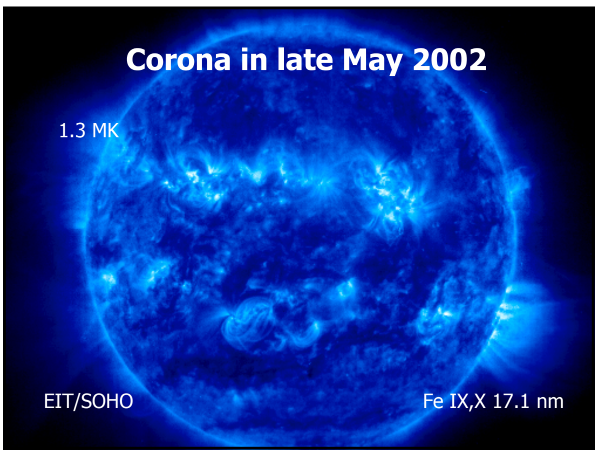
Solar corona and solar wind

1. The Sun's atmosphere and magnetic field
2. Coronal heating and energetics
3. Coronal expansion and solar wind
4. The heliosphere, structure and dynamics
5. The microstate of the solar wind
6. Waves, structures and turbulences
7. Solar energetic particles and cosmic rays

The Sun's atmosphere 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

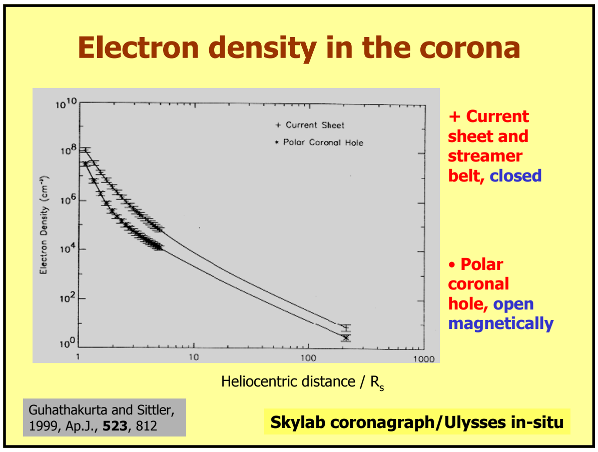


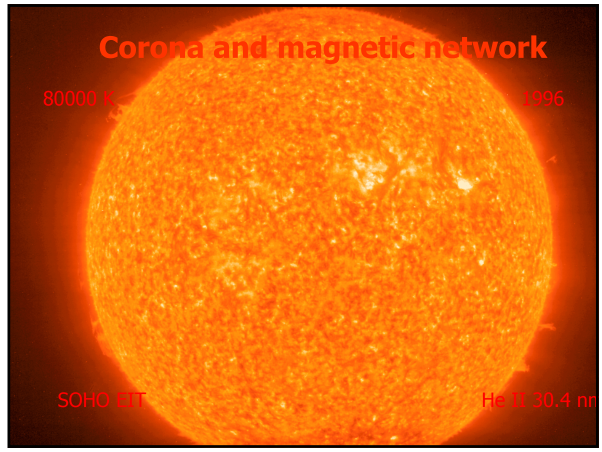
Some historical dates I

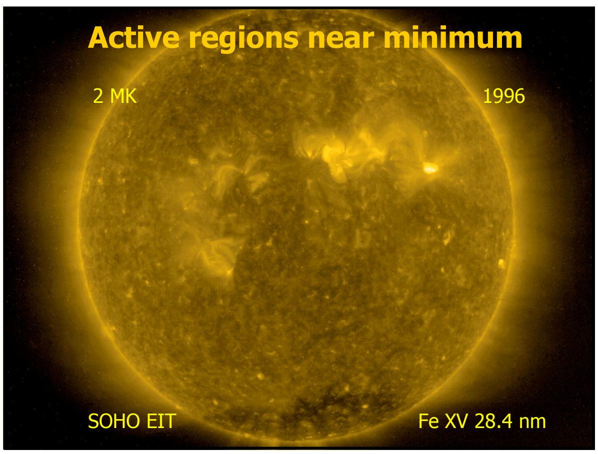
- **1000** (BC) China: Correlations betwenn sunspots and aurora; geomagnetism is known and the magnetic needle
- **500** (BC) Greece: Magnetism
- **350** (BC) Theophrastus observes sunspots with naked eye
- **1200** England: compass, Neekam -> navigation
- **1600** W. Gilbert in England: „de magnete"
- **1850** F. Gauß in Germany: Earth magnetic field, mathematical analysis (multipole expansion) and measurements (10^{-5} precision); currents inside earth (dynamo) and in the atmosphere
- **1814** Fraunhofer discovers hundreds of solar lines (prism)
- **1843** Schwabe: Sunspot activity cycle (11 years)
- **1860** Loomis: auroral oval ($\approx 20^o$ - 25^o)
- **1908** Hale: sunspots have strong magnetic fields

