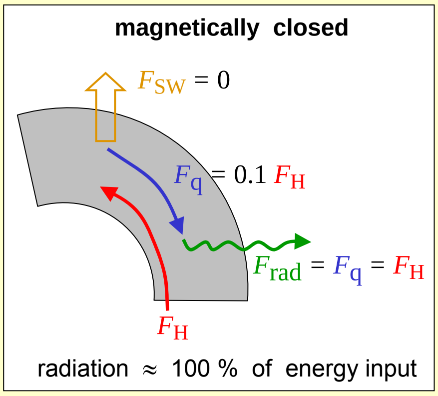
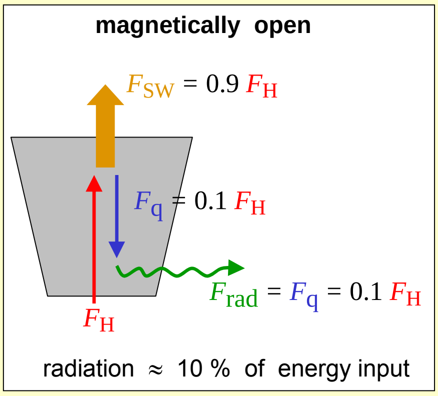
Closed magnetic structures

Hardi Peter
Kiepenheuer-Institut
für Sonnenphysik
Freiburg

solar eclipse, **11.8.1999**, Wendy Carlos and John Kern

Energy budget in the quiet corona





following Holzer et al. (1997)

assume the same energy input into open and closed regions:

→ almost ALL emission we see on the disk outside coronal holes originates from magnetically closed structures (loops) !

Basic building blocks I: coronal loops

EUV / X-ray filtergrams

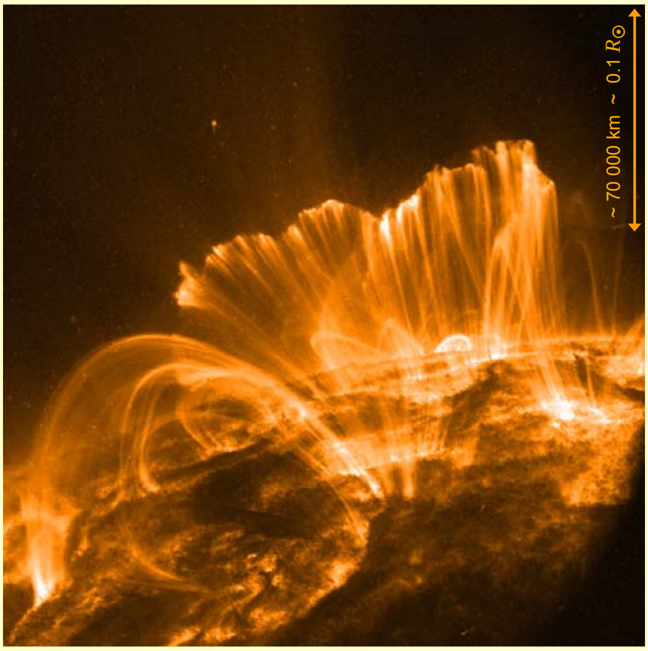
Fe IX / X (17.1 nm)

$\approx 10^6$ K

9. November 2000

Do loops really outline the magnetic field ?

Transition Region and Coronal Explorer (TRACE) — NASA

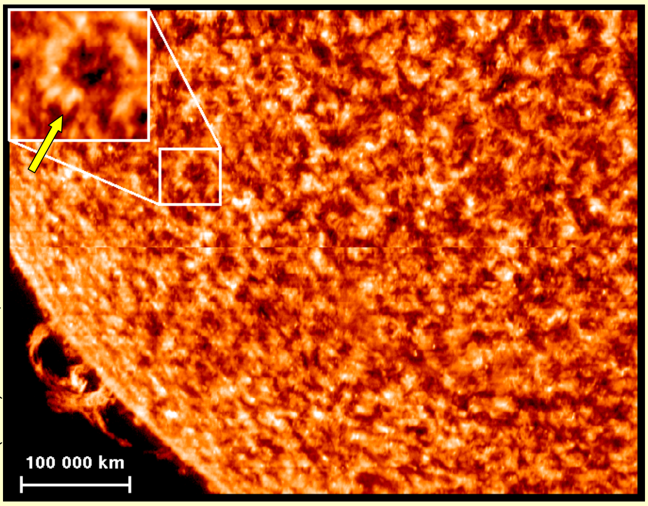


Basic building blocks II: transition region loops

transition region from chromosphere to corona

- small loops across network-boundaries
- low loops across cells

Certainly
not all structures are resolved!
➡ **is it all loops ?**



Peter (2001) A&A 374,1108

see also
Feldman et al. (2003),
ESA SP-1274:
"Images of the Solar Upper Atmosphere from SUMER on SOHO".

28.1.1996
C III (97.7 nm)
~80 000 K

SUMER
EUV spectrograph

MHD equations

$\nabla \times \boldsymbol{B} = \mu \boldsymbol{j}$ $\quad \boxed{\nabla \cdot \boldsymbol{B} = 0}$

$\nabla \times \boldsymbol{E} = -\partial_t \boldsymbol{B}$ $\quad \nabla \cdot \boldsymbol{E} = \frac{1}{\varepsilon} \rho_e$

$\boldsymbol{j} = \sigma (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$

$$\boldsymbol{j} \times \boldsymbol{B} = \frac{1}{\mu} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B}$$

induction eq.

$$\partial_t \boldsymbol{B} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times (\eta \nabla \times \boldsymbol{B})$$

mag. diffusivity $\eta = \frac{1}{\mu \sigma}$

continuity eq. $\quad \partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = 0$

momentum eq. $\quad \rho \partial_t \boldsymbol{u} + \rho (\boldsymbol{u} \cdot \nabla) \boldsymbol{u} = -\nabla p + \rho \boldsymbol{g} + \boldsymbol{j} \times \boldsymbol{B} + \nabla \cdot \boldsymbol{\tau}$

viscous stess tensor $\boldsymbol{\tau}$:

$$\nabla \cdot \boldsymbol{\tau} = \rho \nu \left(\Delta \boldsymbol{u} + \frac{1}{3} \nabla (\nabla \cdot \boldsymbol{u}) \right)$$

energy eq. $\quad (\partial_t + \boldsymbol{u} \cdot \nabla) e + \frac{5}{2} p \nabla \cdot \boldsymbol{u} = -\nabla \cdot \boldsymbol{q} - L_{\mathrm{rad}} + \eta \boldsymbol{j}^2 + Q_{\mathrm{visc}}$

internal energy: $e = n \frac{3}{2} k_{\mathrm{B}} T$

➡ for coronal diagnostics it is essential to get energy equation right

The heating rate sets the coronal pressure

- dump heat in the corona F_{H}

  radiation is not very efficient in the corona (10^6K)

