Energy budget in the quiet corona

magnetically closed

\[ F_{SW} = 0 \]

\[ F_q = 0.1 \cdot F_H \]

\[ F_{rad} = F_q = F_H \]

radiation \approx 100\% \text{ of energy input}

magnetically open

\[ F_{SW} = 0.9 \cdot F_H \]

\[ F_q = 0.1 \cdot F_H \]

\[ F_{rad} = F_q = 0.1 \cdot F_H \]

radiation \approx 10\% \text{ of energy input}

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

Do loops really outline the magnetic field?

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!
\( \Rightarrow \) is it all loops?

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

- Dump heat in the corona $F_H$
  - Radiation is not very efficient in the corona (10⁶K)
- 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: $p \sim F_{rad}$

$F_{corona} \sim F_H$

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:

\[ L_{\text{rad}} = n_e n_H P_{\text{rad}} \approx n^2 P_{\text{rad}} \]

- excitation: \( C_{12} \propto n_e \)
- emissivity: \( \xi \propto n_{\text{upper}} \propto n_E \)

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: \[ \text{observed quantity } \mathcal{O} = \int K(T, \rho, u, B, \ldots) \, dl \] (\(*\))
with a kernel \( K \) including e.g. atomic physics, radiative transfer, etc...

physical model \( \rightarrow \) 1D loop code 3D MHD code \( \rightarrow \) physical quantities \( T, \rho, u, B \)

forward model approach:
start from \( ab\text{-initio} \) model
with good control of assumptions,
synthesize observables
and compare these to observations

apply Eq (\(*\))
synthesized observation \( \mathcal{O}_S \) \( \leftrightarrow \) "real" observation \( \mathcal{O} \)
1D loop models

continuity equation \[ \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z} (\rho u) = 0 \]
momentum equation \[ \rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial z} = \frac{\partial p}{\partial z} - \rho g \]
energy equation \[ \frac{\partial}{\partial t} (\rho e) + \frac{\partial}{\partial z} (\rho u e) + p \frac{\partial u}{\partial z} = -\frac{\partial q}{\partial z} + H_m - L_{rad} \]

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

Condensations in coronal loops

- vary damping length \( \lambda_m \) of heating rate \( \propto \exp (-z / \lambda_m) \)
- constant heating vs. footpoint concentrated
- for wide range of \( \lambda_m \): 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)

Condensations: observation and model

- EIT 17.1 nm / BBSO Hα
  - ~10⁶ K
  - ~10⁴ K

- 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

  - Braiding of magnetic field lines through random motions on the stellar surface
  - Braided magnetic field in the corona
  - Strong currents
    - \( j \sim \nabla \times B \)
  - Ohmic dissipation
    - \( H \sim \eta j^2 \)
  - 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

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

However:
- correlation tracking observations provide velocity field
  $u(x,y,t)$ only down to ~2 Mm
- needed are <0.5 Mm!

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

Bingert, Peter, Gudiksen & Nordlund (2005)

histogram of currents
**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

![Diagram showing force-free fields with twist and flux braiding](image)

Sakurai (1979) PASJ 31, 209

**Emissivity from a 3D coronal model**

From the MHD model:  
- density \( \rho \) (fully ionized) \( \rightarrow n_e \)
- temperature \( \rightarrow T \)  

Emissivity at each grid point and time step:

\[
\varepsilon(x,t) = h v n_2 A_{21} = n_e^2 G(T,n_e) \begin{bmatrix} W \end{bmatrix}
\]

\[
G(T,n_e) = h v A_{21} \frac{n_2}{n_e} \frac{n_\text{ion}}{n_e} \frac{n_\text{cl}}{n_\text{H}} \frac{n_\text{H}}{n_e}
\]

- total ionization \( \approx 0.8 \)
- abundance = const.