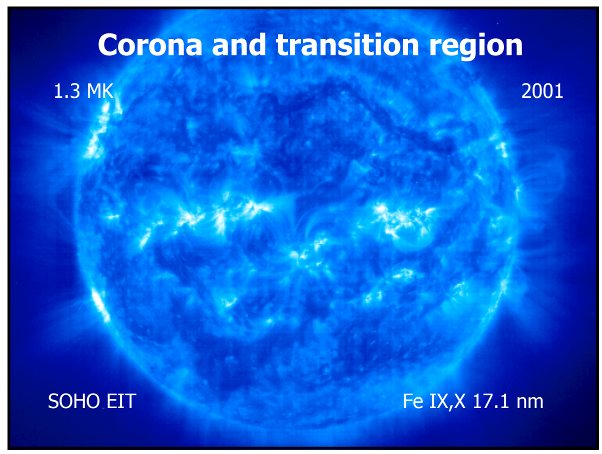
Some historical dates II

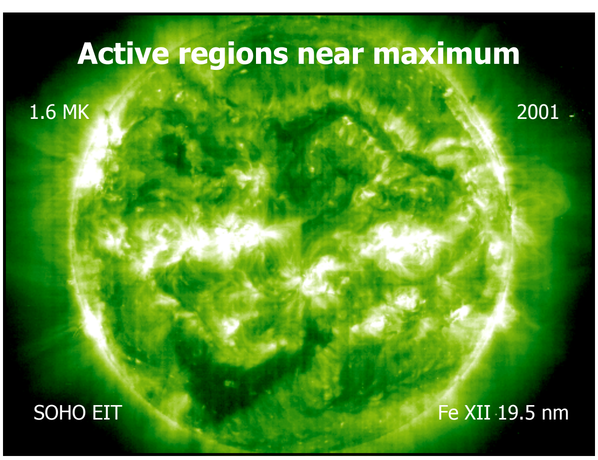
- **1920** Existence of Earth ionosphere from radio waves (whistlers)
- **1930** „Clouds" of particles and magnetic fields from solar flares (broadband flashes of light) on the Sun
- **1940** Edlén and Grotrian, coronal emission from highly ionised elements, temperature T > 1 MK
- **1958** Explorer 1, Earth radiation belts (van Allen)
- **1958** E. Parker: Solar wind as supersonic plasma flow
- **1950** Leighton: 5-minute oscillations in photosphere
- **1962** Mariner 2, Solar wind (in-situ) measurements
- **1962/4** Explorer 12/OGO, Bow shock wave in front of the Earth magnetosphere
- **1996** SOHO, comprehensive solar observations from space (near libration point at about 1Mkm)

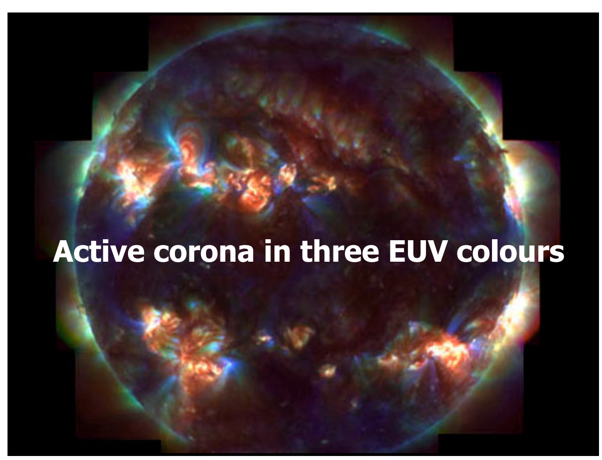

Electron density in the corona
+ Current Sheet
• Polar Coronal Hole
Electron Density (cm⁻³)
10^10
10^8
10^6
10^4
10^2
10^0
1
10
100
1000
Heliocentric distance / R_s
+ Current sheet and streamer belt, closed
• Polar coronal hole, open magnetically
Guhathakurta and Sittler, 1999, Ap.J., 523, 812
Skylab coronagraph/Ulysses in-situ


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
1.3 MK
2001
SOHO EIT
Fe IX,X 17.1 nm


Active regions near maximum
1.6 MK
2001
SOHO EIT
Fe XII 19.5 nm


Active corona in three EUV colours

EUV line excitation processes

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

$A + e^- \rightarrow A^* + e^-$ ($n_e > 10^8\ cm^{-3}$)

$A^* \rightarrow A + h\nu$ **Line radiance: $L_\lambda \sim n_e^2$**

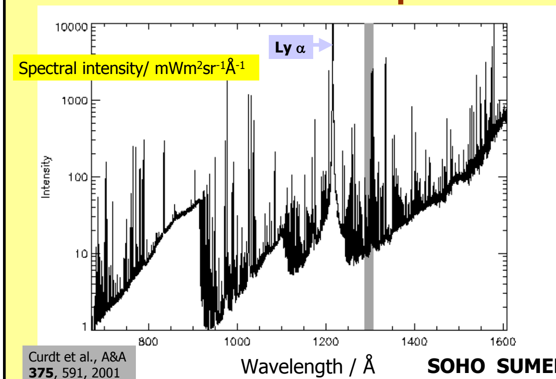
- *Resonant scattering (fluorescence):*

$A + h\nu \rightarrow A^* \rightarrow A + h\nu$ **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



Curdt et al., A&A **375**, 591, 2001

Elementary radiation theory I

Coronal model approximation:
collisional excitation and radiative decay

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

$C_{g,j}$ [$cm^3 s^{-1}$] collisional excitation rate

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

Emissivity (power per unit volume):

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

$\Delta E_{g,j} = E_j - E_g$ 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:

$N_j(X^{+m})/n_e =$

$N_j(X^{+m})/N(X^{+m}) \cdot N(X^{+m})/N(X) \cdot N(X)/n(H) \cdot n(H)/n_e$

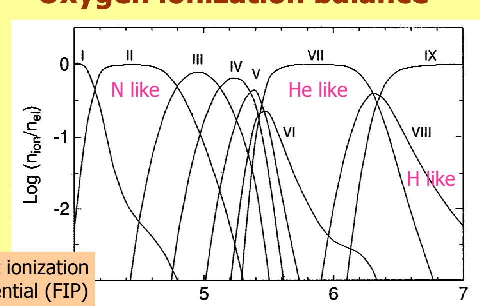
excitation level — ionic fraction — abundance — n(H) [cm^3] hydrogen