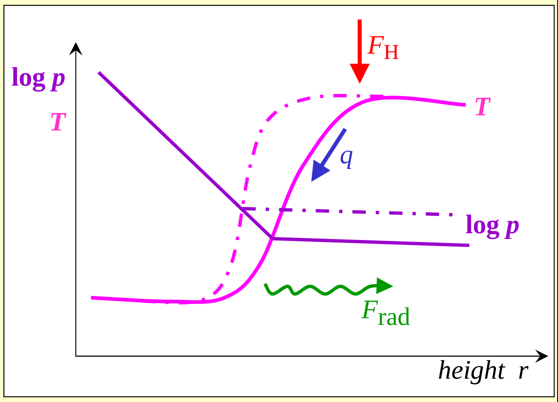
- heat conduction $\nabla \cdot q$ transports energy down

- energy is radiated in the low transition region and upper chromosphere F_{rad}

  radiation depends on particle density

  pressure: $p \sim F_{\mathrm{rad}}$

➡ $p_{\mathrm{corona}} \sim F_{\mathrm{H}}$



increase the heating rate:

more has to be radiated ⟹ higher base pressure

➡ transition region moves to lower height !

The "details" might change (e.g. spatial distribution of heating) but the basic concept remains valid!

Radiative losses

in an optically thin medium in equilibrium through collisionally excited emission lines:

$$L_{rad} = n_e \, n_H \, P_{rad} \approx n^2 P_{rad}$$

exitation: $C_{12} \propto n_e$ emissivity: $\varepsilon \propto n_{upper} \propto n_H$

often:
piecewise
power law: $P_{rad} = \chi T^{\alpha}$

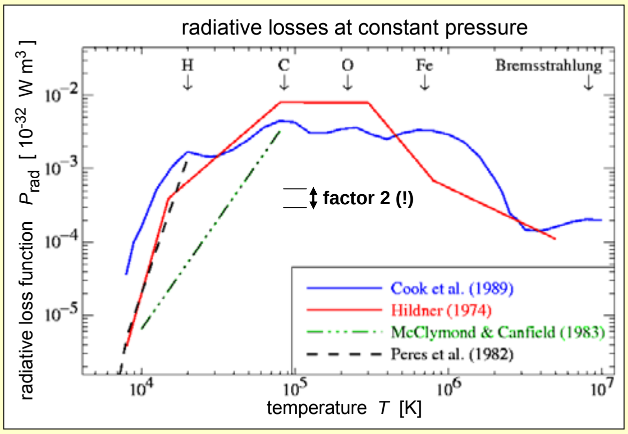
Problems:

- different studies give different losses: often factor 2x or more (!)
- ionization equilibrium may be bad assumption

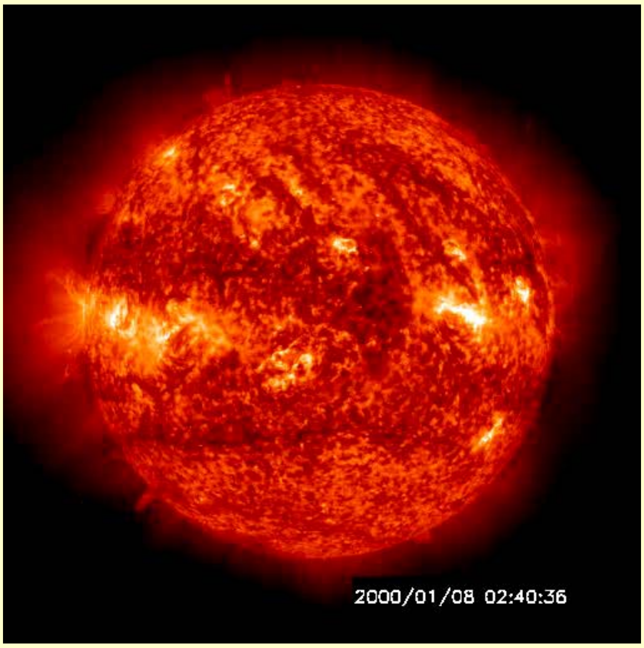
Needed (but difficult…):

self-consistent treatment:

- get ionization stages
- calc. dominant lines
- integrate for total losses
- feed into energy equation



The dynamic Sun



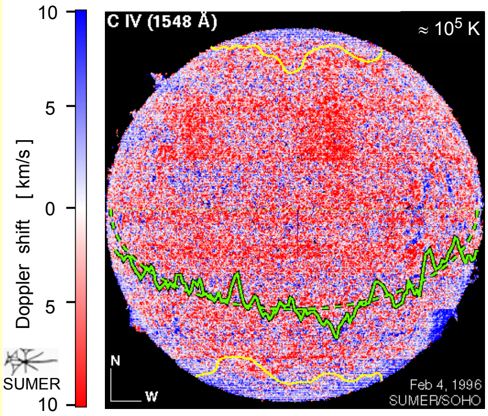
SOHO / EIT
He II (304 Å)
~ 30 000 K

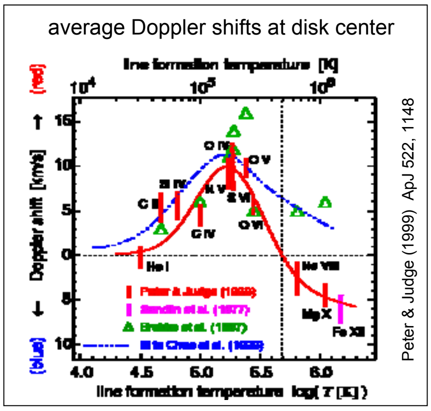
The Sun
is changing
everywhere
all the time!

