Modern observational techniques for coronal studies

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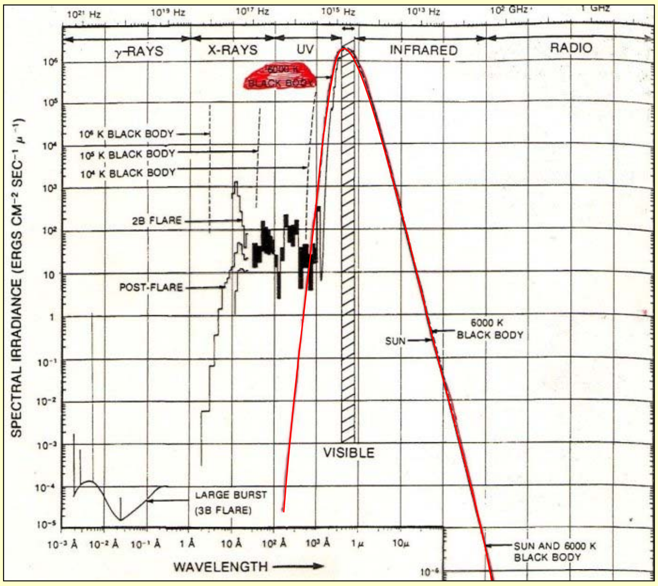
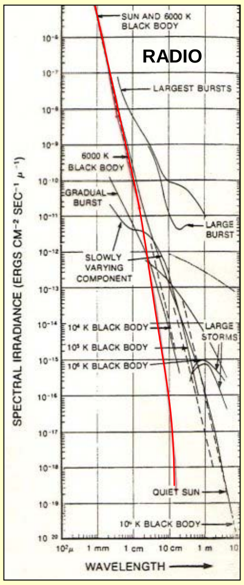
solar eclipse, **11.8.1999**, Wendy Carlos and John Kern

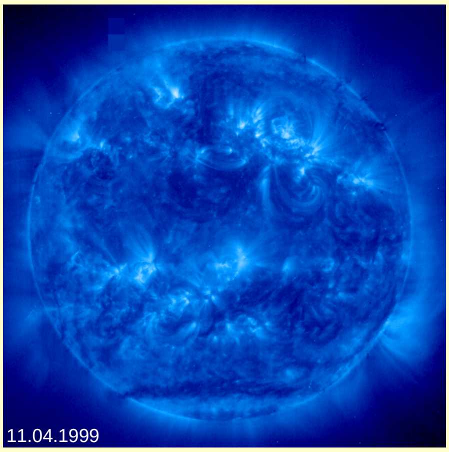
The spectrum of the Sun





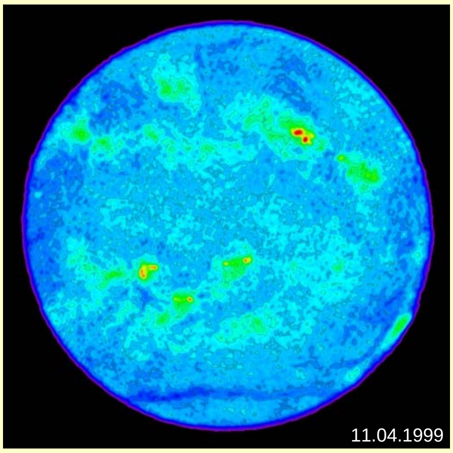
observing in radio or EUV & X-rays $\lesssim$ 1500 Å: ➡ the corona seen in front of dark disk!
➡ "better" than eclipses!

The Sun in EUV and radio



EUV corona, Fe IX/X 171 Å
EIT / SOHO
spatial resolution ~5"

emission measure / density at ~10^6 K



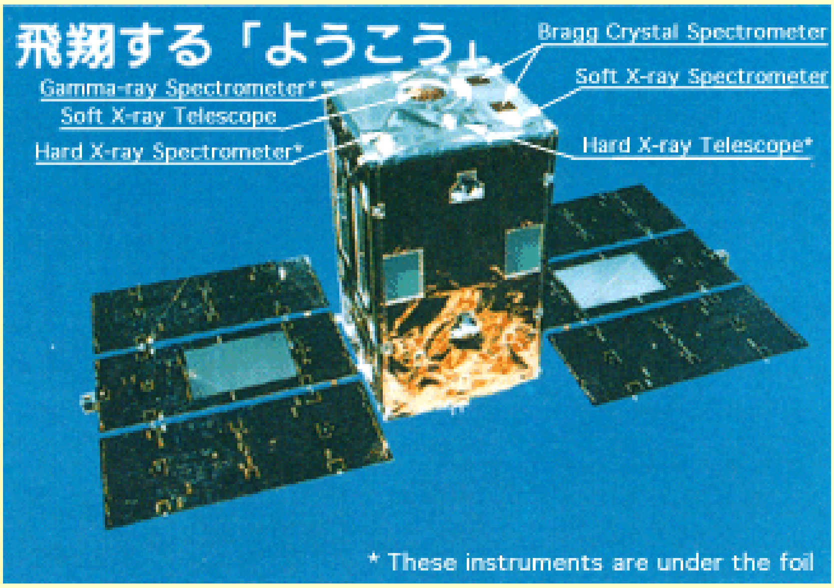
radio corona @ 5.0 GHz (6 cm)
Stephen White, Very Large Array (VLA)
spatial resolution ~12" (8400 km on the Sun)

red: hot ~10^6 K / presence of strong B
green: less hot but denser
blue: cool < 30 000 K material

Image courtesy of NRAO/AUI and
Image courtesy of Stephen White, University of Maryland, and of NRAO/AUI.