Collisonal excitation rate (Maxwellian electrons):

$$C_{i,j} \sim 1/T_e^{1/2} \exp\{\Delta E_{i,j}/(k_B T_e)\}$$

Boltzmann factor

Oxygen ionization balance



First ionization potential (FIP)
I = 13.62 eV

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

LTE -> $N(X^{+m})/N(X)$ follows from Saha's equation; $\sim \exp(-I/k_B T_e)$

Emission measure

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

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

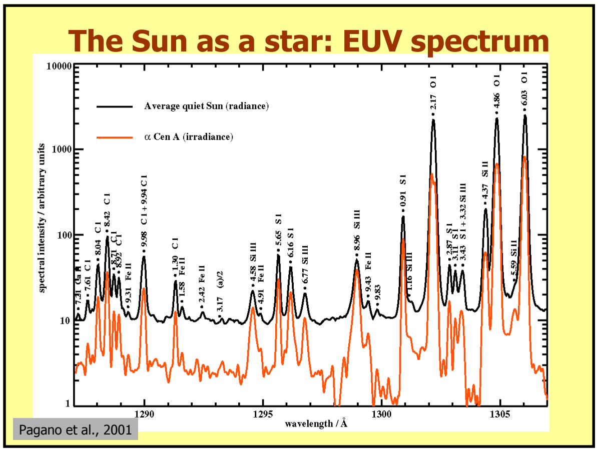
Contribution function (strongly peaked in T_e):

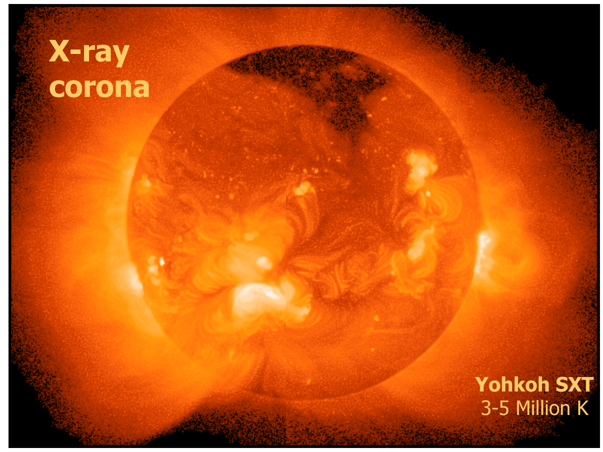
$$G(T_e, \lambda_{g,j}) = N(X^{+m})/N(X)\ C_{g,j}$$

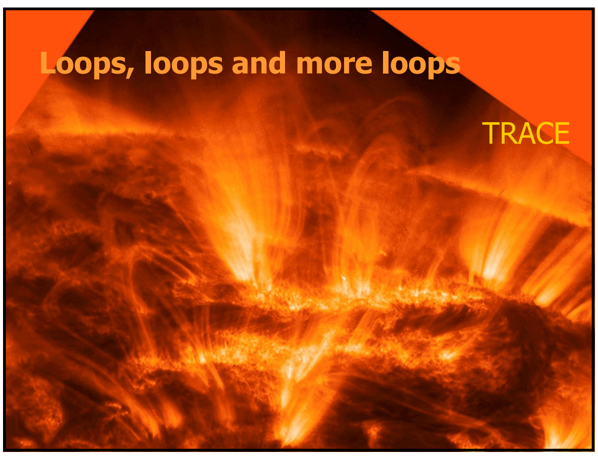
Emission measure:

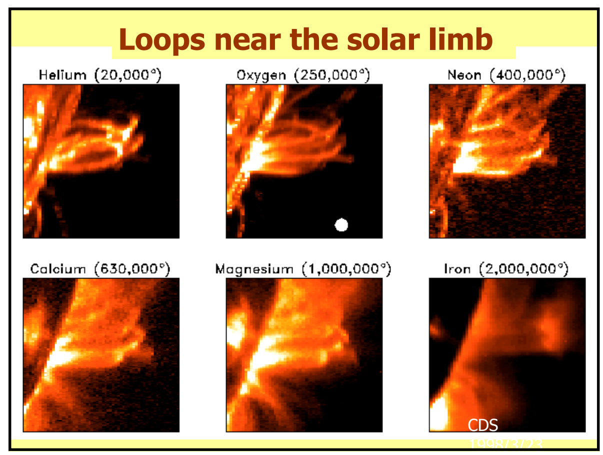
$$\langle EM \rangle = \int_V n_e^2\, dV$$

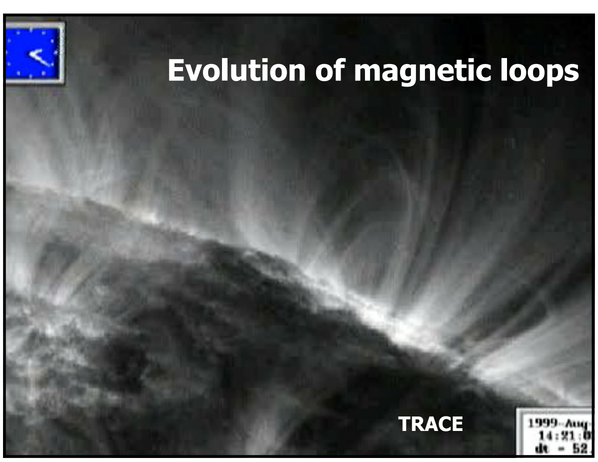
The emission measure depends on the amount of plasma (at temperature T_e) emitting in the observed spectral line.
Radiation power (line strength) ~ < EM >