How to describe this mess ? — Ask right questions!

- **investigate individual structures**
  pick a “good / typical” example – but what is “good / typical” ?
- **study “ensemble averages”**
  – structures on a star come in many types
  – it is not sufficient for a “good” model to reproduce a singular observation...

example for ensemble observations: **quiet Sun Doppler shifts**



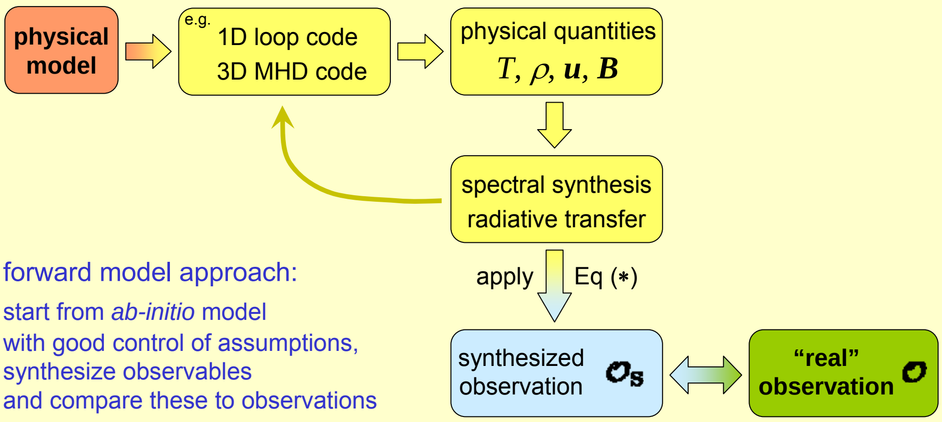


Modeling approach

We observe only photons: flux, polarisation, and energy

in general: $\boxed{\textbf{observed quantity} \quad \mathcal{O} = \int K(T, \rho, \mathbf{u}, \mathbf{B}, \ldots) \mathrm{d}l}$ (∗)

with a kernel K including e.g. atomic physics, radiative transfer, etc...



forward model approach:

start from *ab-initio* model
with good control of assumptions,
synthesize observables
and compare these to observations

1D loop models

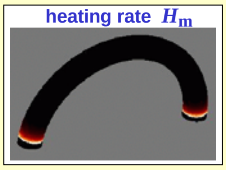
continuity equation
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho u) = 0$$

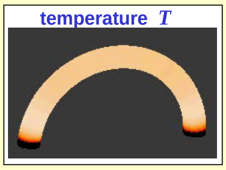
momentum equation
$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial z} = \frac{\partial p}{\partial z} - \rho g_{\parallel}$$

- adaptive mesh
- proper energy equation
  - heat conduction
  - parameterized heating
- non-equilibrium ionization
- self-consistent treatment of radiative losses

Müller, Hansteen & Peter (2003) A&A 411, 605

energy equation
$$\frac{\partial}{\partial t}(\rho e) + \frac{\partial}{\partial z}(\rho u e) + p \frac{\partial u}{\partial z} = -\frac{\partial q}{\partial z} + H_{\mathrm{m}} - L_{\mathrm{rad}}$$





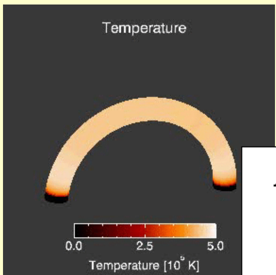
radiative losses: self-consistently or from table

heating: $H_{\mathrm{m}} \propto \exp(-z/\lambda_{\mathrm{m}})$

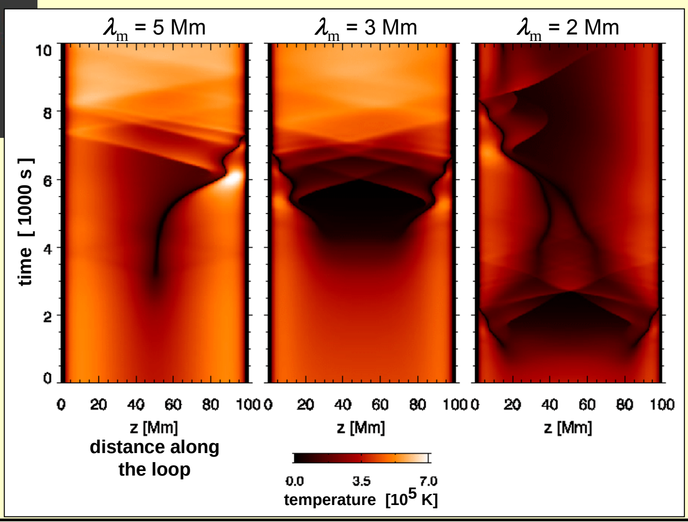
heat conduction: $q = \kappa_0 T^{5/2} \frac{\partial T}{\partial z}$

rate equations for ionisation and radiation
$$\frac{\partial}{\partial t}(n_{i,k}) + \frac{\partial}{\partial z}(n_{i,k}\, u) = \begin{cases} \text{ionization} + \text{recombination} \\ + \text{exitation} + \text{deexcitation} \end{cases}$$

Condensations in coronal loops



- vary damping length λ_{m} of heating rate $\propto \exp(-z/\lambda_{\mathrm{m}})$
  constant heating vs. footpoint concentrated
- for wide range of λ_{m} : thermal instability at top
  ➔ condensation



- quasi-periodic and chaotic repetitions of condensations

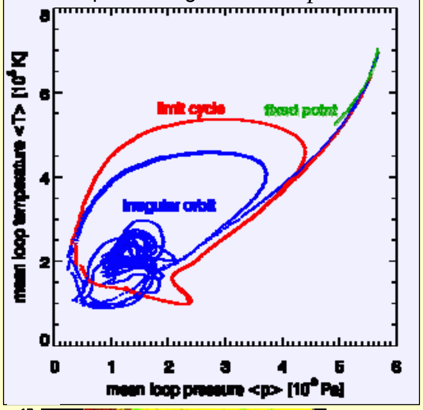
  for heating *constant in time !*

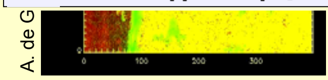
- spectral signatures comparable to observations (TRACE 1550 Å)