Solar A: Yohkoh

study hot parts of solar corona:
– observations from X-rays to gamma-rays
– detect very energetic radiation during flares



Yohkoh SXT design

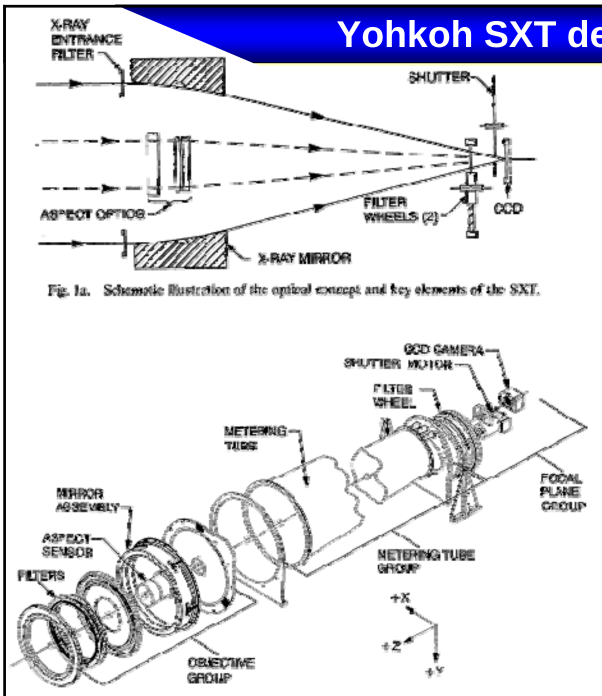


Fig. 1a. Schematic illustration of the optical concept and key elements of the SXT.

Fig. 1b. Exploded diagram of the SXT. Sub-assemblies mentioned in the text are identified.

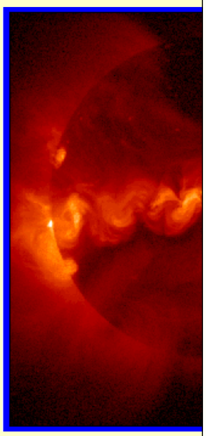
Soft X-ray telescope (SXT):

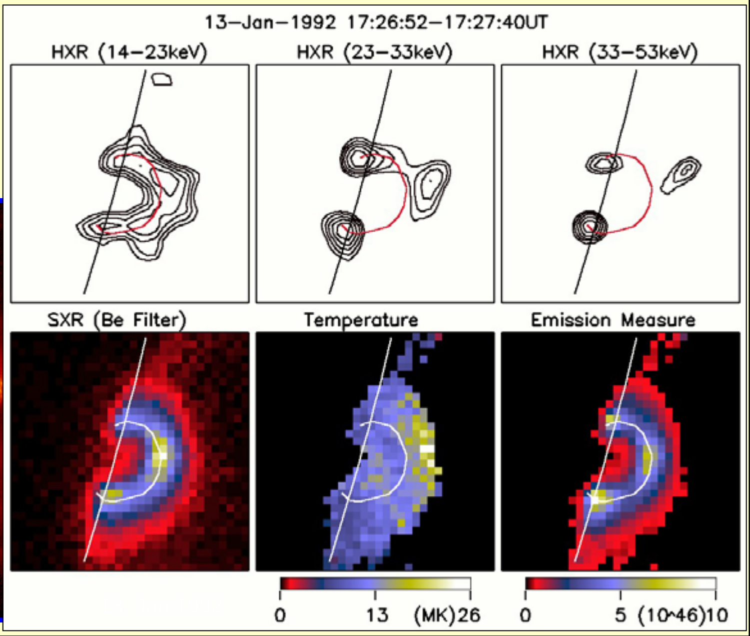
- Wolter-type design
- full-disk images:
  - 1024^2 pixels
  - every 2 min
- partial readout down to 2 sec
- temperatures >2…3 MK
- diagnostics
  - T & ρ structure
  - dynamics of X-ray
  - 3D morphology

Hot, hotter, the hottest: Yohkoh flares

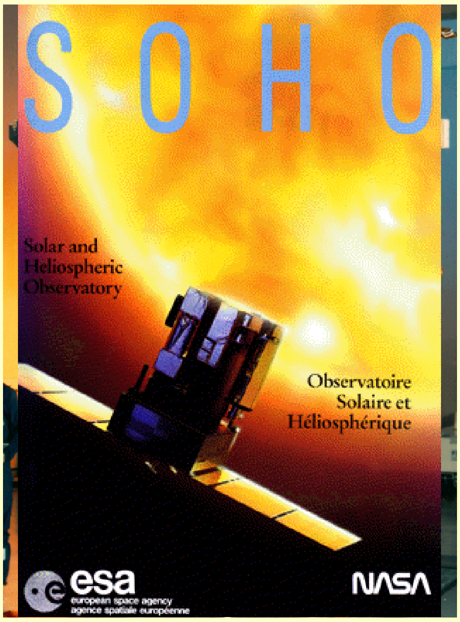
flares are (also) heated at the top! (reconnektion)

energetic particals go down and heat footpoints





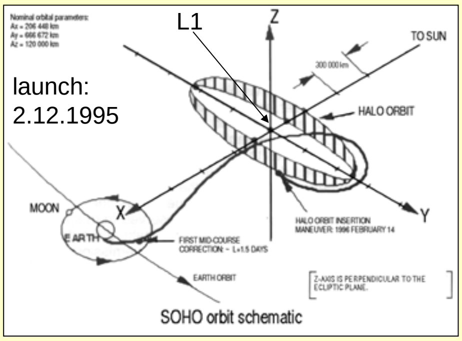
Solar and Heliospheric Observatory – SOHO



