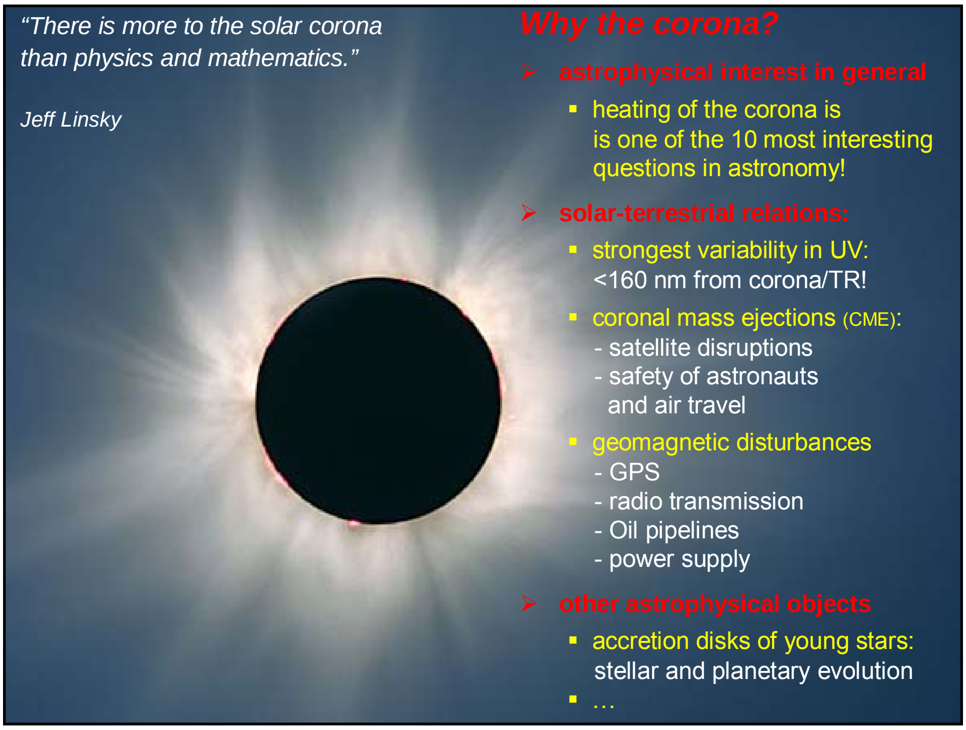

The low solar corona and the stars
Solar eclipse, 11.8.1999, Wendy Carlos & John Kern
Sun
Hardi Peter
Kiepenheuer-Institut
für Sonnenphysik
Freiburg
KIS
α Coronae Borealis
➢ energetics
➢ the transition region
➢ heating the corona
➢ stellar coronae


"There is more to the solar corona
than physics and mathematics."
Jeff Linsky
Why the corona?
➢ astrophysical interest in general
▪ heating of the corona is
is one of the 10 most interesting
questions in astronomy!
➢ solar-terrestrial relations:
▪ strongest variability in UV:
<160 nm from corona/TR!
▪ coronal mass ejections (CME):
- satellite disruptions
- safety of astronauts
and air travel
▪ geomagnetic disturbances
- GPS
- radio transmission
- Oil pipelines
- power supply
➢ other astrophysical objects
▪ accretion disks of young stars:
stellar and planetary evolution
▪ …

Drawing vs. photography

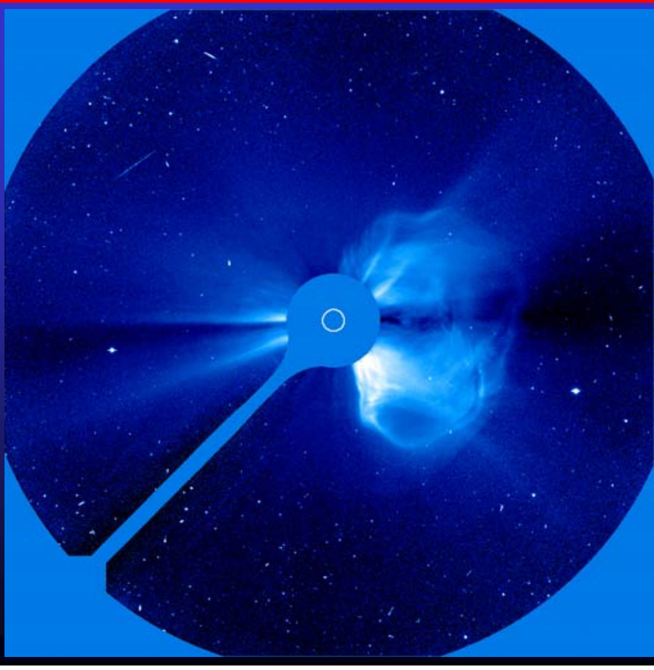
18. July 1860

Spain,
Drawing after eclipse,
Warren de la Rue

Desierto, Spain,
40 s exposure,
Angelo Secchi

from: Secchi / Schellen: Die Sonne, 1872

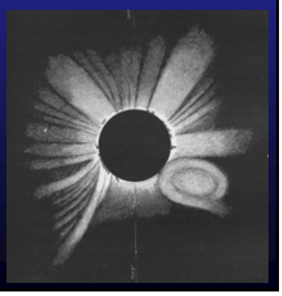
CMEs: now and then ....



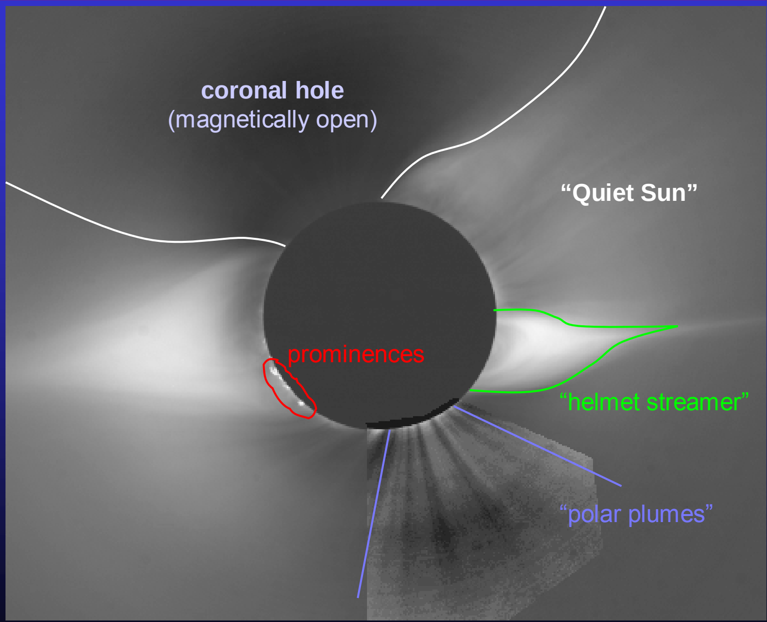
SOHO / Lasco C3
20.4.1998

(with Mars and Saturn...)

compare:
drawing of
G. Tempel
of the corona
during an eclipse
18.7.1860



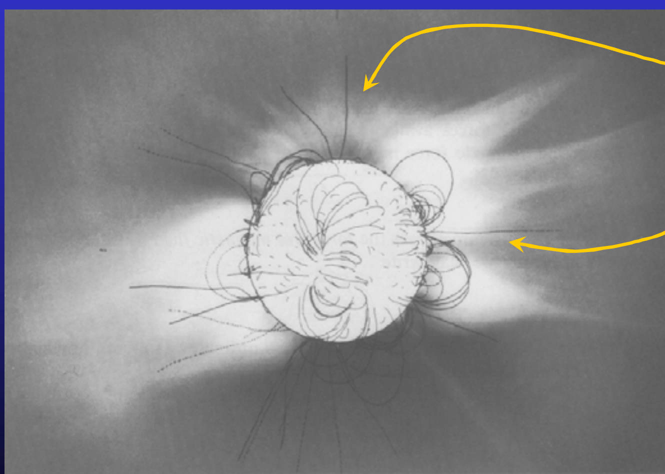
The “global” corona: minimum of solar activity