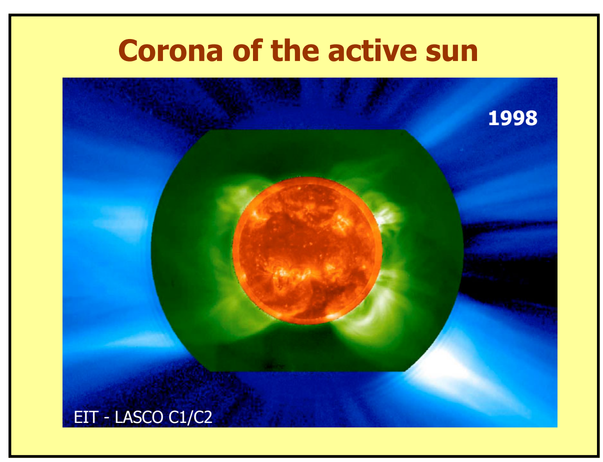

The Sun as a star: EUV spectrum
Average quiet Sun (radiance)
α Cen A (irradiance)
spectral intensity / arbitrary units
wavelength / Å
Pagano et al., 2001

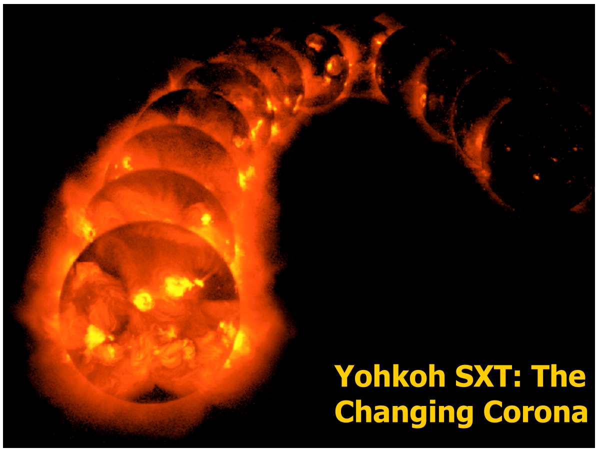

X-ray corona
Yohkoh SXT
3-5 Million K


Loops, loops and more loops
TRACE

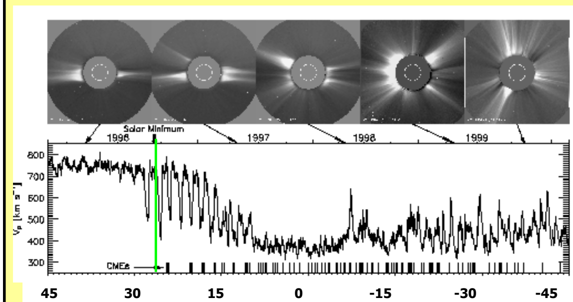

Loops near the solar limb
Helium (20,000°)
Oxygen (250,000°)
Neon (400,000°)
Calcium (630,000°)
Magnesium (1,000,000°)
Iron (2,000,000°)
CDS


Evolution of magnetic loops
TRACE


Corona of the active sun
1998
EIT - LASCO C1/C2



Changing corona and solar wind



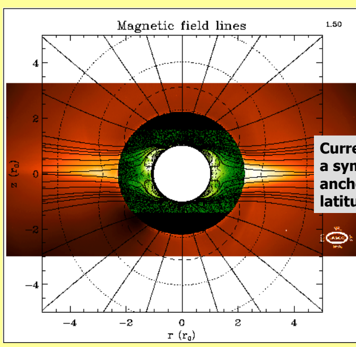
North | Heliolatitude / degree | South

McComas et al., 2000

LASCO/Ulysses

Coronal magnetic field and density

Dipolar, quadrupolar, current sheet contributions



Polar field: B = 12 G

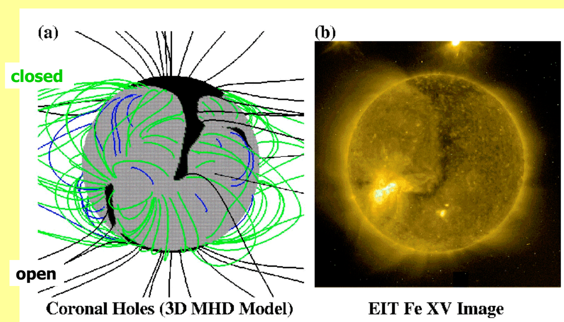
Current sheet is a symmetric disc anchored at high latitudes !

LASCO C1/C2 images (SOHO)

Banaszkiewicz et al., 1998;

