}\nabla p_e - \boxed{\eta\vec{J}}$$

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

Crucial point: current sheets





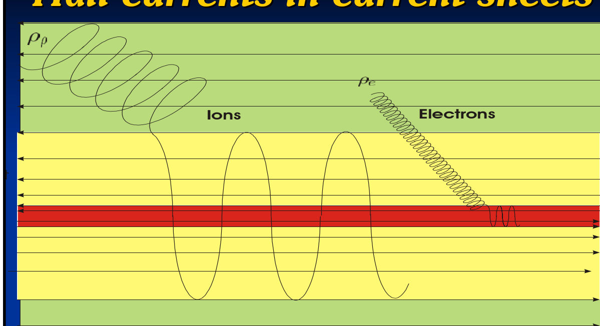
$$\vec{\nabla}\times\vec{B} = \frac{4\pi}{c}\vec{j}$$

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

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

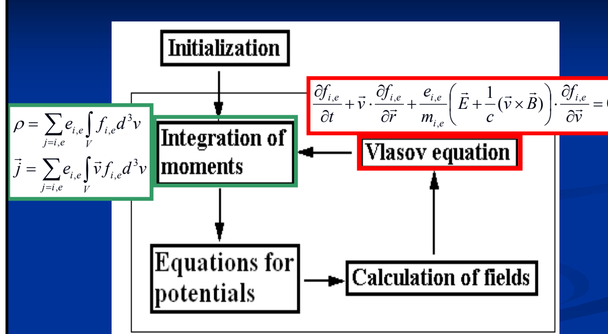
$$B_x = B_0 * \tanh(z/L)$$

Hall currents in current sheets

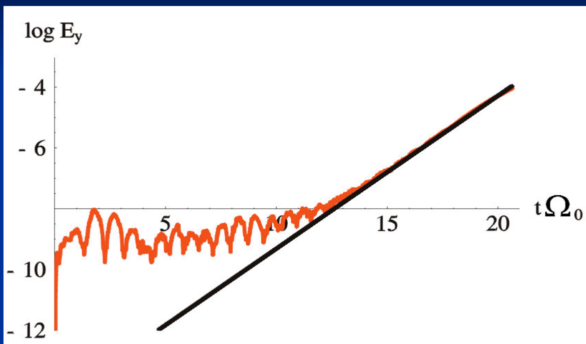


(Thin current sheet with ρ_{io} ~> L)

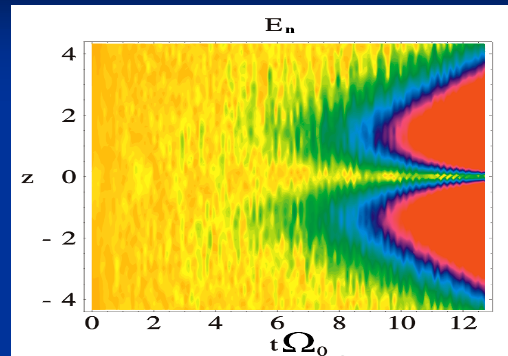
Vlasov-code kinetic Simulation



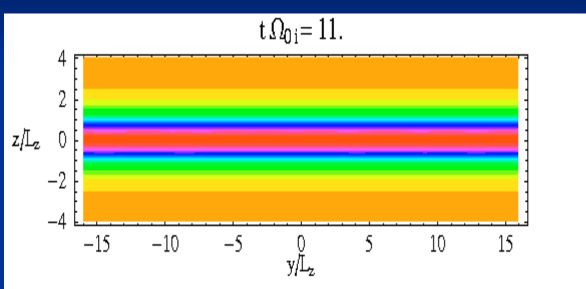
From microscopic fluctuations and turbulence to a global instability: TIME



From microscopic fluctuations and turbulence to global instability: SPACE



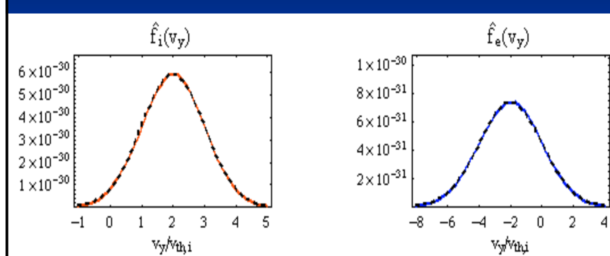
Current sheet decay: from microscopic fluctuations to global instability