Solar eclipse, 3. Nov. 1994, Putre, Chile, High Altitude Observatory / NCAR

The corona is structured by the magnetic field

1. magnetic fields in the photosphere (“solar surface”) → Zeeman-effect
2. potential field extrapolation (or better)
3. compare to structures in the corona ➔ “hairy ball”



coronal holes: magnetically open

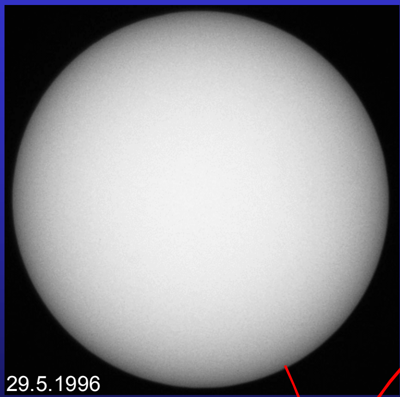
quiet Sun: magnetically closed

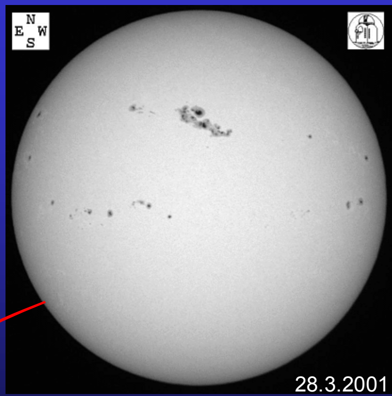
Solar eclipse, 30.Juni 1973, Serge Koutchmy
Potential field extrapolation: Altschuler at al. (1977) Solar Physics 51, 345

The cycle of activity of the Sun

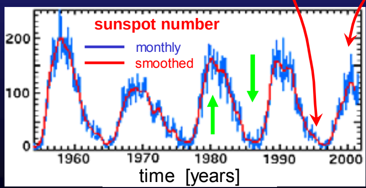
KIS Hardi Peter

Minimum Sun in white light **Maximum**





Big Bear Solar Observatory



11-years cycle of the Sun:

- sunspot number (since 1843)
- magnetic polarity (since 1908)
- magnetic activity

driving mechanism:

⇨ magnetic field generating dynamo

The solar corona: minimum vs. maximum

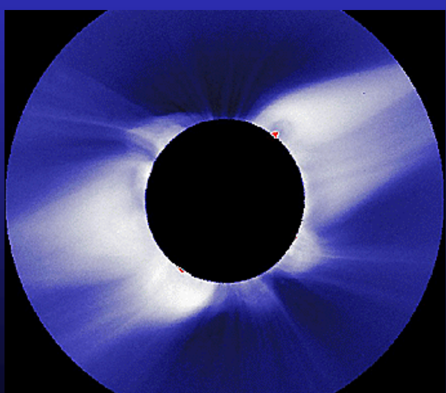
KIS Hardi Peter

Minimum

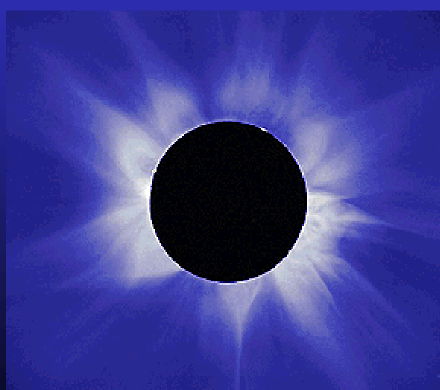
- "simple" dipolar structure
- few active regions (sunspots)
- prominent coronal holes
- "helmet streamer" only at equator

Maximum

- complex magnetic structure
- many active regions
- almost no coronal holes
- "helmet streamer" at all latitudes



18. 3. 1988, Philippines



16. 2. 1980, India

High Altitude Observatory - NCAR

The solar corona: minimum vs. maximum

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Minimum **Maximum**

The solar X-ray corona during the cycle

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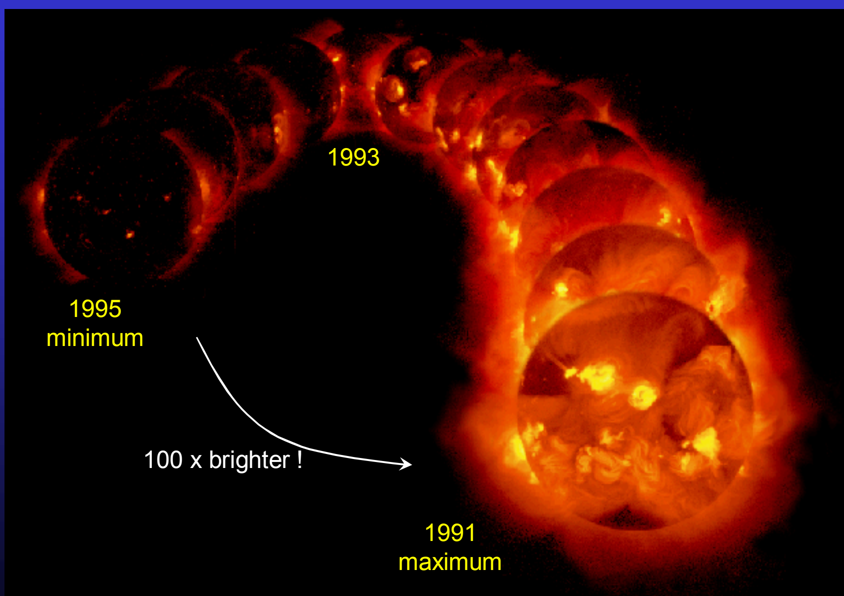

Yohkoh Soft X-ray Telescope (SXT), X-ray Emission at ≈1 nm, ≈2· 10^6 K

Photospheric magneto-convection / Granulation

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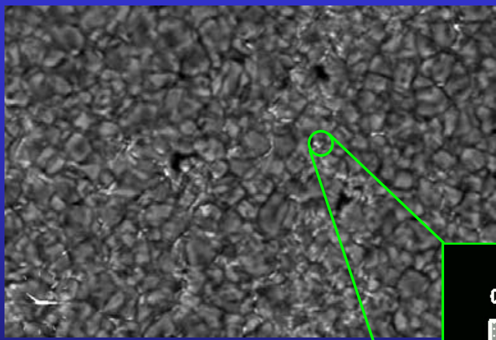
Dutch Open Telescope, La Palma
12. Sept. 1999 (Sütterlin & Rutten)



≈ 38 000 km x 25 000 km, ≈ 27 min

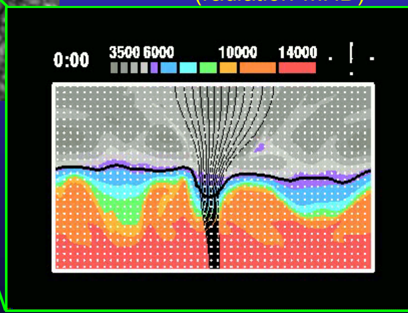
observation in G-Band ≈ 430 nm

granulation (Ø ≈1000 km)

G-band bright points:
small magnetic flux tubes,
which are brighter than their surrounding

2D-simulation of a flux tube embedded in photospheric granulation

(radiation-MHD)



≈ 2400 km x 1400 km, ≈ 18 min

Steiner et al. (1997) ApJ 495, 468

...well, the ultimate energy source is the fusion in the center of the Sun...

Chromospheric network: magnetic structure and flows

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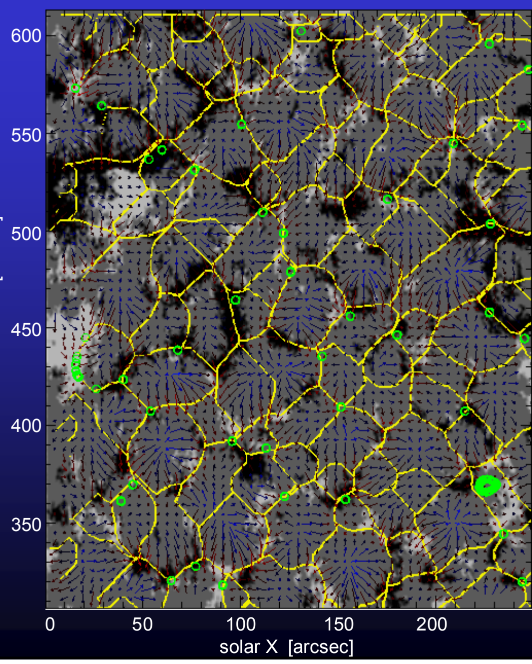


supergranulation

- flows define supergranulation boundaries
- magnetic field is transported to the boundaries

SOHO / MDI, 23.2.1996

magnetogram	(b/w image)
flows	(arrows)
network boundaries	(yellow)

Transition region: emission patterns

KIS Hardi Peter

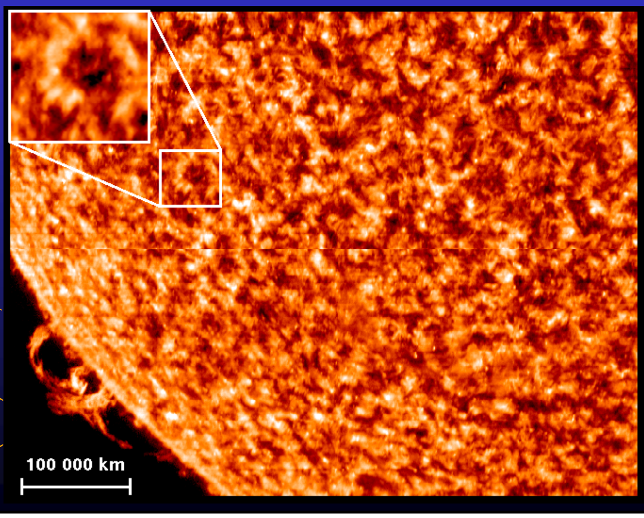
transition region above chromospheric network