Schwenn et al., 1997

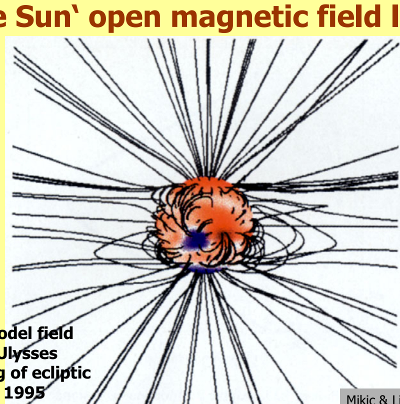
MHD model coronal magnetic field



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

„Elephants trunk" coronal hole

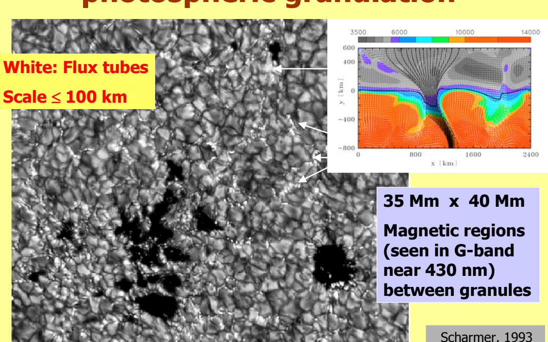
The Sun' open magnetic field lines



MHD model field during Ulysses crossing of ecliptic in early 1995

Mikic & Linker, 1999

Small magnetic flux tubes and photospheric granulation



White: Flux tubes

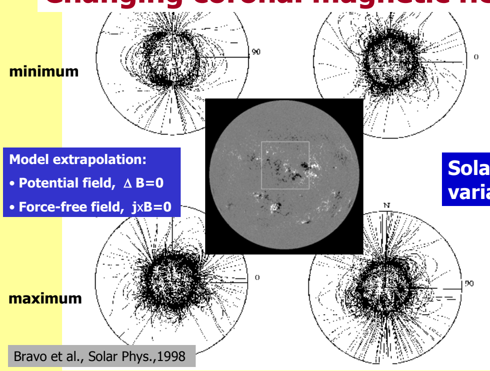
Scale ≤ 100 km

35 Mm x 40 Mm

Magnetic regions (seen in G-band near 430 nm) between granules

Scharmer, 1993

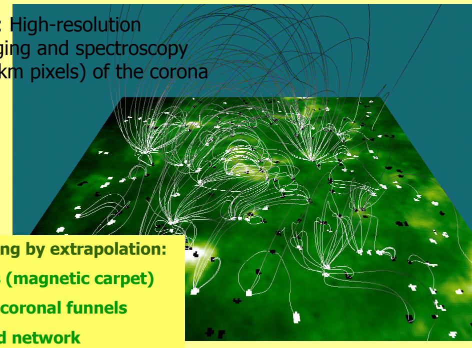
Changing coronal magnetic field



Bravo et al., Solar Phys.,1998

The elusive coronal magnetic field

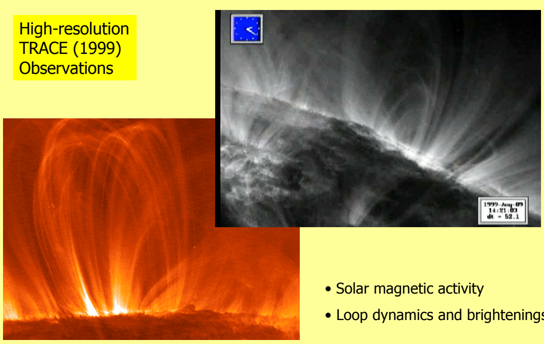
Future: High-resolution imaging and spectroscopy (35 km pixels) of the corona



Modelling by extrapolation:
- Loops (magnetic carpet)
- Open coronal funnels
- Closed network

Magnetic field loops

High-resolution TRACE (1999) Observations

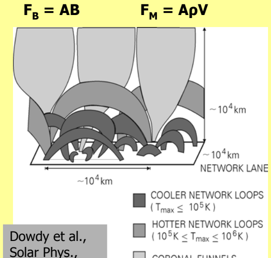


- Solar magnetic activity
- Loop dynamics and brightenings

Magnetic network loops and funnels

Structure of transition region

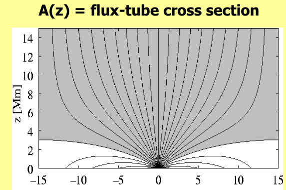
$F_B = AB$ $F_M = A\rho V$



Dowdy et al., Solar Phys., **105**, 35, 1986

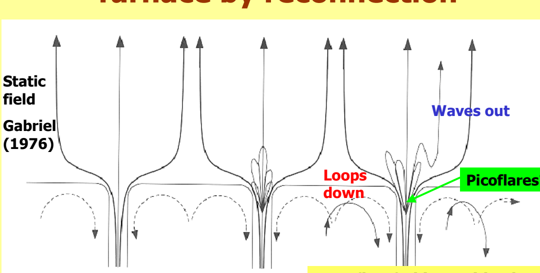
Magnetic field of coronal funnel

A(z) = flux-tube cross section



Hackenberg, Marsch and Mann, Space Sci. Rev., **87**, 207, 1999

Dynamic network and magnetic furnace by reconnection



Axford and McKenzie, 1992, and Space Science Reviews, **87**, 25, 1999

New flux fed in at sides by convection (t ~ 20 minutes)

$F_E = 10^7$ erg cm^{-2} s^{-1}

Doppler spectroscopy

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

$v_i = c(\lambda-\lambda_0)/\lambda_0 = c\Delta\lambda_D/\lambda$ (+, red shift, - blue)

v_i line of sight velocity of atom or ion; c speed of light in vacuo
λ_0 nominal (rest) wave length; λ observed wave length
$\varepsilon = h\nu = hc/\lambda = 12345$ eV/λ[Å] ; 1 eV = 11604 K

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

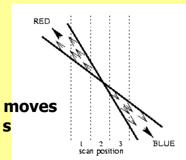
$T_{eff} = T_i + m_i\xi^2/(2k_B) = m_i c^2\{(\Delta\lambda_D)^2 - (\Delta\lambda_I)^2\}/(2k_B\lambda^2)$

