The Sun's corona and magnetic field

- The Sun's corona and magnetic field
- EUV radiation of the corona
- The magnetic network
- Doppler spectroscopy in EUV
- Small-scale dynamics and turbulence
- Temperature profiles in the corona
The visible solar corona

Eclipse 11.8.1999
Electron density in the corona


+ Current sheet and streamer belt, closed

• Polar coronal hole, open magnetically

Skylab coronagraph/Ulysses in-situ

Heliocentric distance / $R_s$
Coronal magnetic field and density

Dipolar, quadrupolar, current sheet contributions

Polar field: $B = 12\, \text{G}$

Current sheet is a symmetric disc anchored at high latitudes!

Banaszkiewicz et al., 1998;
Schwenn et al., 1997

LASCO C1/C2 images (SOHO)
Plasma beta I

Starting from the MHD equation of motion for a plasma at rest in a steady quasineutral state, we obtain the simple force balance:

$$\nabla \cdot \mathbf{P} = -\frac{1}{\mu_0} \mathbf{B} \times (\nabla \times \mathbf{B})$$

which expresses *magnetohydrostatic equilibrium*, in which thermal pressure balances magnetic tension. If the particle pressure is nearly isotropic and the field uniform, this leads to the total pressure being constant:

$$\nabla \left( p + \frac{B^2}{2\mu_0} \right) = 0$$

The ratio of these two terms is called the *plasma beta*:

$$\beta = \frac{2\mu_0 p}{B^2}$$
Plasma beta II

Aschwanden, 2004
Corona and magnetic network

80000 K 1996

SOHO EIT He II 30.4 nm
Active regions near minimum

2 MK 1996

SOHO EIT Fe XV 28.4 nm
Corona and transition region

SOHO EIT

Fe IX,X 17.1 nm

2001

1.3 MK
Active regions near maximum

1.6 MK 2001

SOHO EIT Fe XII 19.5 nm
X-ray corona

Yohkoh SXT
3-5 Million K
Yohkoh SXT: The changing corona
Ten photospheric magnetograms:
The solar cycle 1992 - 1999 (NSO)
Corona of the active sun

EIT - LASCO C1/C2

1998
How is the solar corona heated?
EUV line excitation processes

- **Collisional excitation of atom or ion, A, followed by a radiative decay:**

  \[ A + e^- \rightarrow A^* + e^- \quad (n_e > 10^8 \text{ cm}^{-3}) \]

  \[ A^* \rightarrow A + h\nu \quad \text{Line radiance: } L_\lambda \sim n_e^2 \]

- **Resonant scattering (fluorescence):**

  \[ A + h\nu \rightarrow A^* \rightarrow A + h\nu \quad \text{Line radiance: } L_\lambda \sim n_e \]

- **Radiative recombination:**

  \[ A^{+z} + e^- \rightarrow A^{+(z-1)*} \rightarrow A^{+z-1} + h\nu \]
Solar EUV emission spectrum

[Spectral intensity (mWm\(^{-2}\)sr\(^{-1}\)Å\(^{-1}\))]

Curdt et al., A&A 375, 591, 2001
**Coronal model** approximation: collisional excitation and radiative decay

\[ N_g(X^{+m}) n_e C_{g,j} = N_j A_{j,g} \]

\( C_{g,j} \text{ [cm}^3\text{s}^{-1}] \) collisional excitation rate

\( A_{j,g} \text{ [s}^{-1}] \) atomic spontaneous emission coefficient ( \( \approx 10^{10}\text{s}^{-1} \))

**Emissivity** (power per unit volume):

\[ P(\lambda_{g,j}) = N_j(X^{+m}) A_{j,g} \Delta E_{j,g} \text{ [erg cm}^3\text{s}^{-1}] \]

\( \Delta E_{g,j} = E_j - E_g \) photon energy

\( N_g(X^{+m}) \) number density of ground state of ion \( X^{+m} \)
Elementary radiation theory II

**Occupation** number density of level \( j \) of an ion (\( m \)-fold ionized atom) of the element \( X \):

\[
N_j(X^{+m})/n_e = \frac{N_j(X^{+m})}{N(X^{+m})} \cdot \frac{N(X^{+m})}{N(X)} \cdot \frac{N(X)}{n(H)} \cdot \frac{n(H)}{n_e}
\]

- ↑ excitation level
- ↑ ionic fraction
- ↑ abundance
- ↑ \( n(H) \) [cm\(^3\)] hydrogen

**Collisonal excitation rate** (Maxwellian electrons):

\[
C_{i,j} \sim \frac{1}{T_e^{1/2}} \exp\{ \frac{\Delta E_{i,j}}{(k_BT_e)} \}
\]