(!) network built up by bright structures

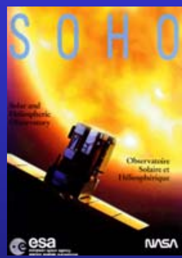
(?) loops across network-boundaries

(?) low loops across cells

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



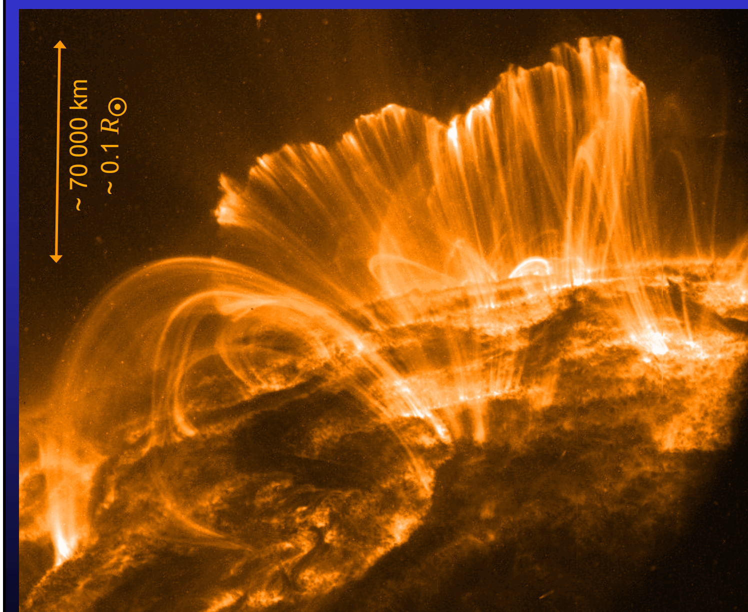
Peter (2001) A&A 374,1108



SUMER / SOHO
C III (97.7 nm)
≈80 000 K
28.1.1996

Magnetic loops in the low corona

KIS Hardi Peter



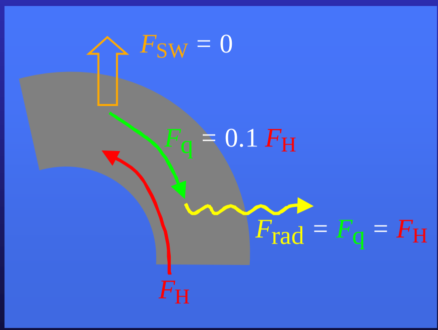
emission lines of
Fe IX / X (17.1 nm)
≈ 10^6 K

9. November 2000

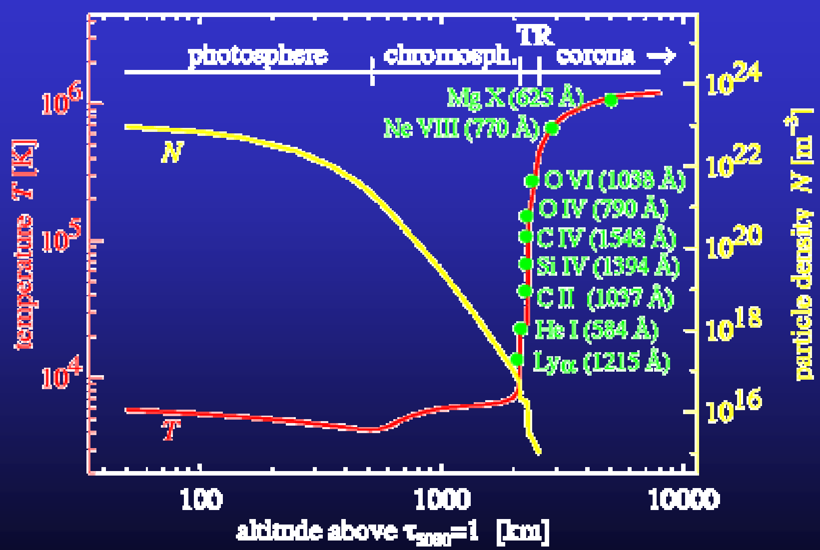
be careful: light ≠ magnetic field

Transition Region And Coronal Explorer (TRACE), NASA

considerations on the energetics



An “old” 1D temperature structure



T, *N* following Vernazza et al. (1981) ApJS 45, 635

Energy budget in the quiet Corona

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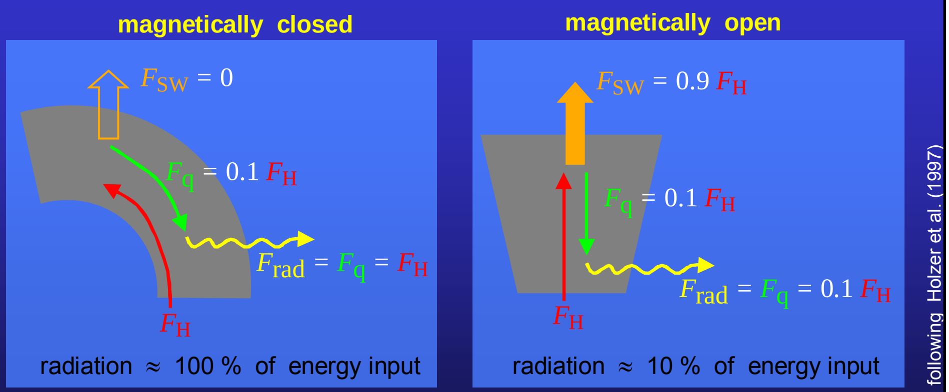

assume the same energy input into open and closed regions:

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

Temperature in a static corona

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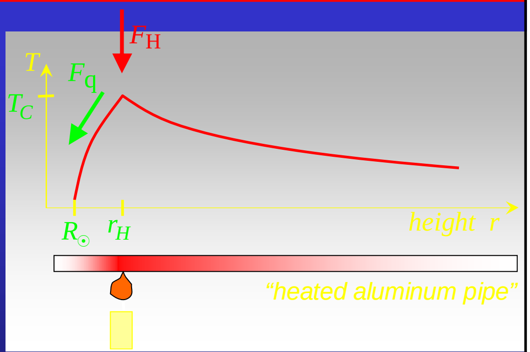
Heating at the coronal base

$$F_H = 4\pi r_H^2\, f_H = 4\pi R_\odot^2\, f_0$$

typical: $f_0 = 100\ \mathrm{W/m^2}$



inner part: $R_\odot < r < r_H$

➢ Equilibrium of heating and heat conduction:

$$4\pi r^2\, f_q = F_q = -F_H$$

conductive flux: $$f_q = -\kappa_0\, T^{5/2}\, \frac{\mathrm{d}T}{\mathrm{d}r}$$

boundary condition: $$T(r = R_\odot) << T_C$$

Integration: $R_\odot \to r_H$ $\quad\Longrightarrow\quad$ $$T_C = \left(\frac{7}{2}\, \frac{f_0}{\kappa_0}\, \frac{r_H - R_\odot}{r_H / R_\odot} \right)^{2/7}$$

The corona: a thermostat

KIS Hardi Peter

1. thermal conductivity:

$f_W \propto T^{5/2}$

$T_C \propto f_0^{2/7}$

- increased heating: → T-Anstieg
  - → effective heat conduction
  - → only small T-increase
- similar for decreased heating

2. solar wind

- magnetically open regions: 90% of the energy into acceleration
- more heating → even higher losses due to acceteration
  - → less energy for heating

changing the hating rate f_0 by some orders of magnitude leads to small changes of the peak temperature of the corona

f_0 [W/m²]	T_C [10^6 K]	
17600	5.0	
150	1.0	← like Sun
0.29	0.5	

following Leer (1998)

Where does this apply?

