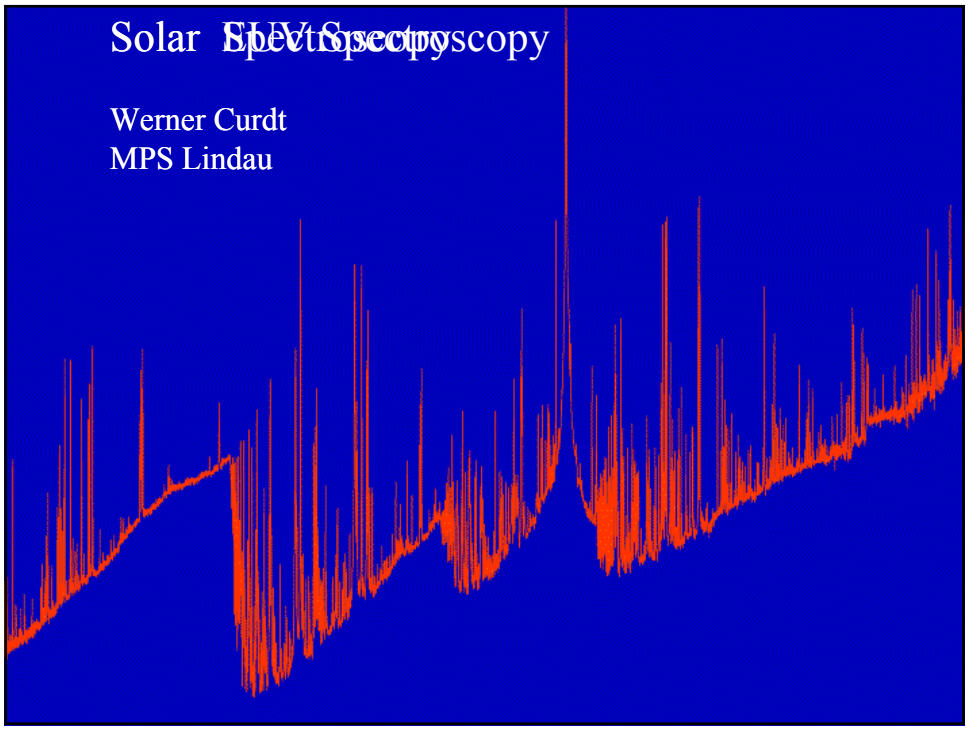
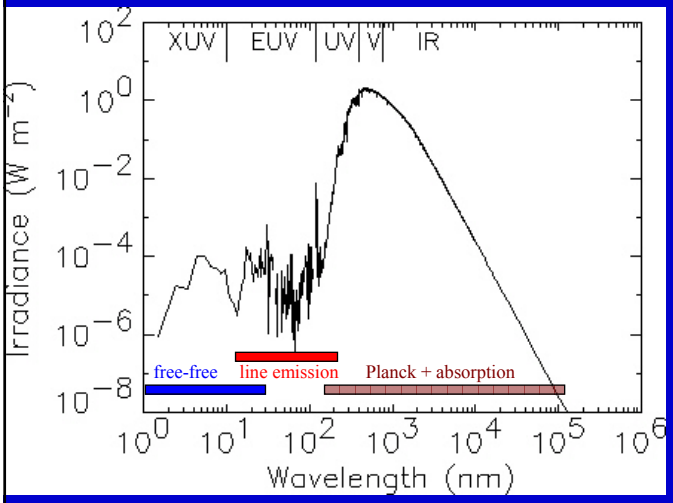
# Solar EUV Spectroscopy

Werner Curdt
MPS Lindau



## Outline

- motivation
  - the Sun‘s electromagnetic spectrum
  - spectroscopic methods
  - observational examples
- instrumental aspects
  - optical design
  - detectors
  - others
- highlights and outlook




spectral categories:

XUV 0.1 – 10 nm
- HXR < 0.1 nm
- SXR 0.1 – 10

VUV 10 – 200 nm
- EUV 10 – 121
- FUV 121 – 200

MUV 200 – 300 nm
- UV- C 100 – 280

NUV 300 – 400 nm
- UV- B 280 – 315
- UV- A 315 – 400

VIS 380 – 760 nm

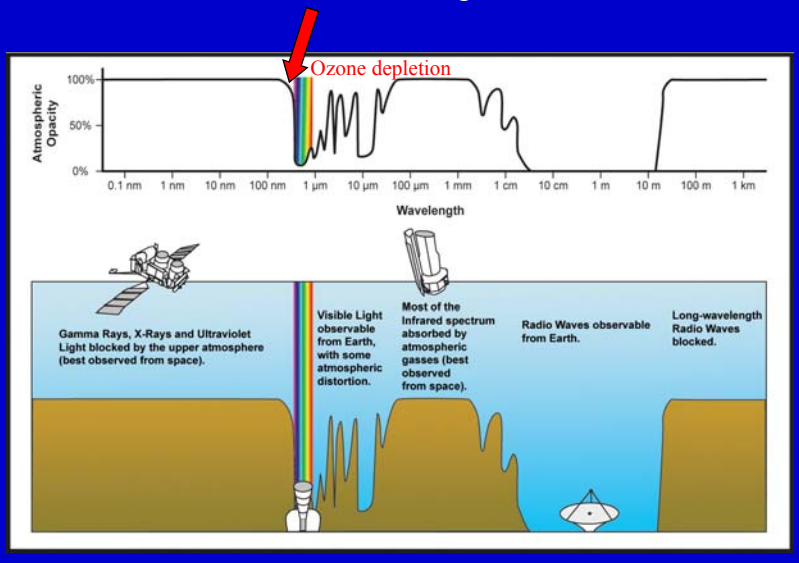
IR 760 nm – 1 mm

radio 1mm – 100 m

The solar irradiance spectrum above earth atmosphere (SOLAR2000)