$\Delta\lambda_D$ ($\Delta\lambda_I$) Doppler (instrumental) width of spectral line; T_i ion temperature
ξ amplitude of unresolved waves/turbulence; m_i ion mass
For optically thin emission and Gaussian line profile; $\Delta\lambda_I \approx 6$ pm for SUMER

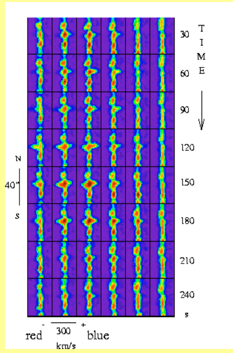
EUV jets and reconnection in the magnetic network

Evolution of a jet in Si IV 1393 Å visible as blue and red shifts in SUMER spectra

- **E-W step size 1" , Δt = 5 s**



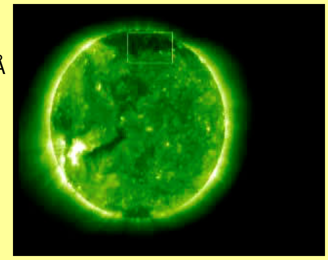
Jet head moves 1" in 60 s



Innes at el., Nature, **386**, 811, 1997

On the source regions of the fast solar wind in coronal holes

Image: EIT Corona in Fe XII 195 Å at 1.5 MK



Insert: SUMER Ne VIII 770 Å at 630 000 K

Chromospheric network Doppler shifts
Red: down
Blue: up

Outflow at lanes and junctions

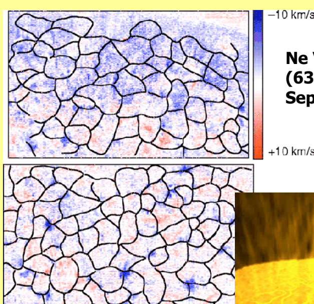
Hassler et al., Science 283, 811-813, 1999

Solar wind outflow from magnetic network lanes and junctions

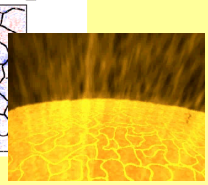
Line-of-sight Doppler velocity images

North and mid-latitude polar region

Raster scan: 540" × 300"
Network in Si II 1553 Å (10 000 K)

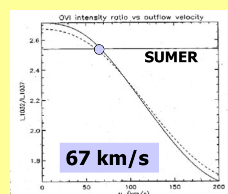


Ne VIII 770 Å (630 000 K) September, 1996

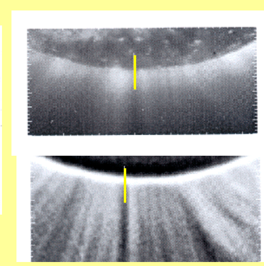


Hassler et al., Science, **283**, 810, 1999

Outflow speed in interplume region at the coronal base



O VI 1031.9 Å / 1037.2 Å line ratio; Doppler dimming

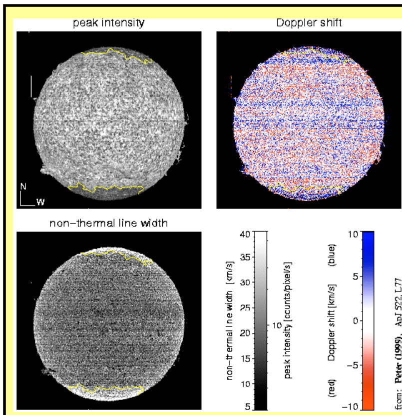


1.05 R_S
EIT FeIX/X

Eclipse 26/02 1998 18:33 UT

$T_e = T_i = 0.9$ M K, $n_e = 1.8\ 10^7\ cm^{-3}$

Patsourakos and Vial, A&A, 359, L1, 2000



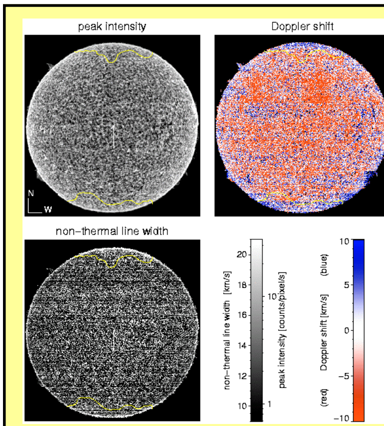
HeI 584Å at 34000 K

Helium ions are mixed blue- and red-shifted, but bluish over the polar caps, where the global magnetic field is open and the He intensity reduced:

Waves, outflow, radiative effects?

Boundaries of CHs indicated yellow

Peter, A&A **516**, 490, 1999



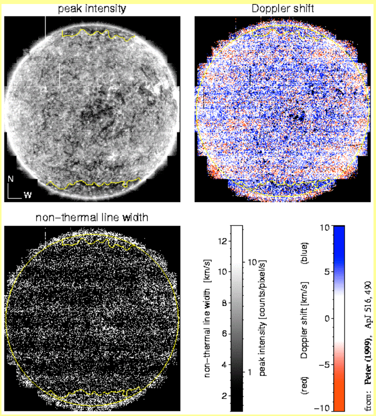
CIV 1548Å at 0.5 MK

Carbon ions are red-shifted, especially at low latitudes where the global magnetic field is closed, and light blue-shifted at the polar caps.

Waves, downflows?

Boundaries of CHs indicated yellow

Peter, A&A **516**, 490, 1999



NeVIII 770 Å at 0.65 MK

Neon ions are blue-shifted everywhere, especially over the polar caps where the global magnetic field is open.

Outflow?