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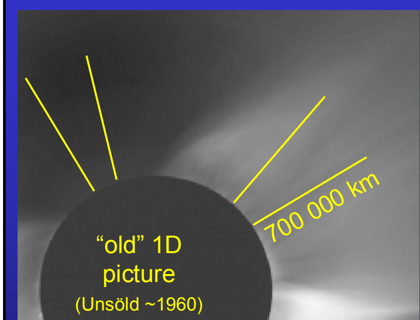
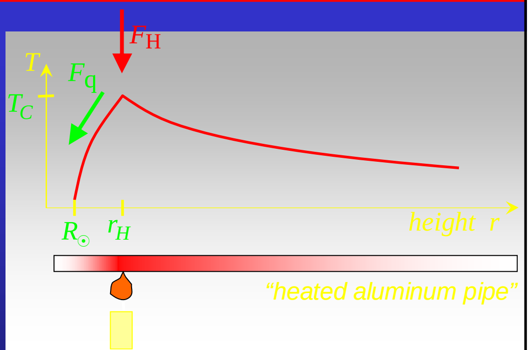
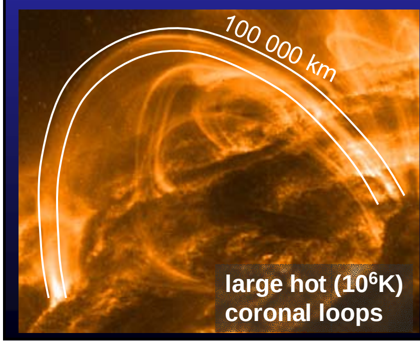
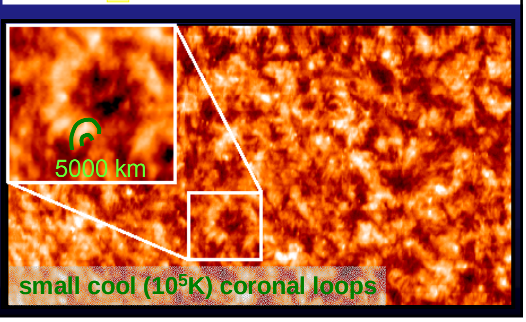








The coronal base pressure

KIS Hardi Peter

- dump heat in the corona F_H

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

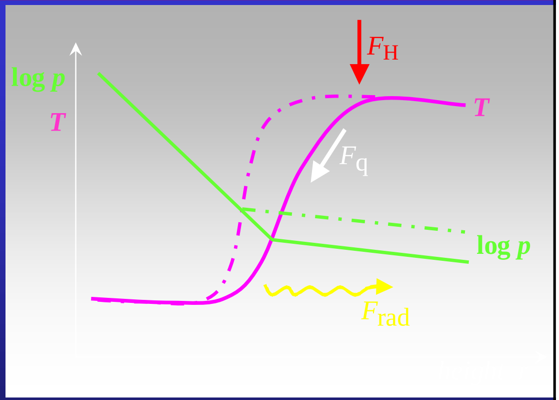
- heat conduction F_q transports energy down

- energy is radiated in the low transition region and upper chromosphere

  radiation depends on particle density

  pressure: $p \sim F_{rad}$

➡ $p_{corona} \sim F_H$



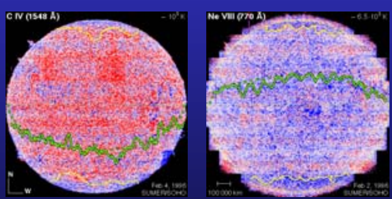
increase the heating rate:

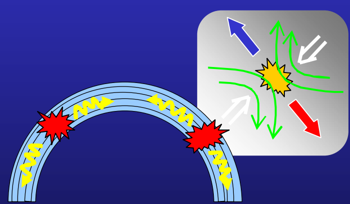
more has to be radiated ⟹ higher base pressure

➡ transition region moves to lower height !

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

investigating the transition region





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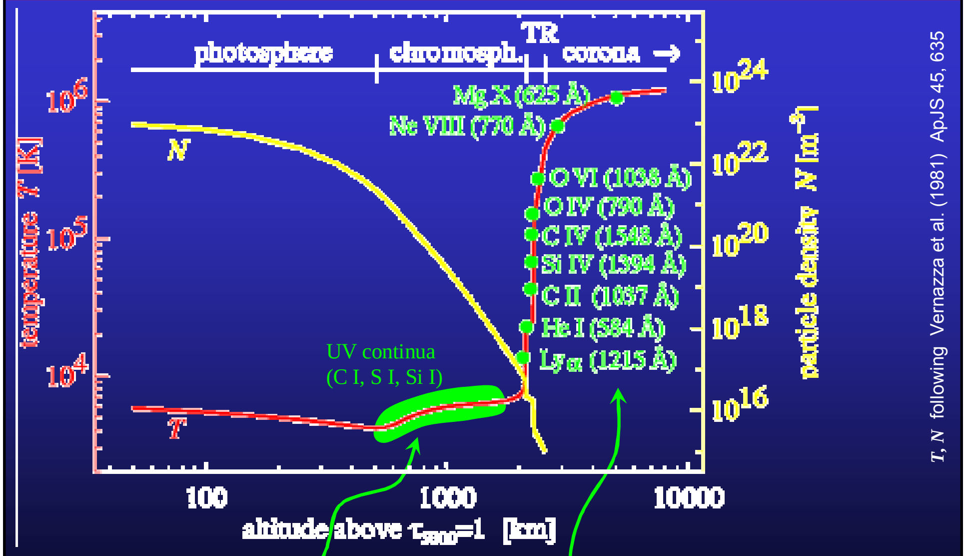
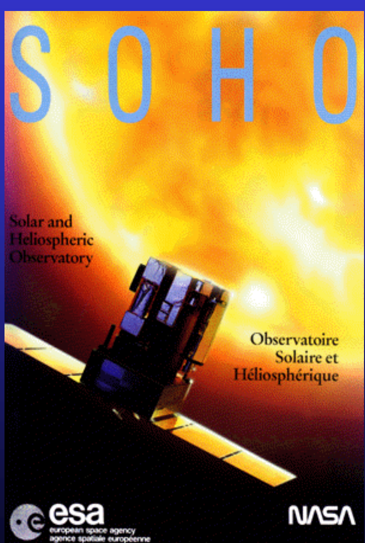
An “old” 1D temperature structure



EUV emission lines from transition region and low corona

and neutral lines & **continua** from the chromosphere

Solar and Heliospheric Observatory / SUMER



EUV-Spectrograph **SUMER**

Solar Ultraviolet Measurements of Emitted Radiation

spatial resolution: 2” (1” pixel) (1500 km)
spectral resolution: $\lambda/\Delta\lambda \approx 30\,000$
wavelength range: 50 – 155 nm

covering temperatures on the Sun: 5000 – 10^6 K

- dynamics and structure of the transition region from the chromosphere to the corona

- **accuracy for Doppler shifts: ~ 2 km/s**

SUMER: spectral range (1st order)

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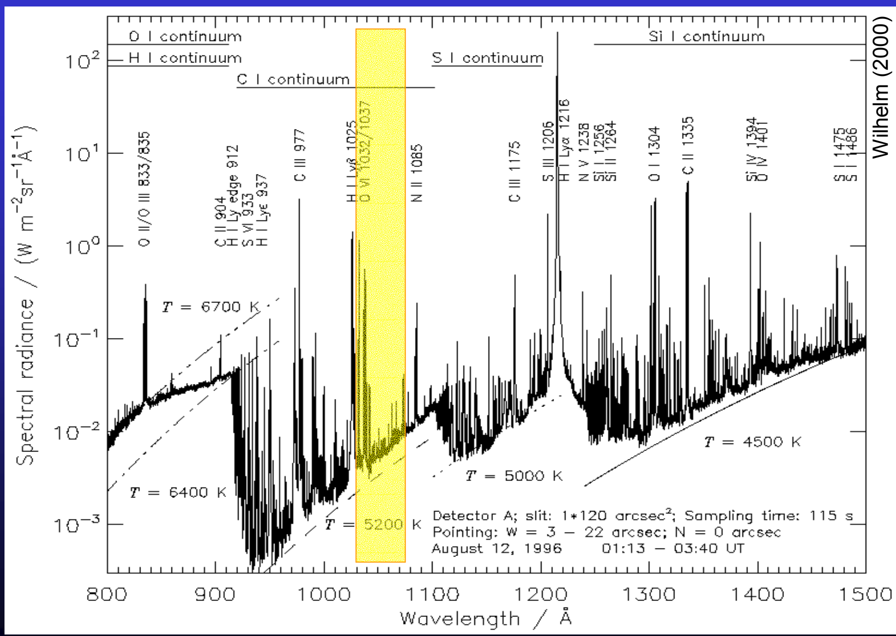