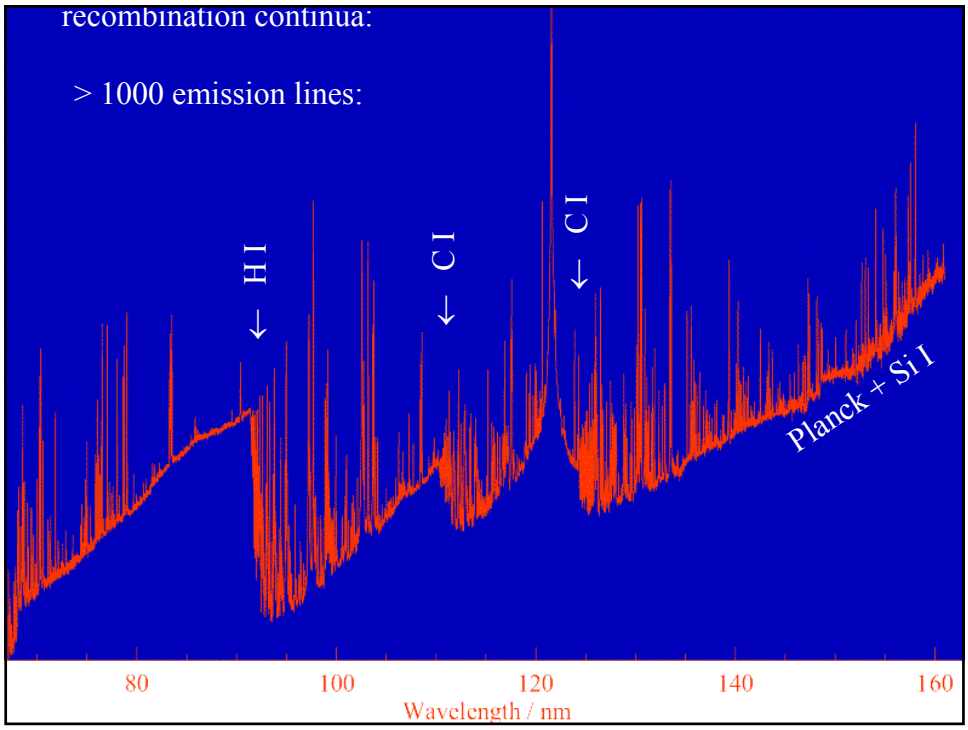
transmission of the Earth atmosphere

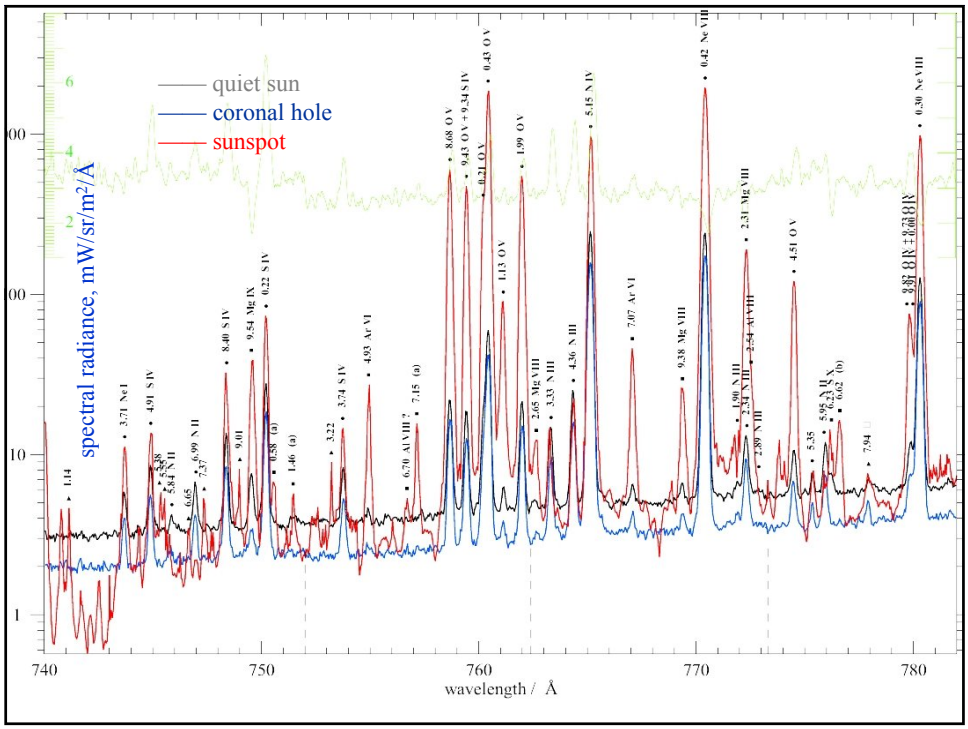


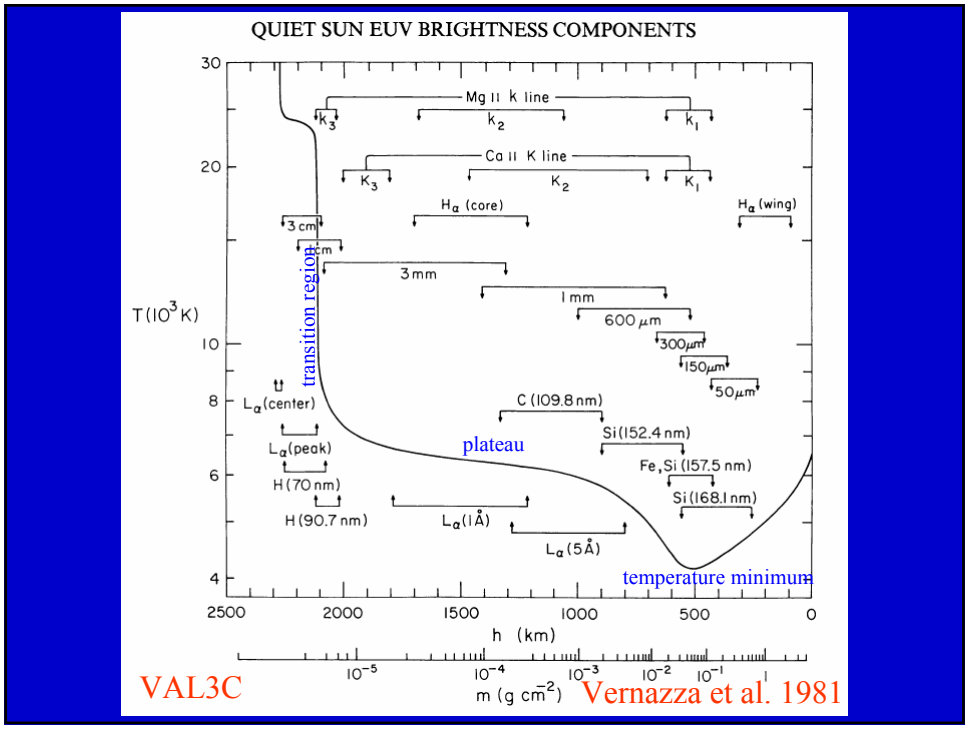
# Spectroscopic methods

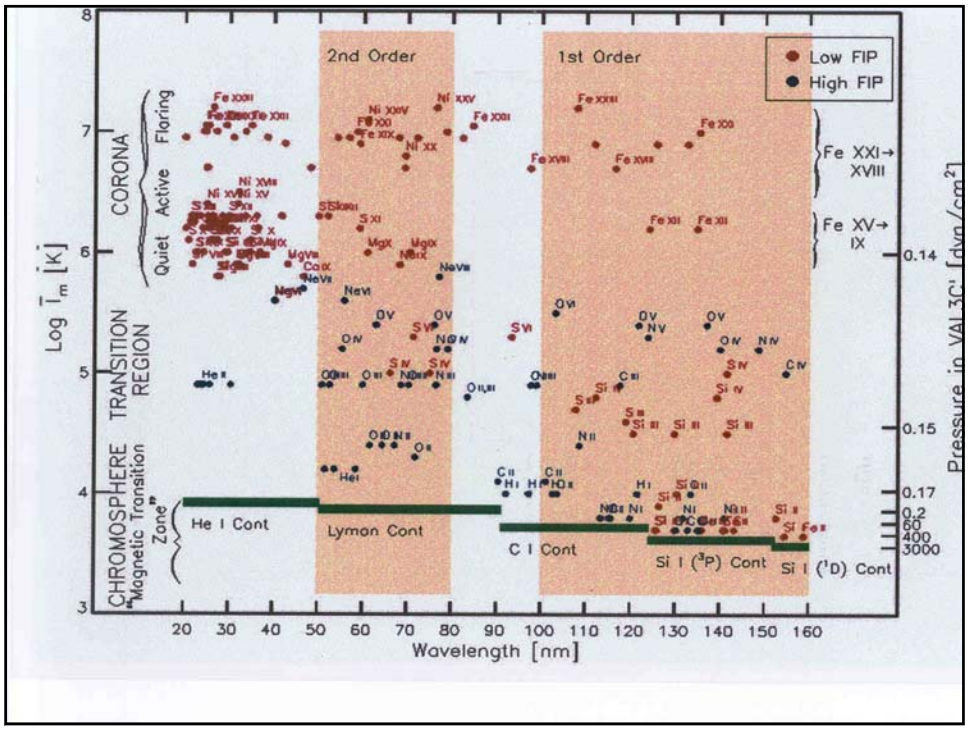
- line identification / selection
- line shifts / Doppler flows
- line widths / line shape
- plasma diagnostics / line ratios
- raster scans
- drift scans
- abundance measurements / FIP effect
- radiance / irradiance
- atomic physics





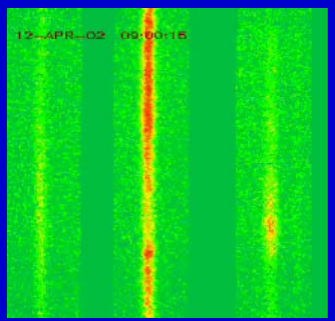

quiet sun
coronal hole
sunspot
spectral radiance, mW/sr/m²/Å
wavelength / Å
740
750
760
770
780