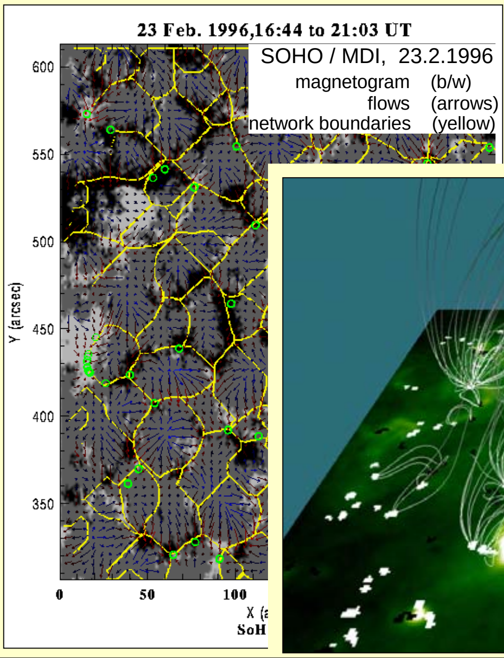
full solar observatory: 24/7 continuous observations

remote sensing:
- photospheric *I, v, B*
- EUV imaging of corona
- EUV spectroscopy (chromosph., TR, corona)

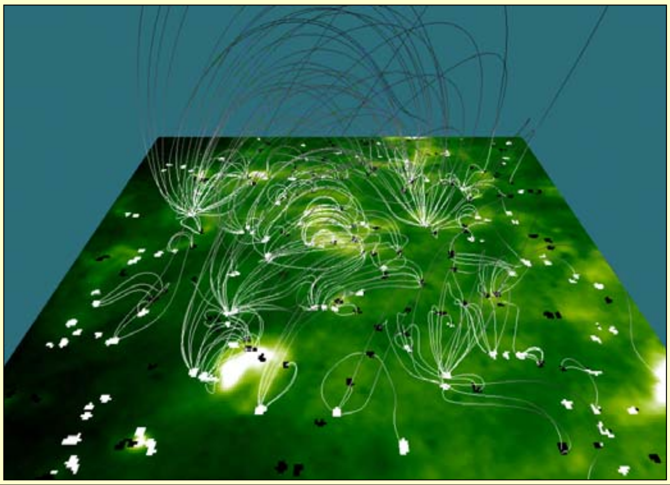
in-situ observations:
- particle fluxes and desities
- abundances
- magnetic fields



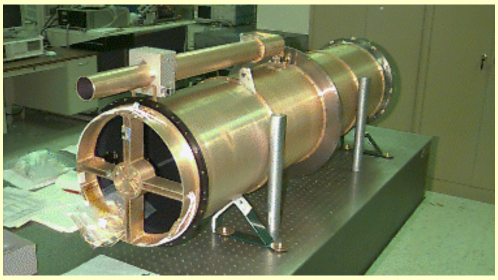
Magnetic field, super-granulation and the corona



supergranulation
- flow defines supergranulation
- magnetic field is transported to the boundaries
  ➡ **magnetic carpet**

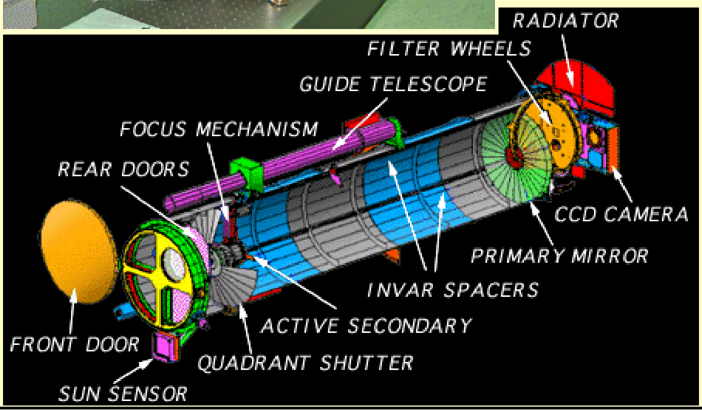


Transition Region And Coronal Explorer – TRACE



30 cm normal incidence telescope

- 4 quadrants of mirror with diferent multi-layer coatings
- additional "narrow band" filters
- 0.5" pixels ➡ resolution: 725 km on Sun
- down to 10 s cadence
- 1024x1024 detector (10% of full Sun)



EUV-channels: **corona**

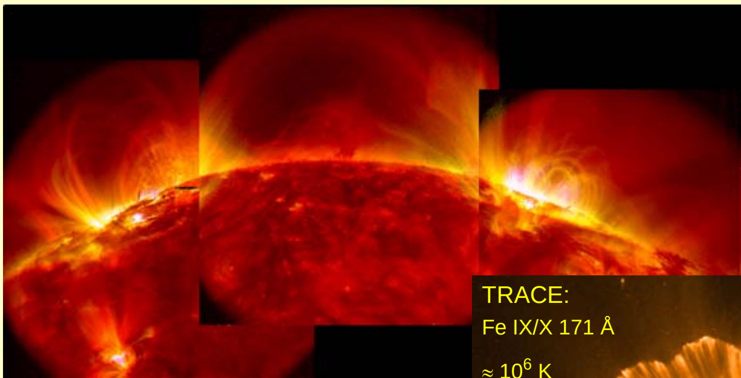
171 Å: Fe IX/X ~1.0 MK
195 Å: Fe XII ~ 1.3 MK
284 Å: Fe XV ~ 2.0 MK

UV channels

1550 Å: } **TR** / C IV 0.1 MK
1600 Å: }
1700 Å: } **chromo**/*T*-min
Ly-a: chromosph. / TR

launch April 1998

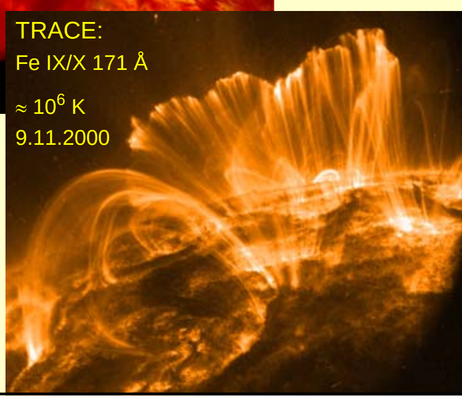
Amazing details…



TRACE does not see the full Sun, but
it shows amazing details in space and time

However: diagnostic value?