Full spectral frame and spectral windows

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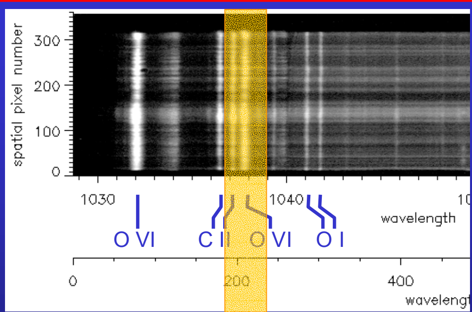
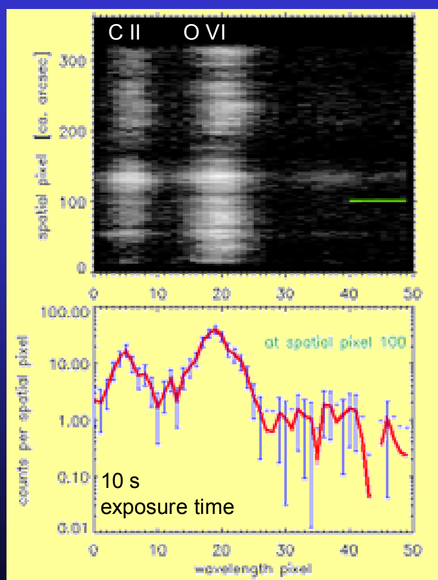




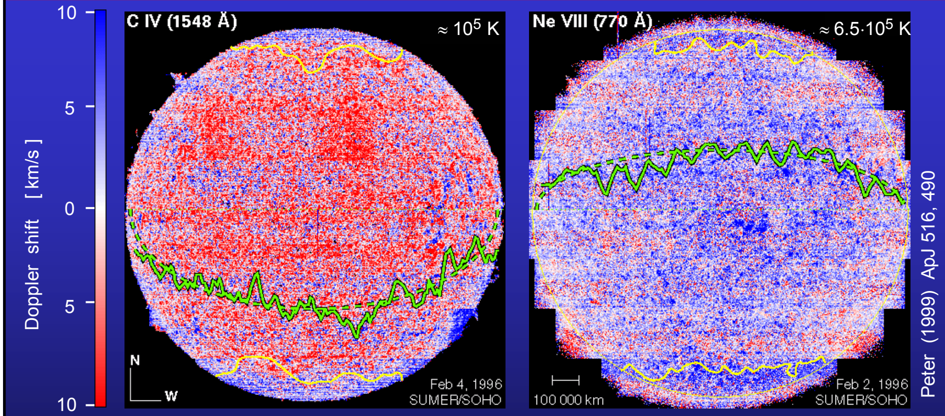
full frame:
1024 spectral pixels ≈ 44 Å (1st order)

spectral window:
often 50 spectr. pxl ≈ 2 Å (1st order)
(or 25, 512, …)

Problem:
sometimes windows not wide enough
(telemetry…)

➡ ***Images* by raster procedure**

Doppler shifts in the transition region



SUMER

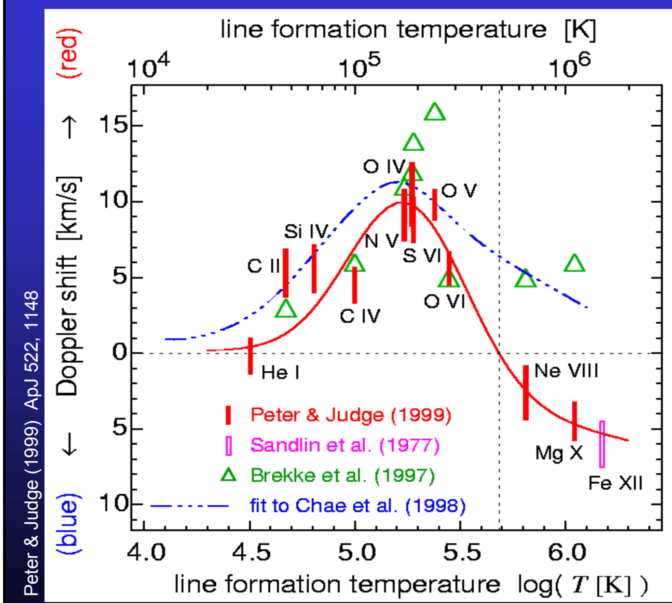
quiet Sun Doppler shifts (along equator)

- low temperatures: $T < 3{\cdot}10^5$ K: redshifts
- high temperatures: $T > 4{\cdot}10^5$ K: blueshifts
- Doppler-shifts: flows ???
  (sound-) waves ???

coronal holes

- "coronal" temperatures:
  $T > 6{\cdot}10^5$ K: blueshifts
- coronal hole outflows:
  base of solar wind

TR Doppler shift as a function of temperature



- basically shows quiet Sun network line shifts
- similar for active region line shifts
  (Teriaca et al. 1999, A&A 349, 636)

SUMER

mean quiet Sun Doppler shifts at disk center

Scatter of line shifts

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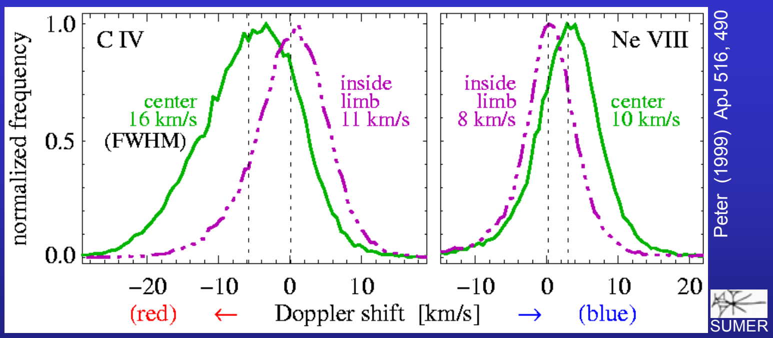

Questions to answer...

(1) How can the persistent net line shift be produced at all ?

(2) How to get redshifts below 5·10^5 K, but blueshifts above ?

(3) What causes the large scatter of line shifts ?

Understanding line shifts Ia: single structure

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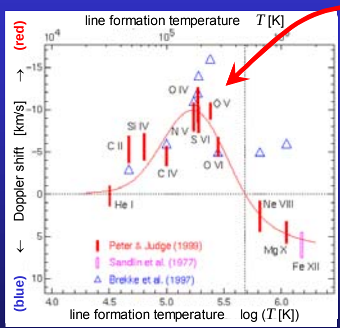
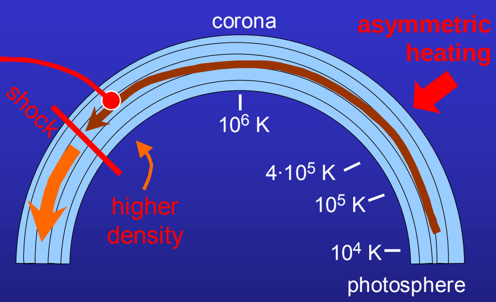
Doppler shift as a function of temperature



asymmetric heating: flows



“every loop has a corona”:

➢ flows ?

more or less like that, i.e. involving flows: e.g.

Antiochos (1984) ApJ 280, 416
Mariska (1988) ApJ 334, 489
Klimchuk & Mariska (1988) ApJ 328, 334
McClymont & Craig (1987) ApJ 312, 402

Understanding line shifts Ib: single structure

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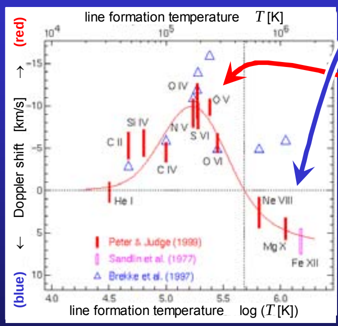
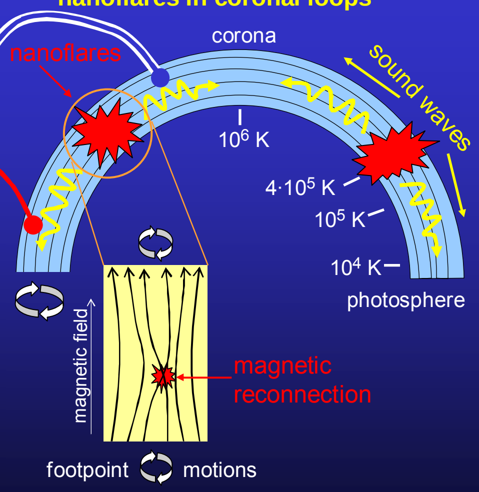
Doppler shift as a function of temperature



nanoflares in coronal loops



"every loop has a corona":

- flows ?
- waves ↔ Doppler shifts ?