Müller, Peter & Hansteen (2004) A&A 424, 289

Condensations: observation and model

phase diagram: $T \sim p$

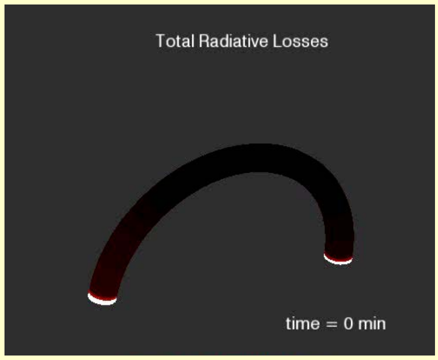




EIT 17.1 nm / BBSO Hα

~10^6 K ~10^4 K

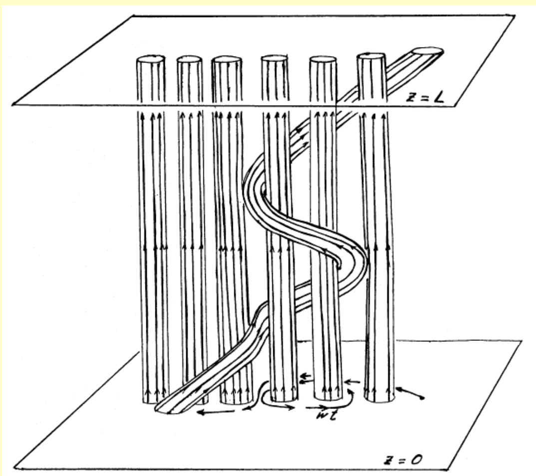
loop model: ~ 2 hours



Müller, Peter & Hansteen (2004) A&A 424, 289

- thermal instability is driven by lack of heating in top part of the loop
- occurring even with **time-constant heating**
- due to non-linear interaction of heating, radiative losses and heat conduction

A concept to heat the corona: magnetic braiding



Eugene Parker *(1972, ApJ 174, 499)*:

braiding of magnetic field lines through **random motions** on the stellar surface

→ braided magnetic field in the corona

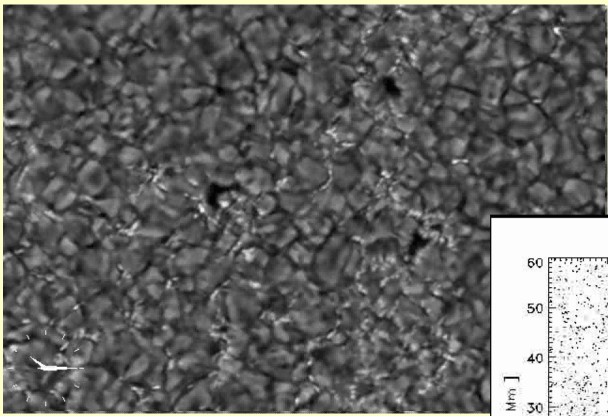
→ strong currents $\boldsymbol{j} \sim \nabla \times \boldsymbol{B}$

→ Ohmic dissipation $H \sim \eta\, \boldsymbol{j}^2$

→ heating of the corona

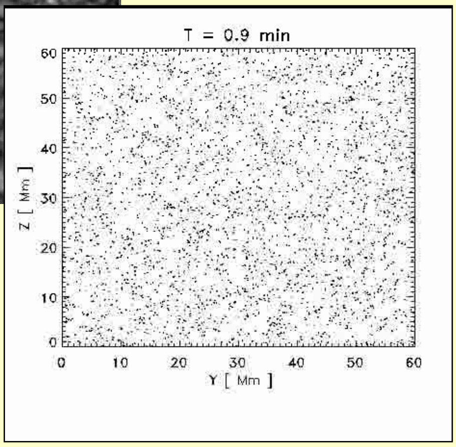
***Problem*: a “realistic” computational model is “costly”…**

The driving force in the photosphere



Dutch Open Telescope, La Palma
12. Sept. 1999 (Sütterlin & Rutten)
≈ 38 000 km x 25 000 km, ≈ 27 min

2 Mm



simulated granulation (Voronoi tessellation):

- "corks" on the solar surface (Boris Gudiksen)
- matches solar velocity and vorticity spectra
  (observed + convection simulations)

3D MHD coronal modeling

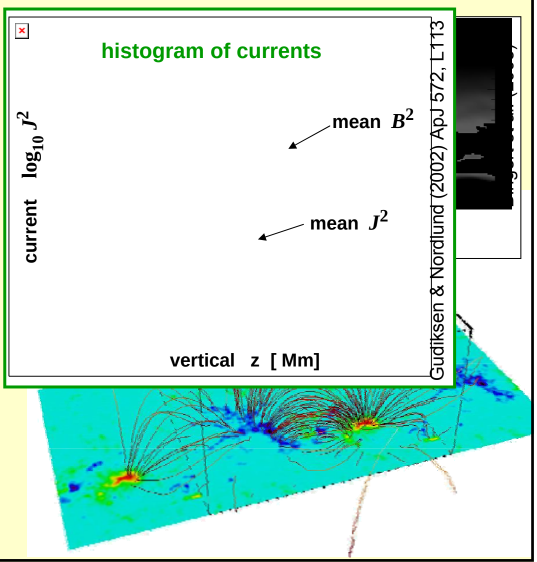
- 3D MHD model for the corona:
  50 x 50 x 30 Mm Box (150^3)
  - fully compressible; high order
  - non-uniform mesh
- full energy equation
  (heat conduction, rad. losses)
- starting with scaled-down MDI magnetogram
  - no emerging flux
- photospheric driver:
  foot-point shuffled by convection
- braiding of mag fields
  (Galsgaard, Nordlund 1995; JGR 101, 13445)

➔ heating: DC current dissipation
(Parker 1972; ApJ 174, 499)