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 \( \varepsilon(x,t) \)
2) velocity along the line-of-sight from the MHD calculation \( v_{\text{los}} \)
3) temperature at each grid point \( T \)

**line profile at each grid point:**
\[
I_{\nu}(x,t) = I_0 \exp\left(-\frac{(\nu - v_{\text{los}})^2}{w_{\text{th}}^2}\right)
\]

**line width corresponding to thermal width**
\[
w_{\text{th}} = \sqrt{\frac{2 k_B T(x,t)}{m_{\text{los}}}}
\]

**total intensity corresponding to emissivity**
\[
I_0 \nu_{\text{th}} \propto \varepsilon(x,t)
\]

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)

- 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!

C IV (1548 Å) ~10^5 K

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
DEM inversion using CHIANTI:

1 – using synthetic spectra derived from 3D MHD model
2 – using solar observations (SUMER, same lines)

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

DEM increases towards low $T$ in the model!

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:**
[Briko, Peter & Solanki (2003), A&A 403, 725]
- rms intensity fluctuations have pronounced peak at $\sim 10^5$ 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?

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–$\beta$

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

- source region of coronal emission: 90% of emission from $\log I/I_0 > 0$
  - there ~5% of volume at $\beta>1$
- corona is *not* in a pure low–$\beta$ state: plasma able to distort magnetic field to some extent

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Coronal emission and magnetic field lines 1

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

emission synthesized from a 3D coronal model
side view / at the limb
Coronal emission and magnetic field lines

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?

$dissipation generates subsidiary smaller and smaller scale structures$

$\sim \text{until scales are small enough to support dissipation...}$

$\text{dissipated power} = \frac{\text{dissipated energy}}{\text{volume and time}} = \frac{E/V}{\tau} \sim \frac{\partial_t (e)}{\tau} \sim \frac{\eta}{\tau} \sim \frac{B^2}{\eta L^2}$

$simulations: R_m \text{ well below 1000}$

$\sim \text{relatively high resistivity } \eta$

$\text{or low conductivity } \sigma$

Using $\eta$ from transport theory: scales $L$ very small ($\ll \text{km}$) $\sim$ too small for simulations

$energy will always be dissipated at the smallest resolved scale...$

$\sim \text{choose } \eta, \text{ so that size of resulting current sheets } L \approx \text{grid size}$
Dissipation mechanism – the kinetic point of view

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

\[
\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_x f + \frac{F}{m} \nabla_x \mathbf{v} = \left( \frac{\delta f}{\delta \mathbf{x}} \right)_{\text{coll}} - \frac{1}{\nu_e} \left( f - f_0 \right) \quad \Rightarrow \quad \nu_e \frac{\partial f_0}{\partial \mathbf{r}} + \frac{F}{m} \frac{\partial f_0}{\partial \mathbf{v}} = -\nu_e f_1
\]

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

\[
K = i \mu = n \left( \frac{m}{2 \pi k_B T} \right)^{3/2} \exp \left( -\frac{m(v - u_0)^2}{2k_B T} \right)
\]

linearized BGK (*)

BGK ~ 1954

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

\[
h = f = n \left( \frac{m}{2 \pi k_B T} \right)^{3/2} \exp \left( -\frac{m(v - u_0)^2}{2k_B T} \right)
\]

to investigate electric conductivity:

homogeneous: $\partial_x = 0 : n, T = \text{const.}$

static: $u_0 = 0, F = ZeE$

\[
\int v^{(+)} dv : \quad \frac{ZeE}{m} \frac{m}{k_B T} \int v^2 f_0 dv = \nu_e \int v f_1 dv \quad \Leftrightarrow \quad \frac{Ze^2 n}{m \nu_e} = \frac{Ze \int v f_1 dv}{k_B T}
\]

\[
\sigma = \frac{Ze^2 n}{m \nu_e} \quad \Rightarrow \quad \sigma \frac{E}{k_B T} = i
\]

Ohm’s law

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 $T, \rho, v, B$)
- 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!