Hansteen (1993) ApJ 402, 741
Peter & Judge (1999) ApJ 522, 1148
Teriaca et. al. (1999) A&A 349, 636

Understanding line shifts II: multiple structures

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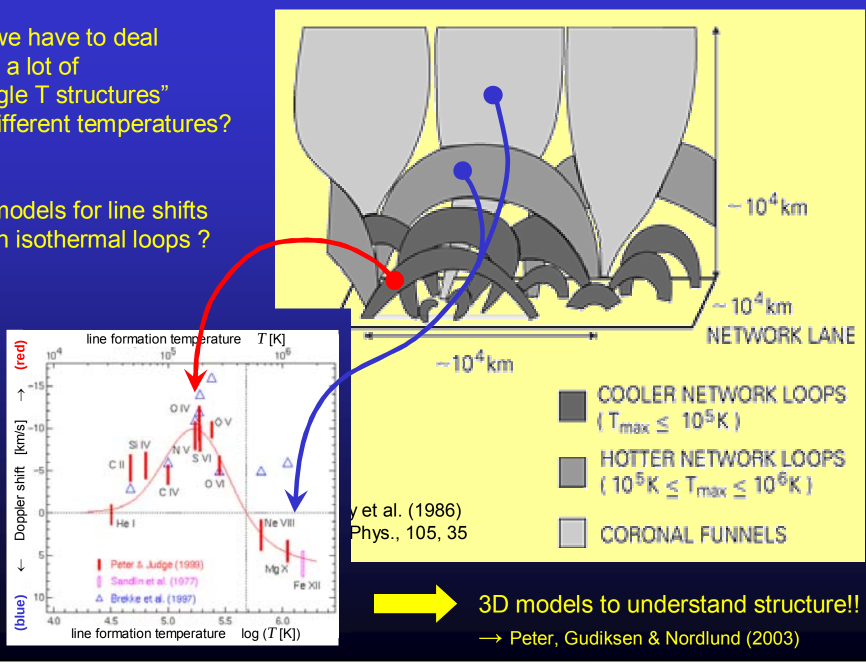
Hardi Peter

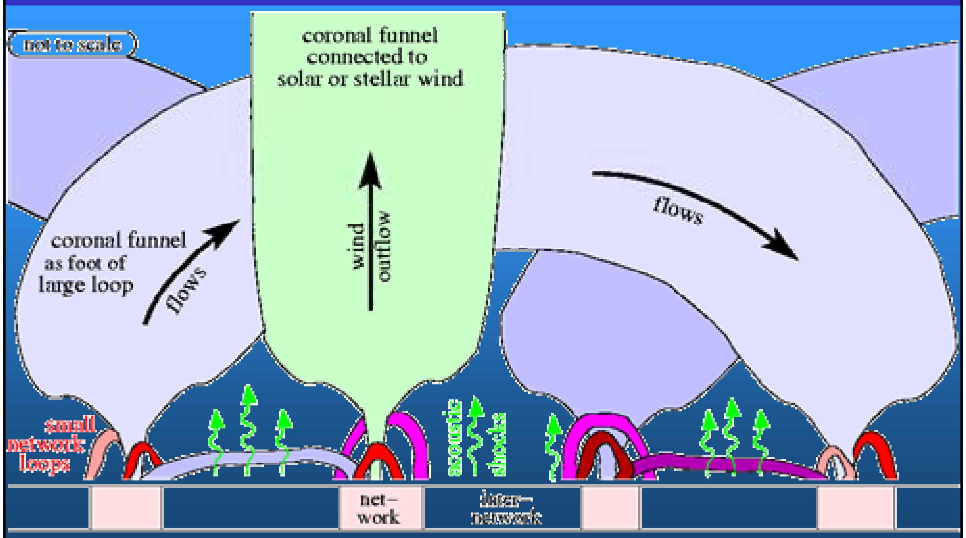
do we have to deal with a lot of "single T structures" of different temperatures?

➔ models for line shifts in isothermal loops ?



3D models to understand structure!!
→ Peter, Gudiksen & Nordlund (2003)

What is the structure of the low corona?



Peter (2001) A&A 374, 1108

*Heating the **quiet** corona*

Thinking of all the suggestions on coronal heating
I wonder how the corona stays that cool !

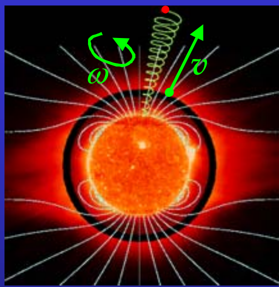
Rob Rutten, Utrecht

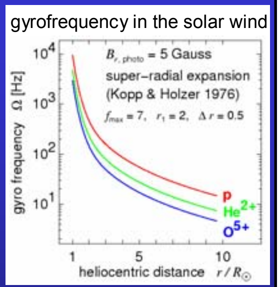
The open corona: ion-cyclotron heating

KIS Hardi Peter

the ions “circle” around the magnetic field with the gyro-frequency:

$$\Omega_j = \frac{Z_j}{A_j} \frac{eB_r}{m_p}$$





Imagine an Alfvén-wave with a frequency ω and wave number k propagating upwards.

If the frequency of the incident wave matches the gyro-frequency,

$$\omega - v_{ion} \cdot k = \Omega_j$$

the wave and the particles can interact efficiently !

[Also solve a wave equation...]

wave energy can be transferred to thermal and kinetic energy:

- preferential heating of the ions
- large “perpendicular” temperature $T_\perp$

Application to the solar wind: e.g.
Tu & Marsch (1997) SP 171, 363
Marsch & Tu (1997) SP 176,87
Hackenberg et al. (2000) A&A 360, 1139
Vocks & Marsch (2002) ApJ 569, 1030

Ion-cyclotron heating in the outer corona

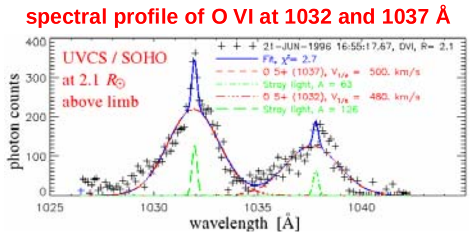
KIS Hardi Peter

observations with UVCS / SOHO
(Ultra-Violet Coronagraphic Spectrograph)

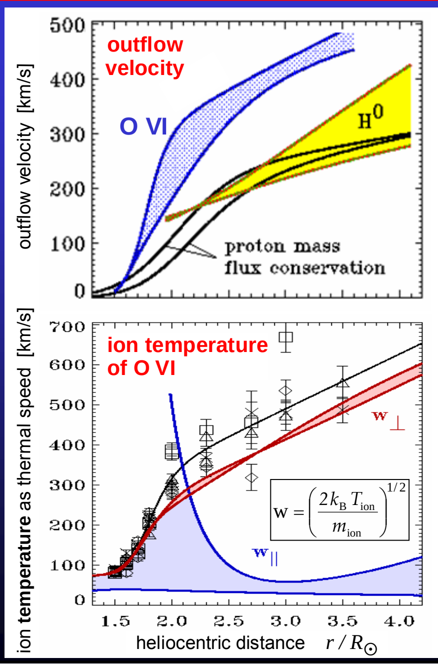
- very broad line profiles in outer corona
  e.g. 500 km/s = 500·10^6 K in O VI !!
- Doppler-dimming analysis:
  — rapid acceleration
  — high ion perpendicular temperatures
  $T_\perp >> T_{||}$

➡ *consistent with ion-cyclotron heating*

spectral profile of O VI at 1032 and 1037 Å



Kohl et al (1998) ApJ 501, L127



Cranmer et al. (1998) ApJ 511,481

The closed corona: flux braiding

- 3D MHD model for the corona: 50 x 50 x 30 Mm Box (100^3)
- full energy equation (heat conduction, rad. losses)
- starting with down-scaled MDI magnetogram
- braiding of magnetic fields due to photospheric motions (Galsgaard, Nordlund 1995; JGR 101, 13445)

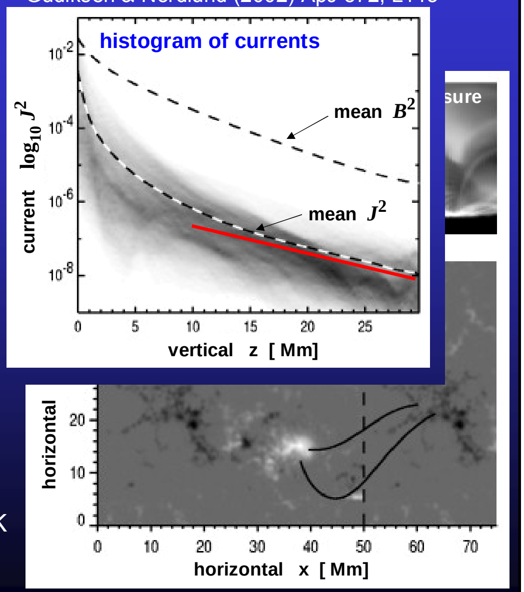
➔ heating: DC current dissipation (Parker 1972; ApJ 174, 499)