- ↑ Boltzmann factor
Oxygen ionization balance

First ionization potential (FIP)
\[ I = 13.62 \text{ eV} \]

\[ \text{LTE} \rightarrow \frac{N(X^{+m})}{N(X)} \text{ follows from Saha’s equation;} \sim \exp\left(-\frac{I}{k_B T_e}\right) \]

Shull and van Steenberg, ApJ. Suppl. 48, 95; 49, 351, 1982
Emission measure

**Emissivity** in the line of ion $X^{+m}$:

$$P(\lambda_{g,j}) = \frac{N(X^{+m})}{N(X)} \frac{N(X)}{n(H)} \frac{n(H)}{n_e} C_{g,j} \Delta E_{g,j} n_e^2$$

**Contribution function** (strongly peaked in $T_e$):

$$G(T_e, \lambda_{g,j}) = \frac{N(X^{+m})}{N(X)} C_{g,j}$$

**Emission measure:**

$$<EM> = \int_V n_e^2 dV$$

The emission measure depends on the amount of plasma (at temperature $T_e$) emitting in the observed spectral line.

Radiation power (line strength) $\sim <EM>$
Loops near the solar limb
• Thin strands, intrinsically dynamic and continuously evolving,
• Intermittent heating (in minutes), primarily within 10-20 Mm,
• Meandering of hot strings through coronal volume,
• Pulsed injection of cool material from chromosphere below,
• Variable brightenings, by braiding-induced current dissipation?
Force-free magnetic field

A special equilibrium of ideal MHD (often used in case of the solar corona) occurs if the beta is low, such that the pressure gradient can be neglected. The stationary plasma becomes force free, if the Lorentz force vanishes:

\[ \mathbf{j} \times \mathbf{B} = 0 \]

This condition is guaranteed if the current flows along the field and obeys:

\[ \mu_0 \mathbf{j} = \alpha_L \mathbf{B} \]

The proportionality factor \( \alpha_L(\mathbf{x}) \) is called lapse field. Ampère’s law yields:

\[ \nabla \times \mathbf{B} = \alpha_L \mathbf{B} \]

By taking the divergence, one finds that \( \alpha_L(\mathbf{x}) \) is constant along any field line:

\[ \mathbf{B} \cdot \nabla \alpha_L = 0 \]
Loop structures

Dipole (potential) field

\[ \phi(r, \theta) = -m \cos \theta / r^2 \quad (m = \pi \alpha a^2 I / c) \]

Sheared (force-free) arcade

\[ \Delta B + \alpha^2 B = 0 \]

Aschwanden, 2004

B = grad \phi

\[ B_x = B_{x_0} \sin(kx) \exp(-\alpha z) \]
Evolution of magnetic loops
Active region loops
Alfvèn waves in prominence

Hinode

Ca II 396.8 nm

Waves generated by reconnection

Okamoto et al., Science, 2007

T = 20000 K

Okamoto et al., Science, 2007

T = 20000 K
Doppler spectroscopy

• **Line shift** by Doppler effect (bulk motion)

\[ v_i = c(\lambda - \lambda_0)/\lambda_0 = c\Delta\lambda_D/\lambda \quad (+, \text{red shift, - blue}) \]

- \( v_i \) line of sight velocity of atom or ion; \( c \) speed of light in vacuo
- \( \lambda_0 \) nominal (rest) wave length;
- \( \lambda \) observed wave length

\[ \varepsilon = h\nu = hc/\lambda = 12345 \text{ eV}/\lambda[\text{Å}] ; \quad 1 \text{ eV} = 11604 \text{ K} \]

• **Line broadening** (thermal and/or turbulent motions)

\[ T_{\text{eff}} = T_i + m_i\xi^2/(2k_B) = m_i c^2\{((\Delta\lambda_D)^2 - (\Delta\lambda_I)^2)/(2k_B\lambda^2) \}

- \( \Delta\lambda_D \) (\( \Delta\lambda_I \)) Doppler (instrumental) width of spectral line;
- \( T_i \) ion temperature
- \( \xi \) amplitude of unresolved waves/turbulence;
- \( m_i \) ion mass

For optically thin emission and Gaussian line profile; \( \Delta\lambda_I \approx 6 \text{ pm for SUMER} \)
Cool loop in transition region

Loop height: 70000 km
Temperature: 200000 K
Scale height: $H = 10000$ km

How can cool material reach this height?
Doppler shifts (SUMER) in the transition region (TR) of the „quiet“ sun

- Blueshifts in lower corona (MgX and NeVIII line), outflow
- Redshifts in upper TR, plasma confined

Peter & Judge, ApJ. 522, 1148, 1999
Nonthermal line broadening

Line widths:

- Width of wing increases and reaches local sound speed!
- $\xi \sim T^{1/4}$, as for undamped Alfvén waves
- $F_A = 1 \text{ kWm}^{-2} \text{ B/G}$

Peter, A&A 374, 1108, 2001
Heavy ion heating by cyclotron resonance

\[ \Omega \sim \frac{Z}{A} \]

Heavy ion temperature

\[ T = (2-6) \text{ MK} \]

\[ r = 1.15 \text{ } R_s \]

- Magnetic mirror in coronal funnel/hole
- Cyclotron resonance \( \Rightarrow \) increase of \( \mu \)

Tu et al., Space Sci. Rev., 87, 331, 1999

SUMER/SOHO
Oxygen and hydrogen thermal speeds in coronal holes

Very Strong perpendicular heating of Oxygen!

Large anisotropy: \( T_{\perp}/T_{\parallel} \geq 10 \)

Magnetic network with loops

SUMER CIII 977 Å
full disk scan

Loops crossing network lanes

Peter, 2002
The elusive coronal magnetic field

Future: High-resolution imaging and spectroscopy (70 km pixels) of the corona

Modelling by extrapolation:
- Loops (magnetic carpet)
- Open coronal funnels
- Closed network
Small magnetic flux tubes and photospheric granulation

White dots: Flux tubes, scale $\leq 100$ km

35 Mm x 40 Mm
Magnetic regions (seen in G-band near 430 nm) between granules

Scharmer, 1993
Equatorial coronal hole

Date: 5 November 1999
Time: 17:07 UT—21:07 UT
Detector: A
Slit: 2

FOV: 252" x 300"

Spectral lines: Si II (1533 Å, ~ 0.02 MK), C IV (1548 Å, ~ 0.10 MK), Ne VIII (770 Å, in 2nd order, ~ 0.63 MK)

Force-free field extrapolation

\[
B_x = \sum_{m,n=1}^{\infty} \frac{C_{mn}}{\lambda_{mn}} \exp(-r_{mn}z) \cdot \left[ \alpha \frac{\pi n}{L_y} \sin \left( \frac{\pi m x}{L_x} \right) \cos \left( \frac{\pi n y}{L_y} \right) - \right. \\
\left. -r_{mn} \frac{\pi m}{L_x} \cos \left( \frac{\pi m x}{L_x} \right) \sin \left( \frac{\pi n y}{L_y} \right) \right]
\]

\[
B_y = -\sum_{m,n=1}^{\infty} \frac{C_{mn}}{\lambda_{mn}} \exp(-r_{mn}z) \cdot \left[ \alpha \frac{\pi m}{L_x} \cos \left( \frac{\pi m x}{L_x} \right) \sin \left( \frac{\pi n y}{L_y} \right) + \right. \\
\left. +r_{mn} \frac{\pi n}{L_y} \sin \left( \frac{\pi m x}{L_x} \right) \cos \left( \frac{\pi n y}{L_y} \right) \right]
\]

\[
B_z = \sum_{m,n=1}^{\infty} C_{mn} \exp(-r_{mn}z) \cdot \sin \left( \frac{\pi m x}{L_x} \right) \sin \left( \frac{\pi n y}{L_y} \right)
\]

\[
j = \alpha B
\]

Magnetic network loops and funnels

Structure of transition region

\[ F_B = AB \quad F_M = A p V \]

\[ \sim 10^4 \text{km} \]

\[ \sim 10^4 \text{km} \]


Magnetic field of coronal funnel

\[ A(z) = \text{flux-tube cross section} \]

Active regions mainly consist of closed magnetic loops, in which plasma is confined and causes bright emission. The large-scale magnetic field is open in coronal holes, from which plasma escapes on open field lines as solar wind, and where the line emission is strongly reduced.

Wiegelmann and Solanki, 2005
MHD model coronal magnetic field

Linker et al., JGR, 104, 9809, 1999

“Elephants trunk” coronal hole
The Sun’s open magnetic field lines

MHD model field during Ulysses crossing of ecliptic in early 1995

Mikic & Linker, 1999
Measuring the polar magnetic field

Solar Orbiter will allow us to study the:

• magnetic structure and evolution of the polar regions,

• detailed flow patterns in the polar regions,

• development of magnetic structures, using local-area helioseismology at high latitudes.

Model magnetogram of the simulated solar cycle (courtesy Schrijver).
Summary

- The Sun's corona is highly structured and changes
- The magnetic field consists of loops and funnels
- EUV radiation of the corona is highly structured
- Doppler spectroscopy in EUV enables plasma diagnostics via line shifts, widths and radiances
- The magnetic network is very dynamic
- Small-scale motions and turbulence prevails
- Temperature profiles indicate minor ion heating