➔ heating rate $\eta j^2 \sim \exp(-z/H)$

➔ loop-structured 10^6K corona

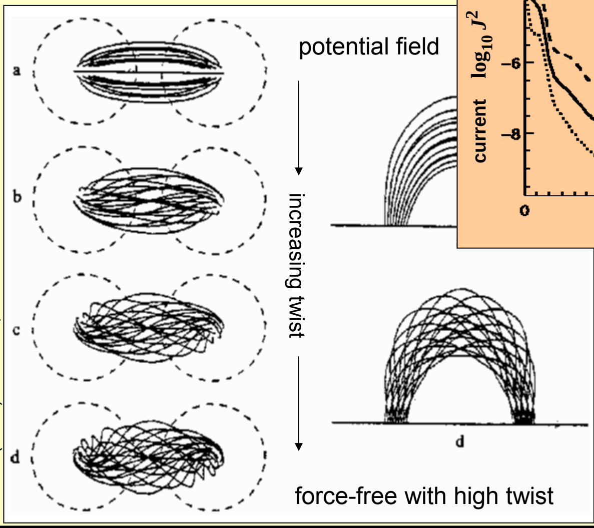
Gudiksen & Nordlund (2002) ApJ 572, L113
(2005) ApJ 618, 1020 & 1031
Bingert, Peter, Gudiksen & Nordlund (2005)



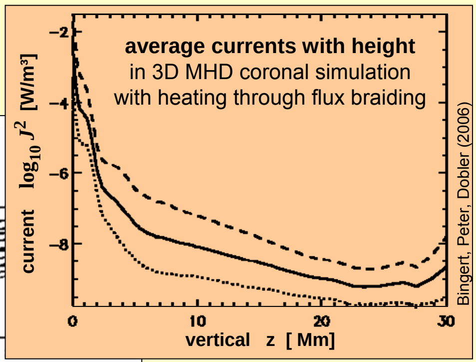
Force-free fields with twist and flux braiding

No plasma / only magnetic field:
solve $j \times B = 0$

➡ twist in B is everywhere
➡ currents are everywhere



Sakurai (1979) PASJ 31, 209



density stratification + footpoint motions with B close to potential:

➡ heating rate (ηj^2) is concentrated at low heights !!

e.g.
Galsgaard & Nordlund (1996)

Emissivity from a 3D coronal model

From the MHD model: – density ρ (fully ionized) → n_e } { at each
– temperature → T } { grid point and time

Emissivity at each grid point and time step:

$$\varepsilon(x,t) = h\nu\, n_2 A_{21} = n_e^2\, G(T,n_e) \quad \left[\frac{\mathrm{W}}{\mathrm{m}^3}\right]$$

$$G(T,n_e) = h\nu A_{21}\ \frac{n_2}{n_e\, n_{ion}}\ \frac{n_{ion}}{n_{el}}\ \frac{n_{el}}{n_H}\ \frac{n_H}{n_e}$$

└ total ionization ≈0.8
└ abundance = const.
└ ionization } ≈ $f(T)$
└ excitation }

Assumptions:
– equilibrium excitation and ionisation (not too bad...)
– photospheric abundances

use CHIANTI atomic data base to evaluate ratios (Dere et al. 1997)

→ G depends mainly on T (and weakly on n_e)

Synthetic spectra

1) emissivity at each grid point – $f(\rho,T)$ – → $\varepsilon(\mathbf{x},t)$
2) velocity along the line-of-sight from the MHD calculation → v_{los}
3) temperature at each grid point → T

line profile at each grid point:

$$I_\nu(\mathbf{x},t) = I_0 \exp\left[-\frac{(v-v_{los})^2}{w_{th}^2}\right]$$

line width corresponding to thermal width $\quad w_{th} = \sqrt{\frac{2k_B T(\mathbf{x},t)}{m_{ion}}}$

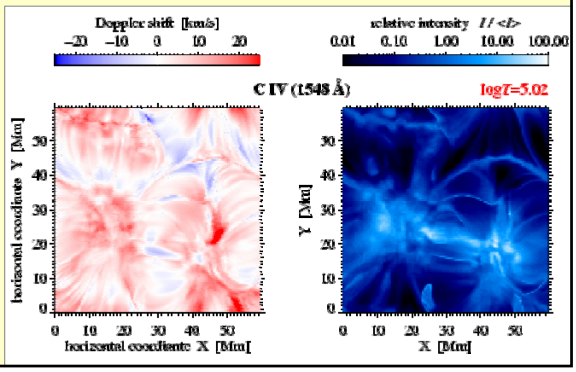
total intensity corresponding to emissivity $\quad I_0\, w_{th} \propto \varepsilon(\mathbf{x},t)$

integrate along line-of-sight

maps of spectra
as would be obtained by a scan
with an EUV spectrograph,
e.g. SUMER

analyse these spectra like observations

- calculate moments:
  line intensity, shift & width
- emission measure (DEM)
- etc. ...

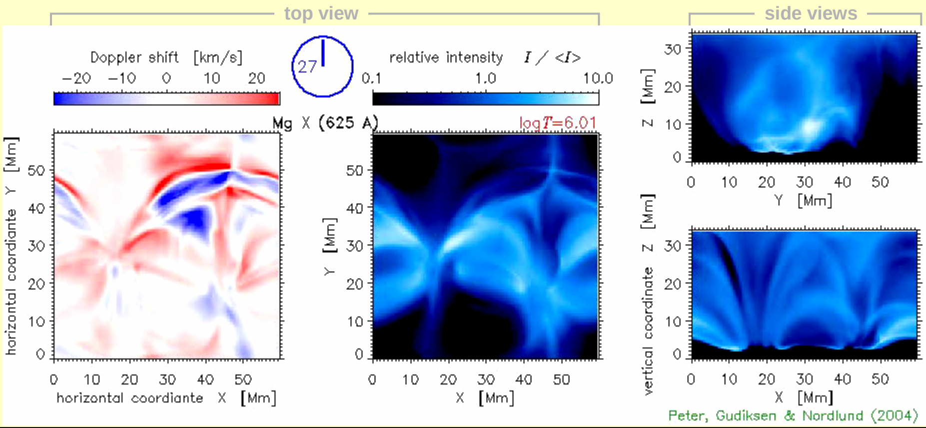


Coronal evolution

Mg X (625 Å)
~10^6 K

- ➢ large coronal loops connecting active regions
- ➢ gradual evolution in line intensity ("wriggling tail")
- ➢ higher spatial structure and dynamics in Doppler shift signal

→ it is important to have full spectral information!