➔ heating rate $J^2 \sim \exp(-z/H)$

➔ coronal temperatures of $> 10^6$ K

➔ good match to TRACE images

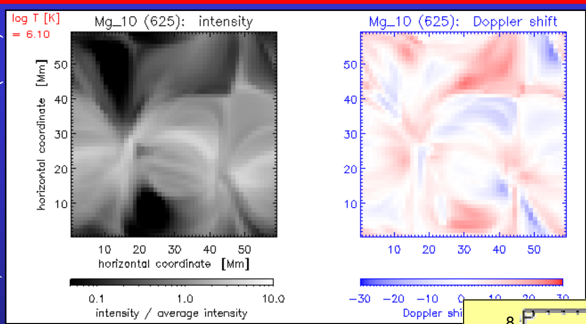
Gudiksen & Nordlund (2002) ApJ 572, L113



First spectra from 3D models

KIS Hardi Peter

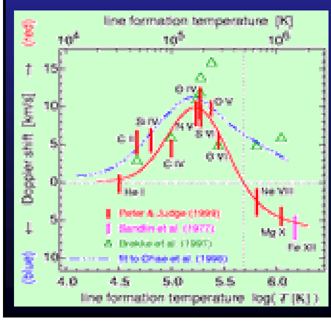
Peter, Gudiksen & Nordlund (2003)



- calculate spectra at each grid point (ionisation eq.)
- integrate along line-of-sight

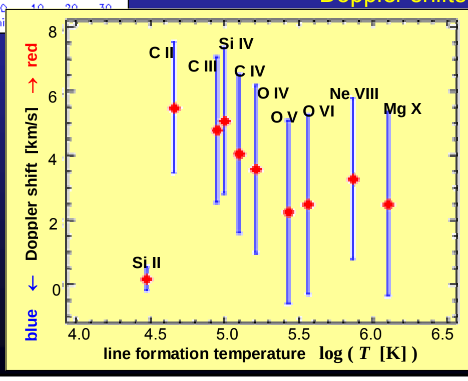
→ maps in intensity, shifts

synthetic average Doppler shifts

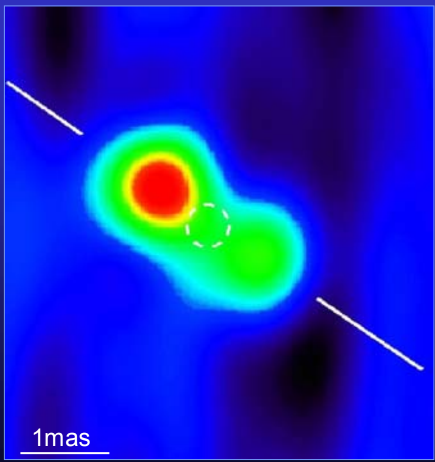


?

observed Doppler shifts



stellar transition regions



Corona of UV Cet directly resolved in radio using VLBI

(Benz et al. 1998, A&A 331,596)
Güdel 2002, Ann.Rev.Astr.Astro. 40, 217)

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What do we see of a stellar corona / TR ?

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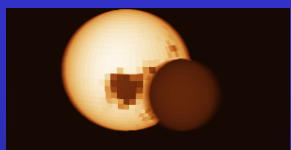
- photosphere: Doppler-(Zeeman)-imaging: stellar surface structures
- corona: emission seems to be dominated by active regions / flares
  ➔ "point sources" in the corona



XY Ursa Major
(A. Collier Cameron)

Yohkoh Soft X-ray Telescope (SXT), ≈1 nm, ≈2· 10^6 K

3D stellar corona: Doppler-Zeeman-Imaging

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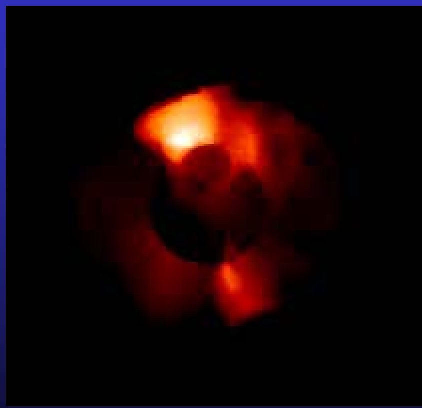
Hardi Peter

- **AB Doradus**
  cool active star (K2V)
  $T_{eff} \approx$ 4000K
  half as luminous as our Sun ($0.4\ L_{\odot}$)
  fats rotator ($50\ \Omega_{\odot}$)
  distance ≈ 49 light years
  observations: 7.–12. 12. 1995
- structures on the surface in intensity and magnetic field using Zeeman-Doppler-imaging (ZDI)
- potential field extrapolation (source surface at 5 R_{*})
- pressure at coronal base: $p \propto B^2$
  at open field lines: $p=0$
- emissivity $\propto n_e^{\,2}$



Collier Cameron, Jardine, Wood, Donati (2000)

Stellar coronal structure from eclipse mapping

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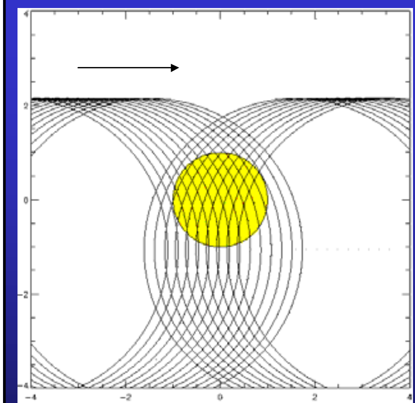
Hardi Peter



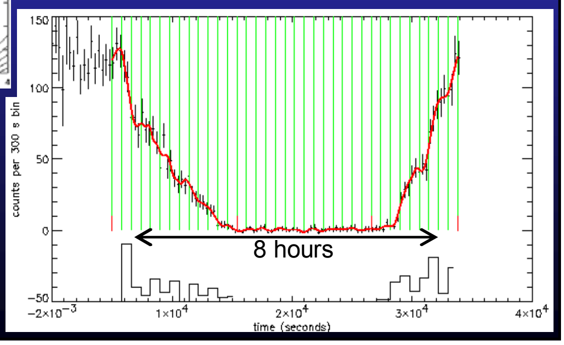
Güdel et al. (2003)
A&A 403, 155

mapping stellar X-ray coronae

A “small” star with a corona is eclipsed by a “big” star without a corona

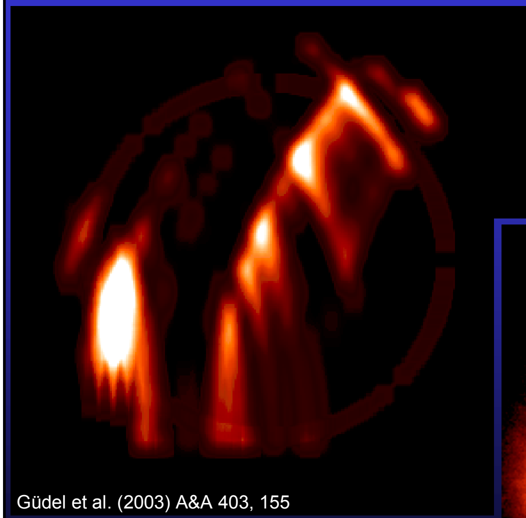
here:
αCoronae Borealis (G5V; solar-like)

⟶ use the light curve of the eclipse to reconstruct the X-ray structures



Stellar and solar corona

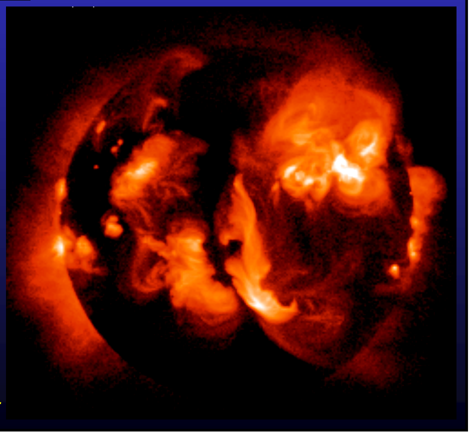
KIS Hardi Peter



Güdel et al. (2003) A&A 403, 155

αCoronae Borealis (G5V)

active star



The Sun (G2V)

inactive star

What are the dominant structures in X-rays?

KIS Hardi Peter

Where does the X-ray emission come from in active stars?

higher "filling-factor" than Sun?