Boundaries of CHs indicated yellow

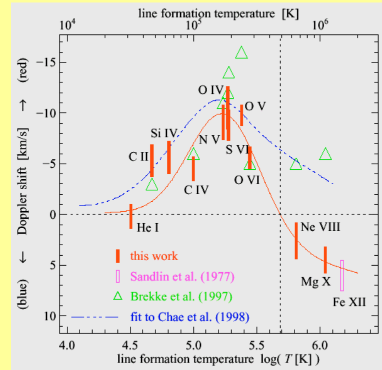
Peter, A&A **516**, 490, 1999

Doppler shift versus temperature

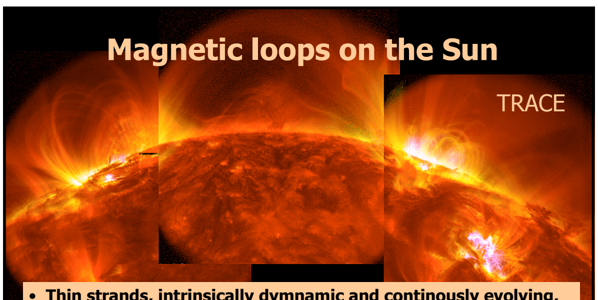
Dopplershifts (SUMER) in the transition region (TR) of the „quiet" sun

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

Peter & Judge, ApJ. **522**, 1148, 1999

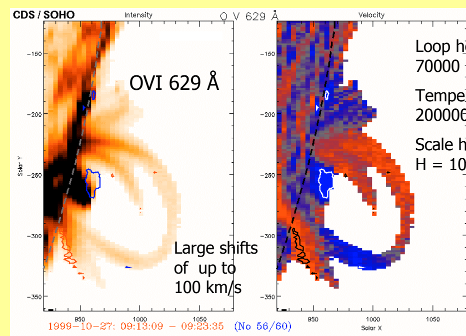


Magnetic loops on the Sun



- **Thin strands, intrinsically dymnamic and continously 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?**

Cool loop in transition region



Loop height: 70000 km

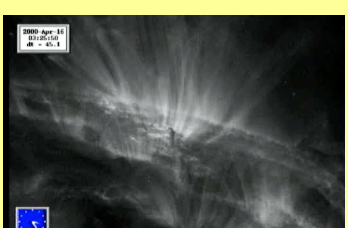
Temperature: 200000 K

Scale height: H = 10000 km

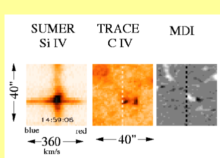
CDS/SOHO web page

How can cool material reach this height?

Close-up observation of a twister loop and mass ejection

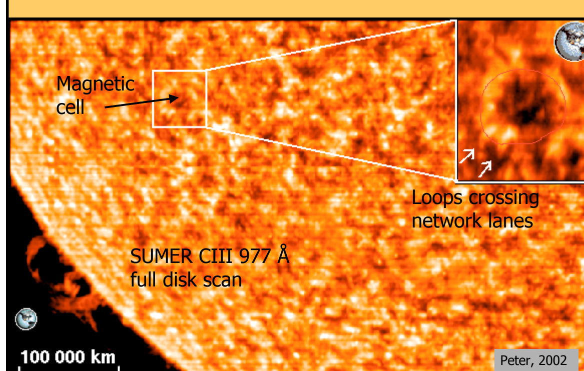


Spectroscopy and polarimetry



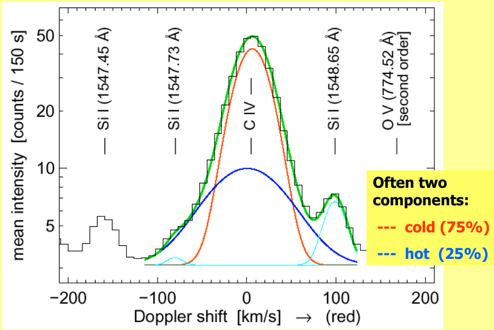
Solar Orbiter will resolve the highly structured solar atmosphere an order of magnitude better than presently possible (both images and spectra)

Magnetic network with loops



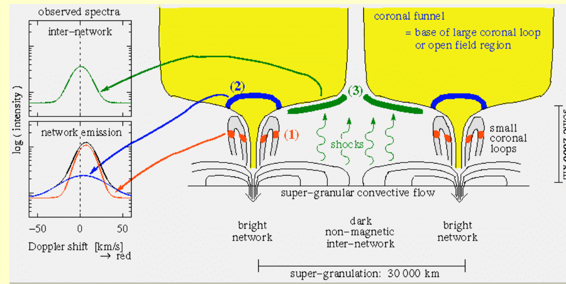
Peter, 2002

Wings in bright network TR lines



Peter, A&A **360**, 761, 2000

Structure of transition region and origin of EUV emission



Peter, 2002

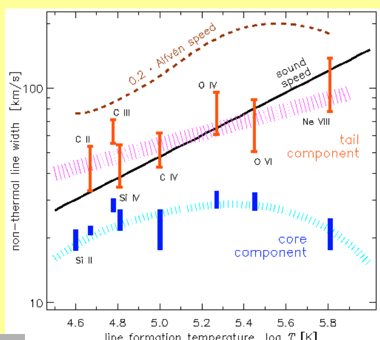
Nonthermal line broadening

Line widths:

I wing

I core

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



Peter, A&A **374**, 1108, 2001

Height profile of wave amplitude

Heliocentric distance / R_S

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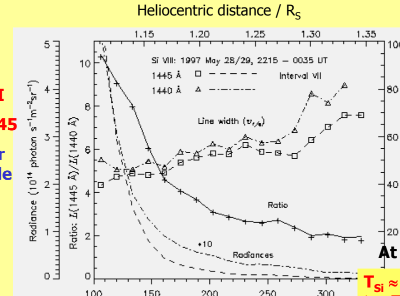
Silicon VIII

λλ1440,1445

North polar coronal hole



Doppler velocity

$V_{1/e}$ / km s^{-1}

At 1.33 R_S:

$T_{Si} \approx 10^7$ K

$\xi \approx 70$ km s^{-1}

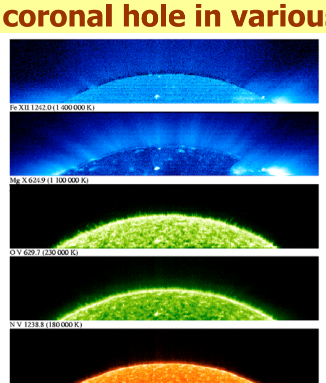
$n_e \approx 10^6$ cm^{-3}

Height above limb / arcsec

Wilhelm et al., Ap.J., **500**, 1023, 1998

North coronal hole in various lines

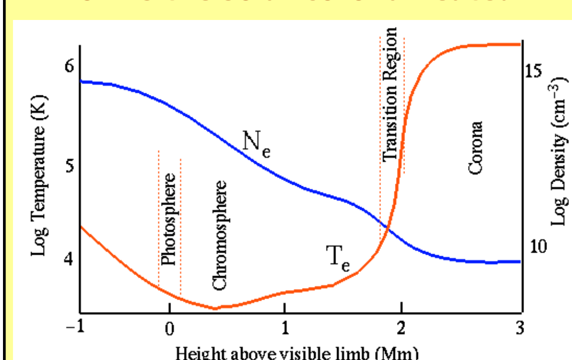
1400000 K	FeXII 1242 Å
1100000 K	MgX 624.9 Å
230000 K	OV 629.7 Å
180000 K	NV 1238.8 Å
10000 K	cont. 1240 Å



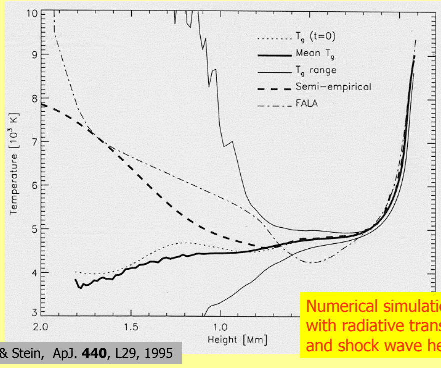
Forsyth & Marsch, Space Sci. Rev., **89**, 7, 1999

SUMER/SOHO 10 August 1996

How is the solar corona heated?



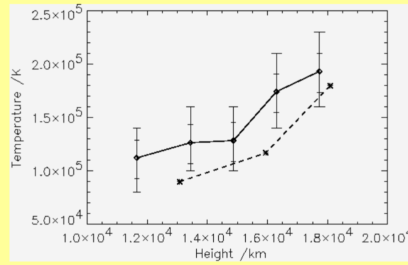
Does the chromosphere exist?



Numerical simulation with radiative transfer and shock wave heating

Carlsson & Stein, ApJ. **440**, L29, 1995

Proton temperature at coronal base



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Hydrogen Lyman series

Transition Region at the base of north polar CH

Marsch et al., A&A, 359, 381, 2000

Charge-exchange equilibrium: $T_H = T_p$

Turbulence broadening: ξ = 30 km s^{-1}

Heavy ion heating by cyclotron resonance

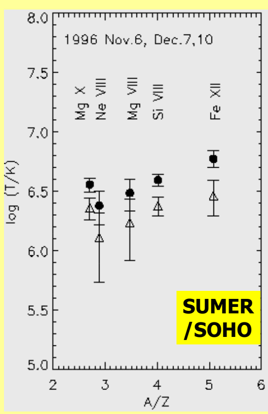
$\Omega \sim Z/A$

Heavy ion temperature

T=(2-6) MK

r = 1.15 R_S

- **Magnetic mirror in coronal funnel/hole**
- **Cyclotron resonance ⇒ increase of μ**



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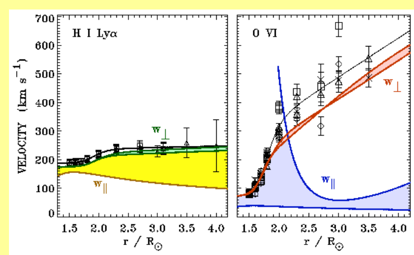
Tu et al., Space Sci. Rev., **87**, 331, 1999

Oxygen and hydrogen thermal speeds in coronal holes

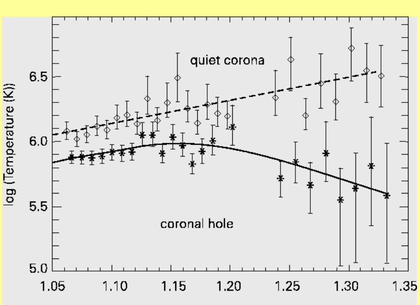


Very Strong perpendicular heating of Oxygen !

Cranmer et al., Ap. J., **511**, 481, 1998

Large anisotropy: $T_{O\perp}/T_{O||} \geq 10$

Electron temperature in the corona



Streamer belt, closed

Coronal hole, open magnetically

David et al., A&A, **336**, L90, 1998

Heliocentric distance

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