- inversion of coronal T ?
  - ➡ to few coronal bands
- plasma flows ?
  - ➡ no line shifts



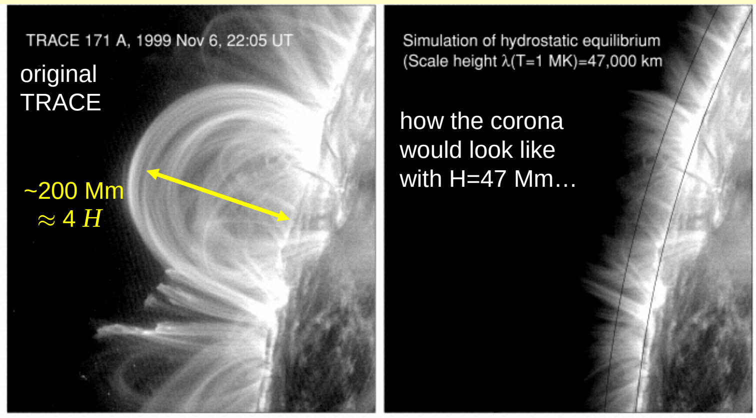
Scale height of the corona

hydrostatic pressure scale height:

$$H = \frac{k_B T}{m g}$$

@ 10^6 K:

$H = 47$ Mm



Why do loops seem to have a rather constant intensity ??

- >70 % of loops cannot be in hydrostatic equilibrium !!
  ➡ e.g. cooling loops
- of the 30 % that might be in equilibrium:
  most have to be heated at the foot points!

Aschwanden (2001)

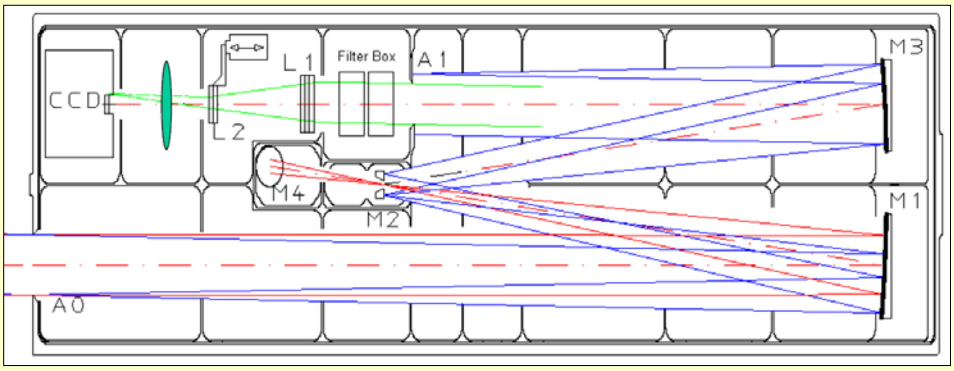
Coronagraph: SOHO / Lasco C1

traditionally: coronagraph has a single lens objective ➡ low straylight

C1 is first operating mirror coronagraph

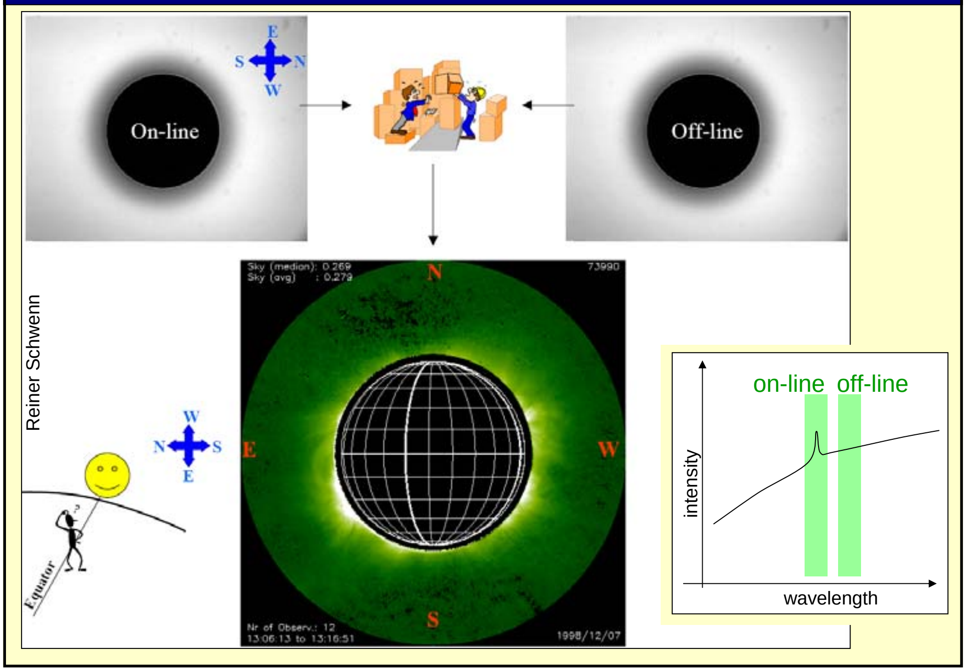
problem: roughness of the mirror ➡ can be handled theses days…

advantage: – no occulter: but hole in a mirror ➡ easy to get rid of solar disk light
– one can even use the solar disk light ➡ simultaneous corona & disk!
(not used with Lasco C1)