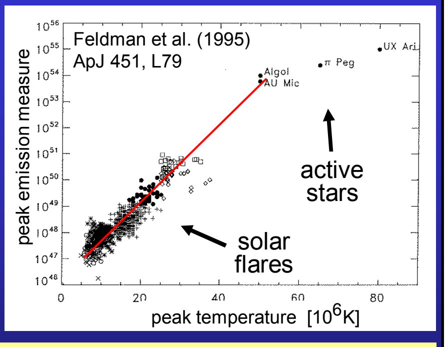
⇨ not enough space on the surface

⇨ and: also stellar X-rays are structured

stellar corona are not only brighter, they have also

⇨ high densities

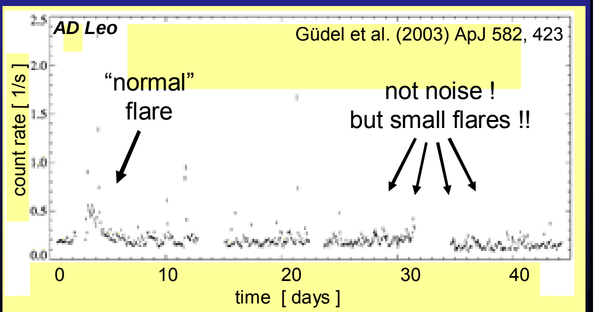
⇨ high temperatures



Could it be flares?

Güdel (2003):

"A stochastic flare model produces emission measure distributions similar to observed DEMs, and predicts densities as observed in "quiescent" sources."



Is there anything left for *solar* physicists ?

KIS Hardi Peter

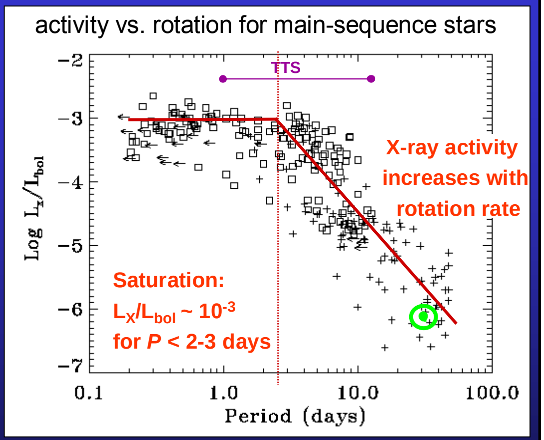
- activity increases with rotation (due to dynamo action) saturation for rapid rotation

  >> scaled-up solar-like magnetic activity ?

- interpretation of on major contribution to X-rays depends on energy distribution of flares

  $dN/dE \propto E^{-\alpha}$

  $\alpha > 2$: flare dominated
  $\alpha < 2$: flares not sufficient



Pizzolato et al. (2003) A&A 397, 147

- thinkable scenarios:

flare-scenario

- same “quiet” corona as Sun
- extra magnetic energy goes into flares of all sizes

>> light curve only due to flares

background scenario

- increased magnetic activity leads to higher densities and temperatures of the quiet corona
- plus some more stronger flares

>> light curve quiet background plus flares!

Is there anything left for *solar* physicists ?

KIS Hardi Peter

➨ ***new models for solar activity***

what happens to

> the quiet corona and
> solar flares

when increasing the emerging magnetic flux?

Well, first we have to understand these phenomena on the Sun before thinking on stars!

flare-scenario

- same “quiet” corona as Sun
- extra magnetic energy goes into flares of all sizes

>> light curve only due to flares

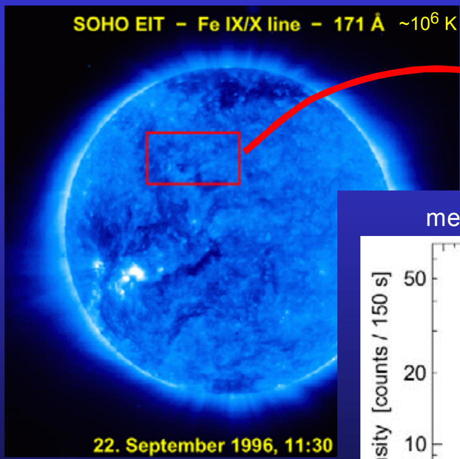
background scenario

- increased magnetic activity leads to higher densities and temperatures of the quiet corona
- plus some more stronger flares

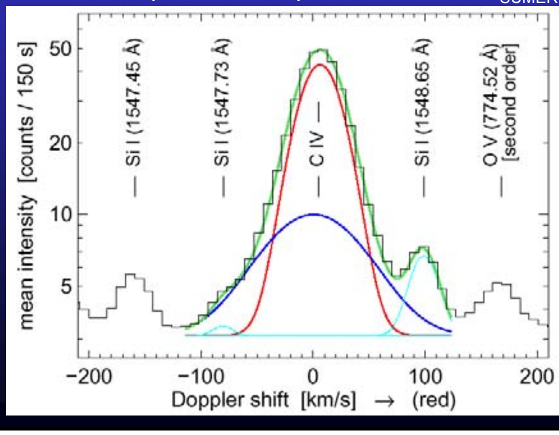
>> light curve quiet background plus flares!

Multi-component transition region spectra

KIS Hardi Peter



mean spectrum — quiet Sun as a star SUMER

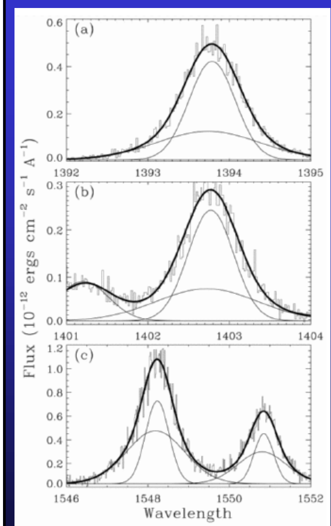


Peter (2000) A&A 364, 933

- multi-component spectra are present everywhere in the network !
- implications for stellar coronae...

Multi-component *stellar* transition regions

KIS Hardi Peter

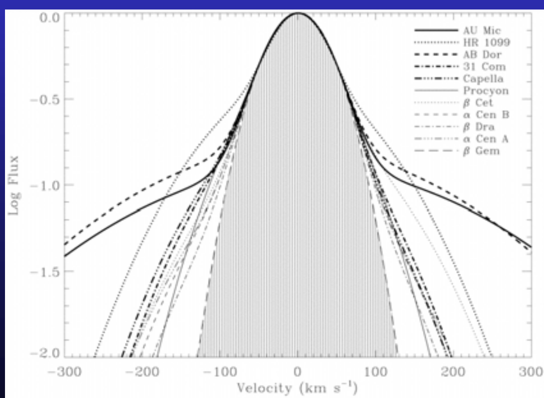


TR spectra of 31 Com (G0 III)

- Si IV (1394 Å)
- Si IV (1403 Å) with O IV blend
- C IV (1548 Å, 1551 Å)

Transition region line profiles
of stars with various activity levels

- profiles are normalized: same intensity and width of core component
- width and strength of tail component increases with activity level!

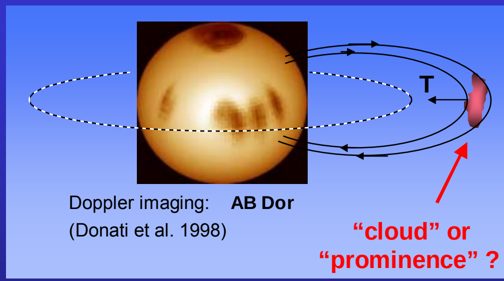


Wood et al. (1997), ApJ 478, 745

Prominences and broad TR lines ?

KIS Hardi Peter

- **Absorption transients in Hα:**
  cool "clouds" of material
  out to co-rotation radius:
  "*prominences*"



- magnetic tension of closed loops
  might provide inward force
  to keep plasma
  in synchronous orbit
  outside co-rotation radius.
  (for AB Dor ~ 3 $R_\star$)

- ~~speculation by Collier Cameron (2001):~~
  ~~could these prominences cause the transition region tail components?~~

  ➔ not very likely:
  tail components on the Sun:
  everywhere in the network…

This shows why it is important for solar physicists to discuss with stellar people…

Conclusions

KIS Hardi Peter

- **The corona is hot !**
  - temperature is controled by heat conduction $\propto T^{5/2}\,\nabla T$
    this provides a "thermostat" (it is hard to change the coronal temperature...)
  - pressure of the corona is set by the heating rate (approx: $p \propto H$)
  - magnetically closed field regions appear brighter than open regions
    (less/no energy to accelerate the wind, all into radiation)
- **The corona is dynamic and highly structured:**
  - systematic persistent net Doppler shifts in transition region lines
  - superposition of loop-like and funnel-like structures
- **Heating of the corona:**
  - *open regions:* e.g. ion-cyclotron resonant absorption of Alfvén waves
  - *closed regions:* e.g. flux-braiding of magnetic field lines
- **Stellar coronae:**
  - resolving stellar corona by eclipse mapping or Doppler-Zeeman-imaging
  - are stellar coronae dominated by flares of all sizes?
  - construct models for various activity levels and compare to stars.....