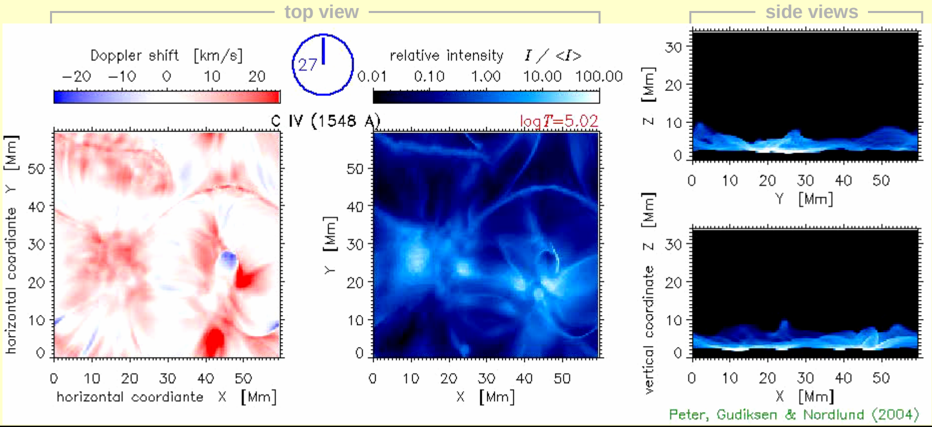
TR evolution: C IV (1548 Å)

C IV (1548 Å)
~10^5 K

- very fine structured loops – highly dynamic
- also small loops connecting to “quiet regions”
- cool plasma flows – locks like “plasma injection”

→ dynamics quite different from coronal material !

top view   side views



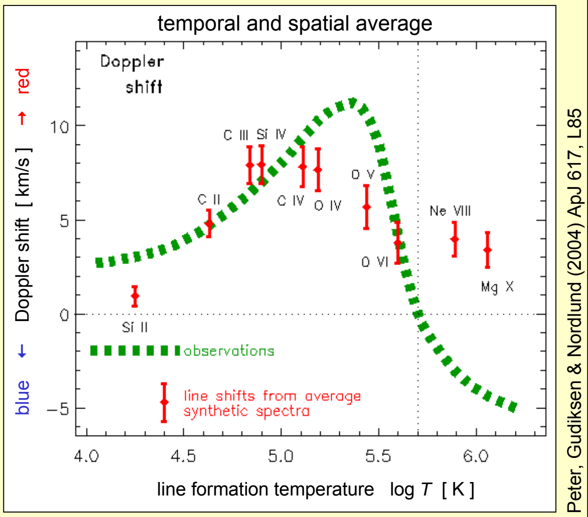
Doppler shifts

spatial averages

- very good match in TR
- overall trend v_D vs. T quite good
- still no match in low corona
  - → boundary conditions?
  - → missing physics?

temporal variability

- high variability as observed
- for some times almost net blueshifts in low corona**!**



➡ **no “fine-tuning” applied !**

➡ **best over-all match of models so far**

Emission measure

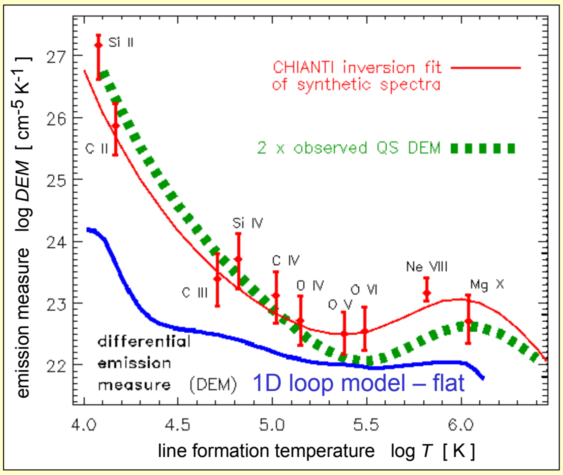
$$DEM = n_e^2 \frac{dh}{dT}$$

DEM inversion using CHIANTI:

1 – using synthetic spectra derived from 3D MHD model

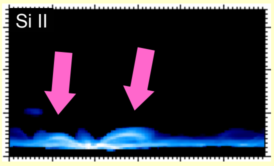
2 – using solar observations (SUMER, same lines)

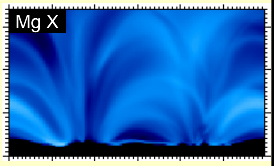
➡ good match to observations!! DEM increases towards low T in the model !



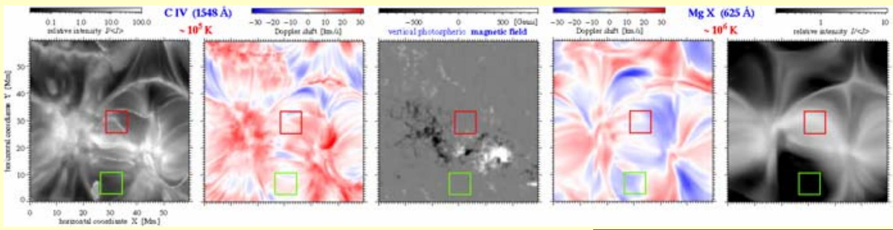
Peter, Gudiksen & Nordlund (2004) ApJ 617, L85

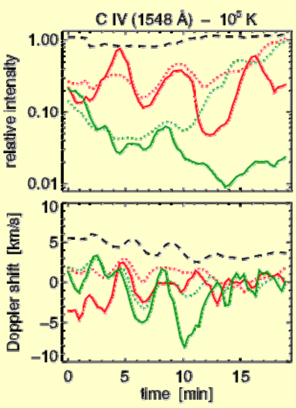
Supporting suggestions that numerous cool structures cause increase of DEM to low T





Temporal variability: individual examples





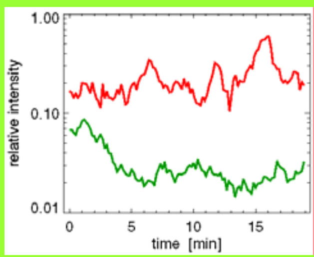
- large variability in TR
- smooth variation in coronal intensity
- variability in coronal shift comparable to TR !!
- ~5 – 7 min variability signature of the photospheric driver?
- similar variations found in observations!