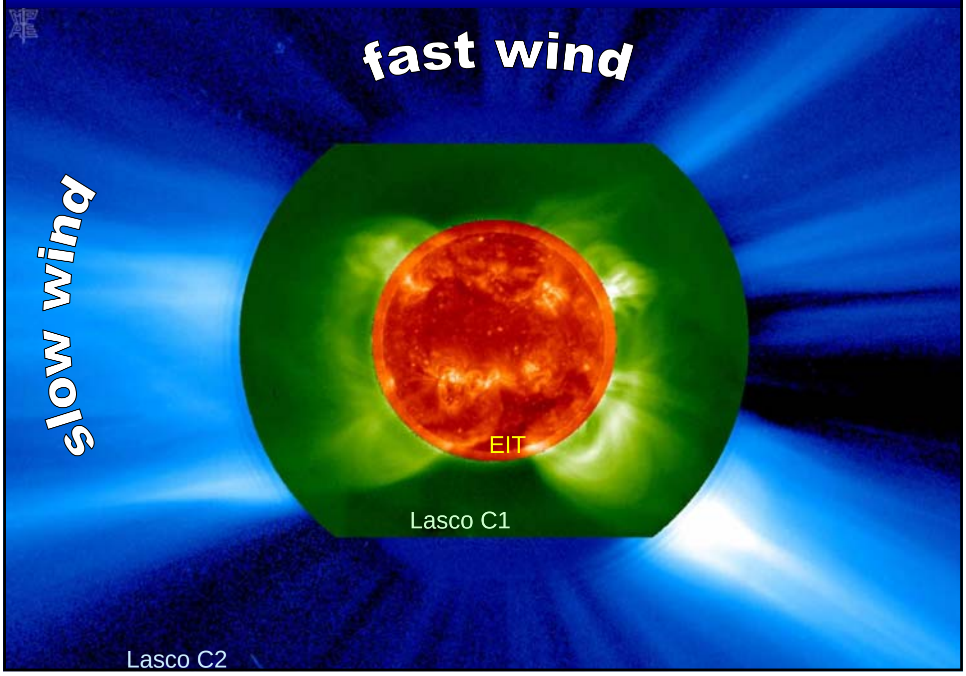


MICA – Mirror coronagraph for Argentina / flight spare of Lasco C1

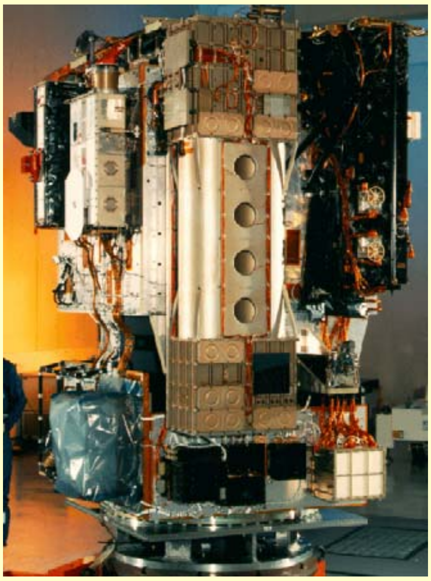
Extracting the emission line corona



The corona – on disk and above limb



EUV Spectroscopy: SOHO / SUMER



SUMER on the SOHO spacecraft

EUV-Spectrograph **SUMER**

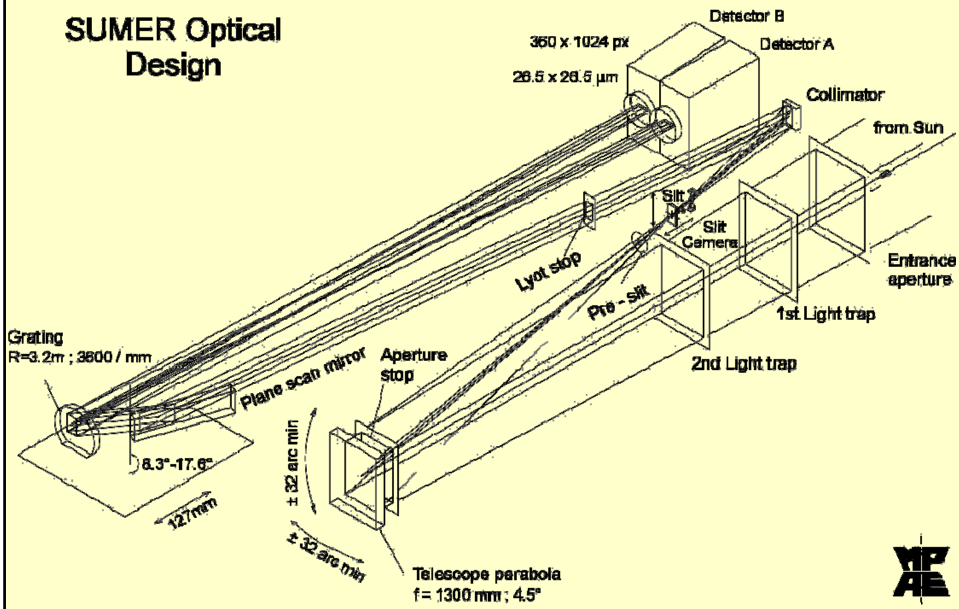
Solar Ultraviolet Measurements of Emitted Radiation