Microscopic dissipation

Ionen distribution in the current direction

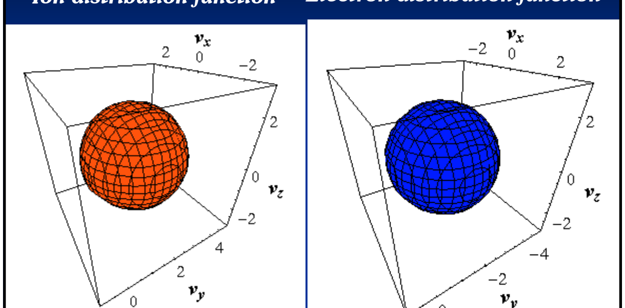
Electron distribution in the current direction



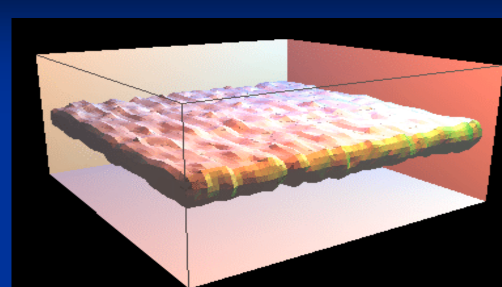
Ions drive waves □ plateau - formation □ electron-heating

Current reduction -> disspation

Ion distribution function *Electron distribution function*

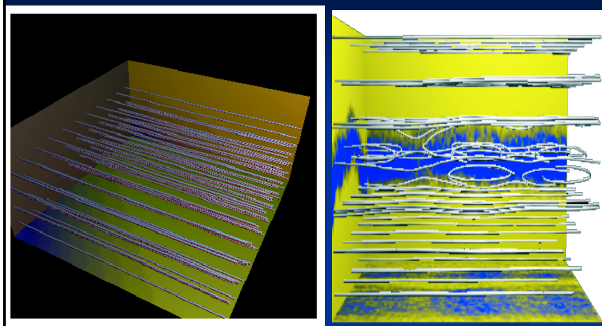


3D current instability

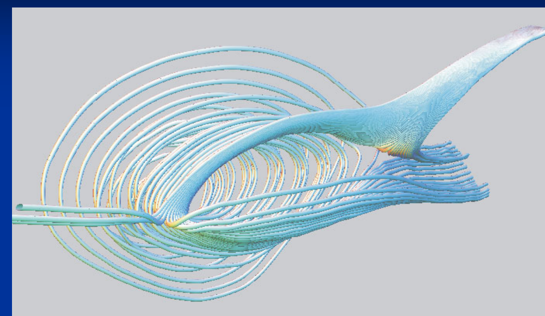


Plasma density wave

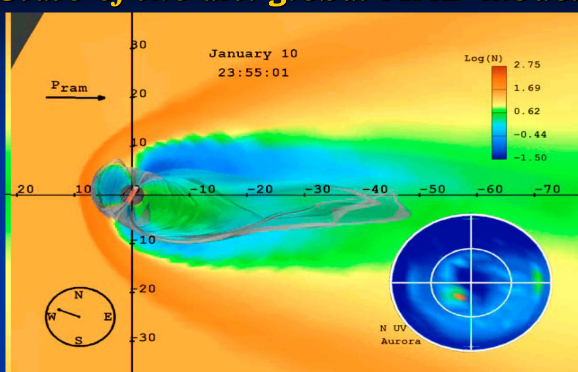
Transition to reconnection



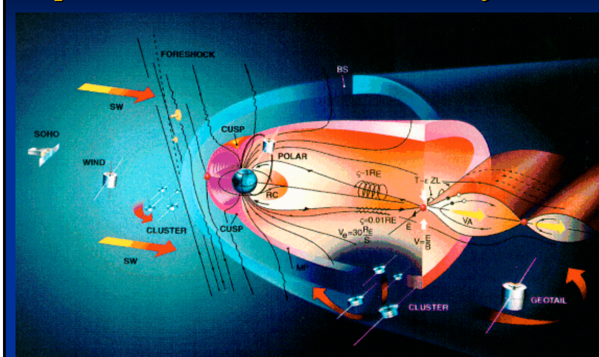
3D magnetic reconnection



State of the art: global MHD models



Multiscale processes in complex system -> plasma simulations necessary



Comparison with observations

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