A real observation:

SUMER / SOHO

S IV (1394 Å) ~ 10^5 K

1x1'', 10 sec exposures



Temporal variability: average properties

observations:
[Brković, Peter & Solanki (2003), A&A 403, 725]

- rms intensity fluctuations have pronounced peak at ~10^5 K
- rms Doppler shift variations increase monotonically

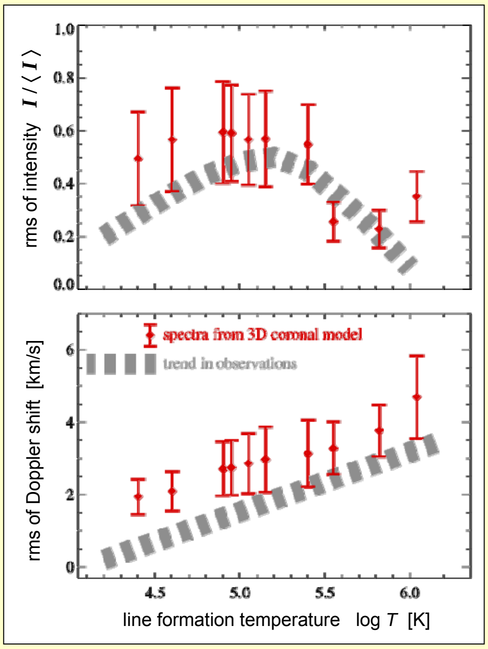
synthetic spectra from 3D model

\+ very good match of observed trend(s)

\+ correct description of "overall" variability

– real Sun shows variations on much shorter times (seconds)

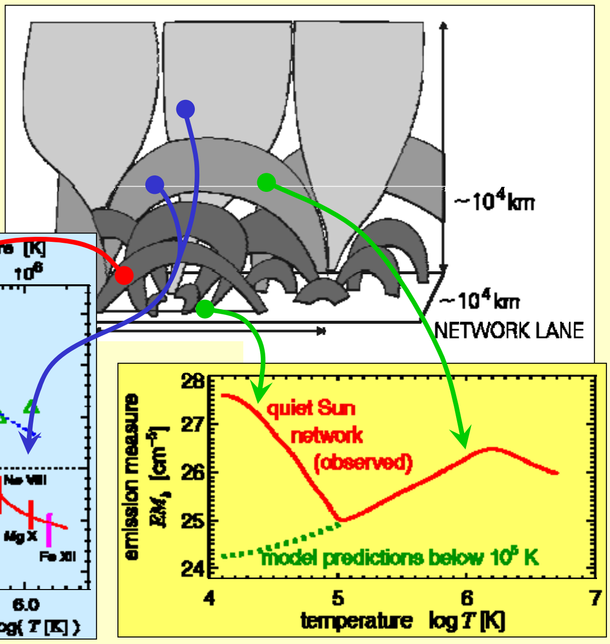
  ➥ lack of spatial resolution in 3D MHD model ?

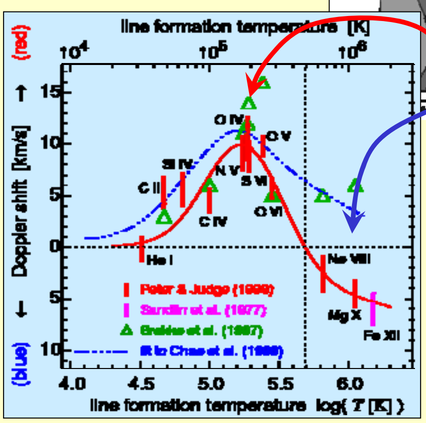


Peter, Gudiksen & Nordlund (2006) ApJ 638, 1086

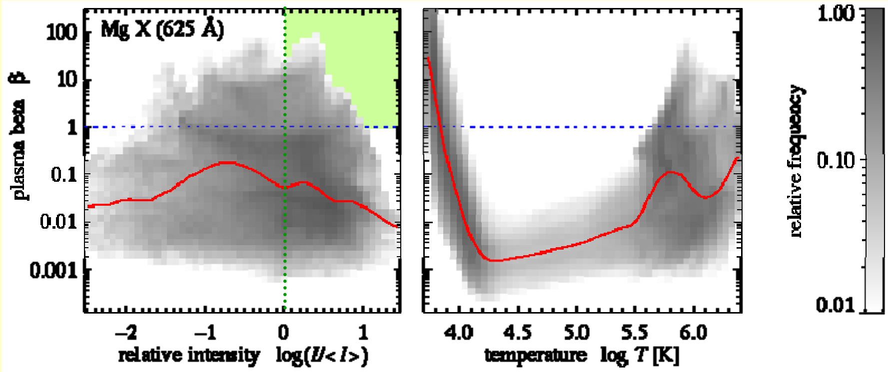
A multi–structured low corona

The 3D model with spectral synthesis confirms old suspicions based on spectroscopic and magnetic field observations !





Coronal emission and plasma–β



Peter, Gudiksen & Nordlund (2006) ApJ 638

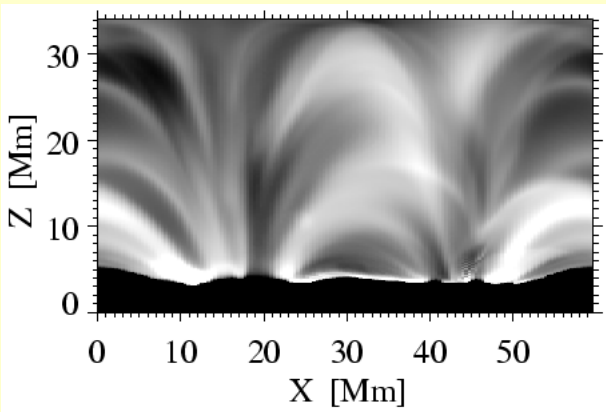
- atmosphere is *mostly* in low–β state,
- numerous $\beta > 1$ regions even at high T (but mostly at low density)