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

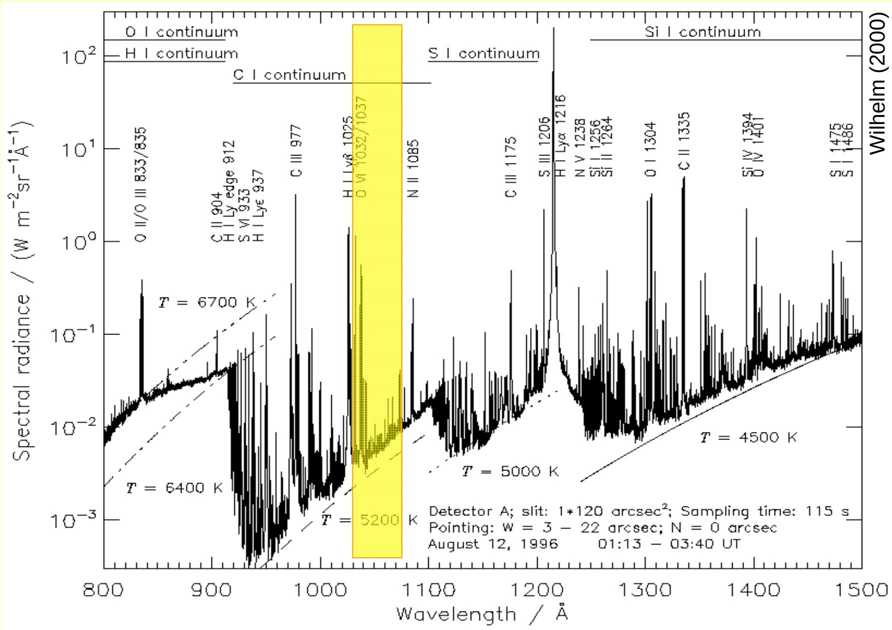
covering temperatures on the Sun: 5000 – 10^7 K

- dynamics and structure of the transition region from the chromosphere to the corona
- **accuracy for Doppler shifts: ~ 2 km/s**

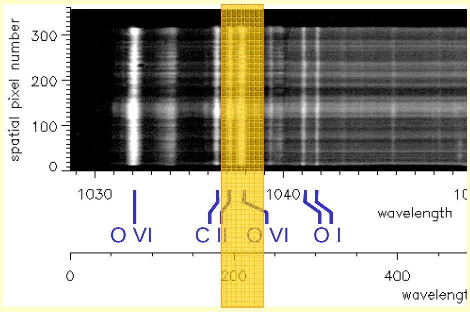
SUMER optical design

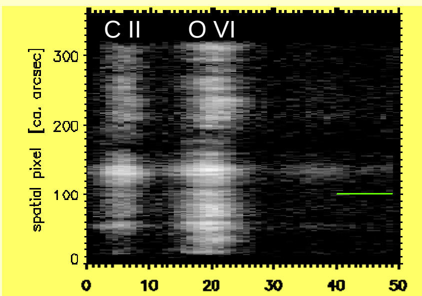


SUMER: spectral range (1st order)



Full spectral frame and spectral windows





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

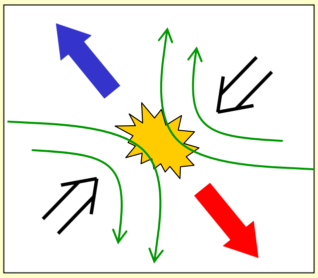
spectral window:
often 50 spectr. pxl ≈ 2 Å (1st order)
(or 25, 512, …)

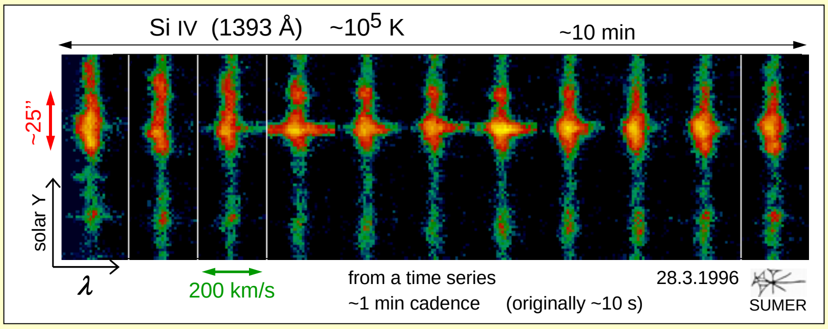
Problem:
sometimes windows not wide enough
(telemetry…)

→ ***Images* by raster procedure**

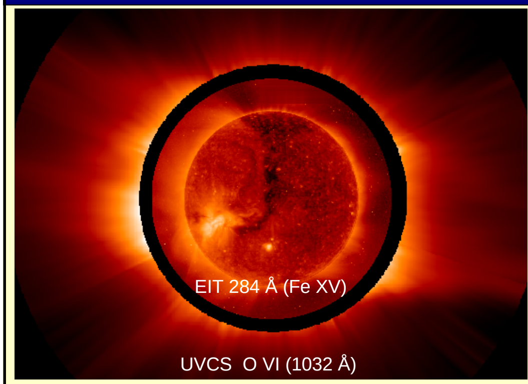
Coronal heating and TR explosive events

- transient broadening of TR emission lines
  sometimes distinct emission peaks visible
  (e.g. Dere et al.,1989, Sol. Phys. 123, 41)
- interpreted as bi-directional jets after reconnection
  (e.g. Innes et al., 1997, Nat. 386, 811)
- explosive events are restricted to TR temperatures
- are they related to the dissipation of energy in the 3D MHD flux-braiding coronal models?





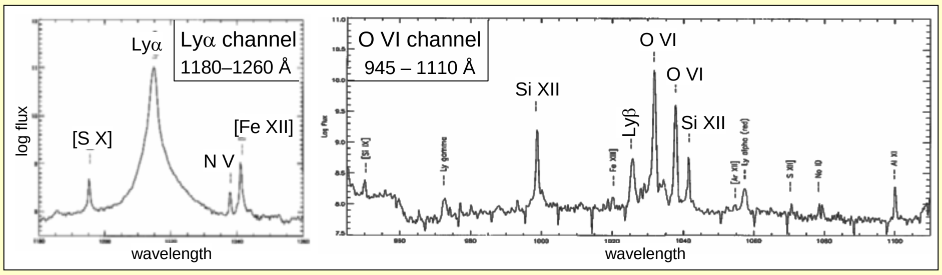
Coronal spectroscopy: SOHO / UVCS



(Ultra-Violet Coronagraphic Spectrograph)

UVCS combines:
- coronagraph and an
- EUV spectrograph

➡ spectroscopic analysis:
- – line widths / temperatures
- – outflow through Doppler dimming
- – hints on abundances



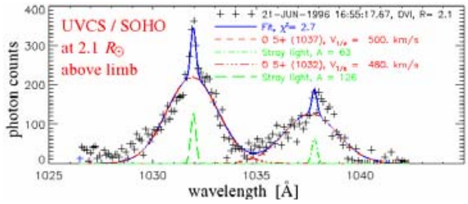
Ion-cyclotron heating in the outer corona

UVCS / SOHO

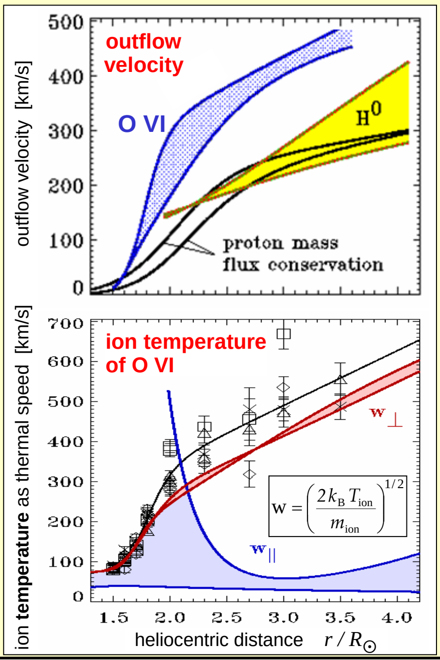
- very broad line profiles in outer corona e.g. 500 km/s = $500 \cdot 10^6$ K in O VI !!
- Doppler-dimming analysis:
  - — rapid acceleration
  - — high ion perpendicular temperatures $T_\perp >> T_\parallel$

➡ *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

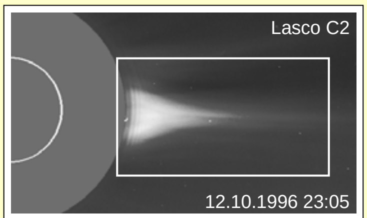
Abundances and solar wind origin

helmet streamer

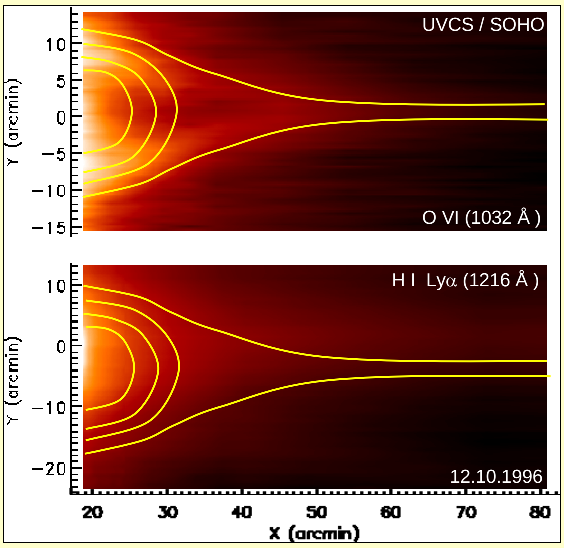
- dark cavity in O VI :
  - ➡ gravitational settling of oxygen / heavy elements ?
- steamer legs show abundances of slow solar wind [SUMER] (FIP-effect)

scenario:

- – wind is leaving through legs
- – inner part is static



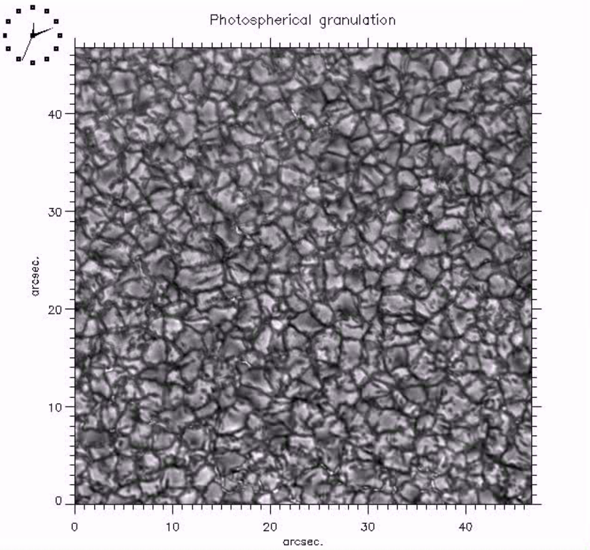
white light corona (K corona)



emission lines in the corona

Raymond et al. (1997) Solar Phys. 175, 645

Ground based observations for coronal physics



v.d. Lühe, Castelli, VTT / Tenerife, blue continuum 4400 Å
with adaptive optics and speckle reconstruction

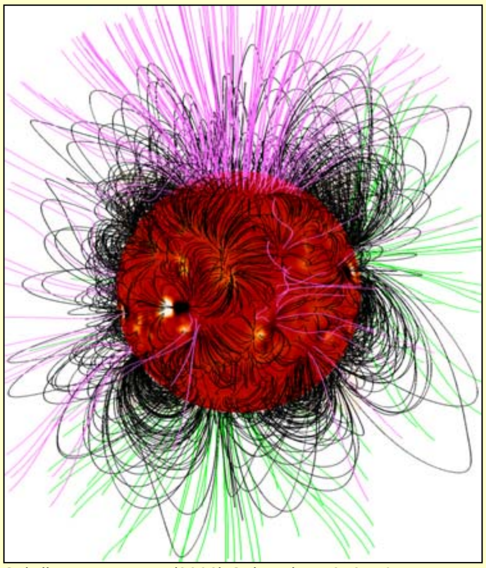
Ultimate driver for coronal heating:

magneto-convection
in the photosphere !!