- source region of coronal emission:
  90% of emission from $\log I/\langle I \rangle > 0$
  ➥ there ~5% of volume at $\beta > 1$

- corona is **not** in a pure low–β state:
  plasma able to distort magnetic field
  to some extent

Coronal emission and magnetic field lines I

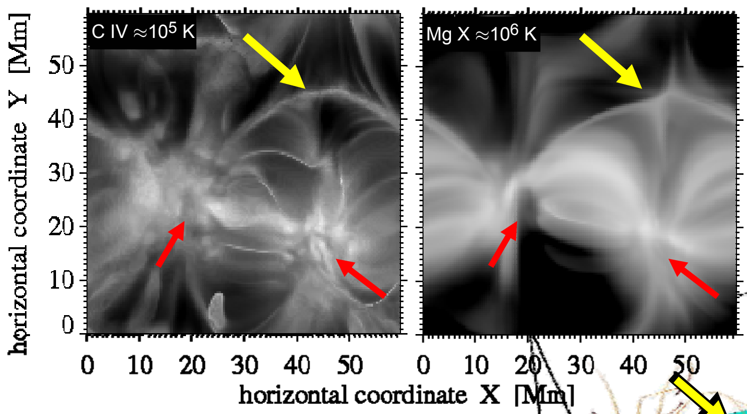
The "usual" paradigm: The coronal emission is aligned with the magnetic field



Peter, Gudiksen & Nordlund (2004) ApJ 618

emission synthesized from a 3D coronal model
side view / at the limb

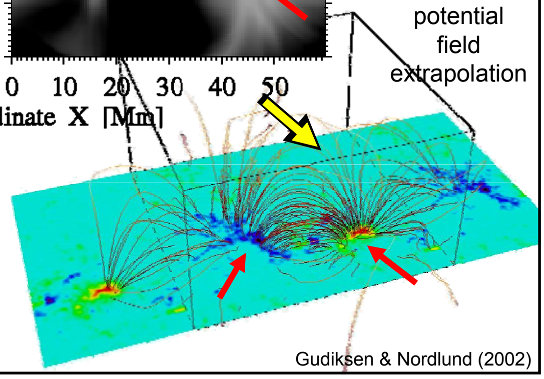
Coronal emission and magnetic field lines II



synthesized emission top view / on the disk

Peter, Gudiksen & Nordlund (2004) ApJ 618

potential field extrapolation



Gudiksen & Nordlund (2002)

Not all emission we see in EUV / X-rays outlines field lines !!!

Dissipation mechanism – the MHD point of view

Why is it (apparently) possible to ignore the fact that the magnetic Reynolds R_m number is huge, work with large scale near-singular structures, and get decent results?
(Åke Nordlund)

$$R_\mathrm{m} = \frac{U\,L}{\eta} = \frac{L^2}{\tau\,\eta}$$

simulations: R_m well below 1000
➡ relatively high resistivity η
or low conductivity σ

dissipation generates subsidiary smaller and smaller scale structures
➡ until scales are small enough to support dissipation…

$$\text{dissipated power} = \frac{\text{dissipated energy}}{\text{volume and time}} = \frac{E/V}{\tau} \sim \underbrace{\partial_t(e) \sim \eta j^2}_{\text{from the energy eq.: Ohmic dissipation}} \sim B^2 \frac{\eta}{L^2}$$

Using η from transport theory: scales L very small ($\ll$ km) ➡ too small for simulations

energy will always be dissipated at the smallest resolved scale…
➡ choose η, so that size of resulting current sheets $L \approx$ grid size

Dissipation mechanism – the kinetic point of view

where do the conductivity σ and
magnetic diffusivity $\eta = 1/(\mu\sigma)$ come from ?

$$\partial_t f + \boldsymbol{v}\cdot\nabla_x f + \frac{\boldsymbol{F}}{m}\nabla_v f = \left(\frac{\delta f}{\delta t}\right)_{\rm coll} \approx -\frac{1}{\tau_c}\left(f - f_0\right) \Rightarrow$$

linearized BGK (*)

$$v\frac{\partial f_0}{\partial r} + \frac{F}{m}\frac{\partial f_0}{\partial v} = -\nu_c f_1$$

BGK ~ 1954

moments of LHS result in
fluid equations (e.g. MHD)

$$f_0 = f_M = n\left(\frac{m}{2\pi k_B T}\right)^{3/2}\exp\left(-\frac{m(v-u_0)^2}{2k_B T}\right)$$

to investigate electric conductivity:

homogeneous: $\partial_x = 0$; $n, T = \text{const.}$
static: $u_0 = 0$
const. E field: $F = ZeE$

$$(*) \rightarrow \quad \frac{ZeE}{m}\frac{\partial f_0}{\partial v} = -\nu_c f_1 \qquad (**)$$

$$\frac{\partial f_0}{\partial v} = -\frac{m}{k_B T} v f_0$$

$$\int v\,(**)\,\mathrm{d}v: \quad \frac{ZeE}{m}\frac{m}{k_B T}\underbrace{\int v^2 f_0 \mathrm{d}v}_{= n\frac{k_B T}{m}} = \nu_c \int v f_1 \mathrm{d}v \quad \Longleftrightarrow \quad \underbrace{\underbrace{\frac{Z^2e^2n}{m\nu_c}}_{\sigma} \; \underset{\updownarrow}{E}\;_{E} = \underbrace{Ze\int v f_1 \mathrm{d}v}_{=j}}_{\text{Ohm's law}}$$

$$\boxed{\sigma = \frac{Z^2e^2n}{m\nu_c}}$$

Summary / lessons learnt

- in the quiet corona emission is dominated by magnetically closed regions
- loops are basic building blocks
- heating rate sets coronal base pressure
- forward modeling allows reliable comparison to observations
  – one observes only photons (and not T, ρ, v, $\boldsymbol{B}$)
- loops evolve very dynamically, even when not driven
- braiding of magnetic field lines is good candidate to heat the corona
  - produces a MK loop-structured corona
  - properties of inferred spectra match observations (line shift, intensity, etc)
  - dynamics as with observations
- however: MHD coronal box model do not describe the
  "real" microphysical processes!