- braiding of coronal magnetic field
  ➡ current dissipation in corona
- drives chromosheric reconnection
  ➡ waves into corona
- builds up stresses of coronal *B*
  ➡ driving CMEs & flares

The future:
high spatial resolution:
resolve feet of
magnetic flux tubes
& (horizontal) motions:
➡ imaging
AND magnetic field

Coronal magnetic fields



Schrijver & DeRosa (2003) Solar Phys. 212, 165

Magnetic field extrapolations
do a pretty good job…

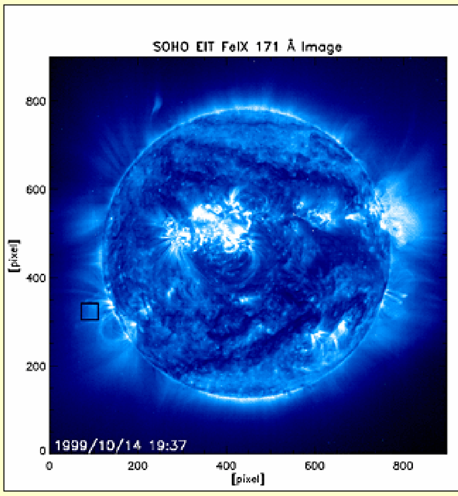
BUT:

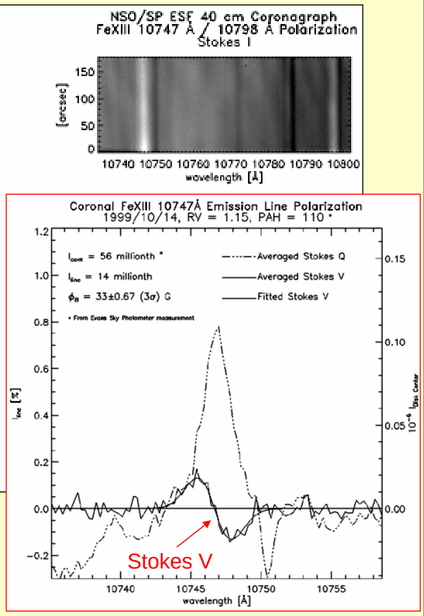
- *B* is not potential or
  (nonlinear) force free everywhere!
- extrapolations assume a
  static magnetic field structure
- dynamic evolution of *B*
  during transient events
- we have to know what *B* really is

➡ Need for direct measurements
of coronal magnetic fields

Direct coronagraphic observations

Haosheng Lin et al. (1999)

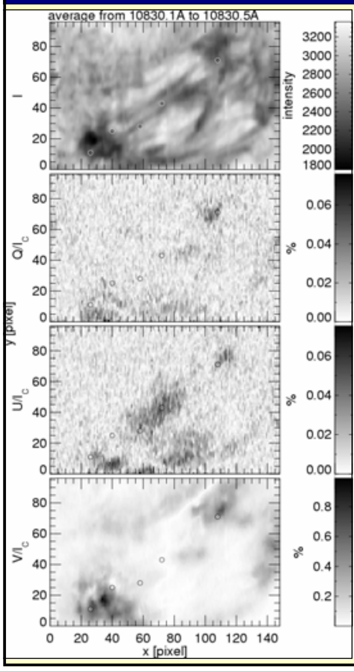


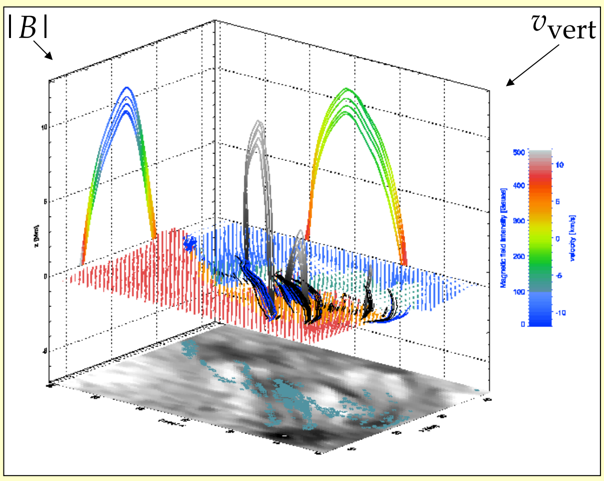


NSO / Sac Peak Evans Solar Facility (ESF)
40 cm coronagraph + IR spectropolarimeter:
first detection of coronal Stokes V signal: 14.10.99

Problem: ➡ *B* only where bright structures…
➡ 3D structure of coronal field?!

3D magnetic fields of emerging flux





magnetic loop is emerging through photosphere carrying cool material seen in He I (10830 Å)

- ➢ polarimetric inversion (data from TIP / VTT / Tenerife)
- ➢ 3D B reconstruction assuming cool material is on loop

Lagg et al (2004), A&A 414,1109; Solanki et al. (2003) Nat 425, 692

Summary / lessons learnt

- **the corona dominates the emission in X-rays, EUV and radio**
- soft X-rays (Yohkoh)
  - hot coronal emission > 3 MK
  - flares, quiescent hot coronal loops
- EUV imaging (TRACE, EIT/SOHO)
  - evolution of 1–2 MK corona
  - corona is very dynamic and fine structured
- coronagraphic imaging (Lasco/SOHO, HAO/Mauna Loa)
  - coronal mass ejections
  - onset of solar wind
- EUV spectroscopy (SUMER, CDS/SOHO)
  - dynamics – from average line shifts to explosive events
  - temperatures, densities, abundances
- coronagraphic spectroscopy (UVCS/SOHO)
  - solar wind acceleration and heating
  - solar wind origin
- coronal magnetic fields (VTT/Tenerife, SacPeak ESF)
  - this is the REAL challenge
  - some information from coronagraphic or IR observations