QUIET SUN EUV BRIGHTNESS COMPONENTS
T(10³K)
transition region
plateau
temperature minimum
Mg II k line
Ca II K line
Hα (core)
Hα (wing)
3 cm
1 cm
3 mm
1 mm
600 μm
300 μm
150 μm
50 μm
Lα (center)
Lα (peak)
H (70 nm)
H (90.7 nm)
C (109.8 nm)
Si (152.4 nm)
Fe, Si (157.5 nm)
Si (168.1 nm)
Lα (1Å)
Lα (5Å)
h (km)
m (g cm⁻²)
VAL3C
Vernazza et al. 1981




# Doppler flows

- $\Delta\lambda / \lambda = v / c$
- Hires spectroscopes can resolve 1- 2 km/s



Si III Ca X Fe IXX

EUV Spectroscopy

# Line emission

$$P(\lambda) = \int \frac{hc}{\lambda} \quad A_{ul} \quad N_u \quad dV$$

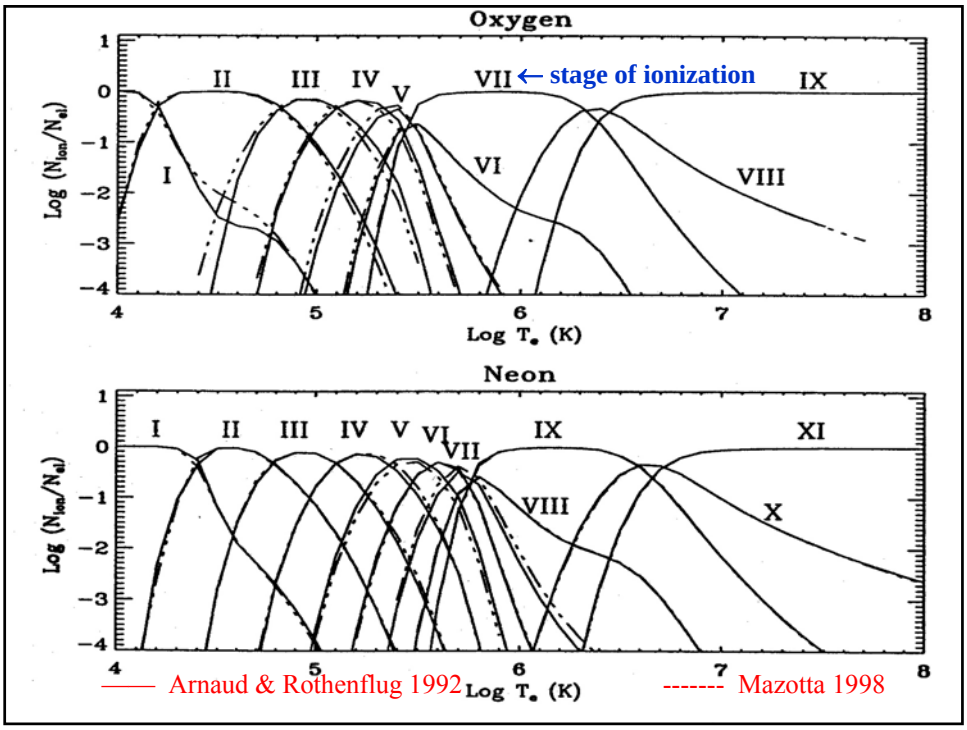
$A_{ul}$ upper/lower level transition probability

$$Nu = \frac{Nu(X^{+p})}{N(X^{+p})} \quad \frac{Nu(X^{+p})}{N(X)} \quad \frac{N(X)}{N(H)} \quad \frac{N(H)}{Ne} \quad Ne$$

excited level population | degree of ionization | elemental abundance | hydrogen abundance

Chianti
ADAS
NIST





# Line shape

- emission profile $\Psi(\lambda)$
  $\Psi(\lambda) = \Psi(\lambda)_{nat} * \Psi(\lambda)_{coll} * \Psi(\lambda)_{th} * \Psi(\lambda)_{NT}$
- Optically thin emission lines are Gaussians
- $\Delta\lambda_D = \lambda_0/c\ (2kT/m + \xi^2)^{1/2}$
  $\xi$ non-thermal velocity (turbulence)



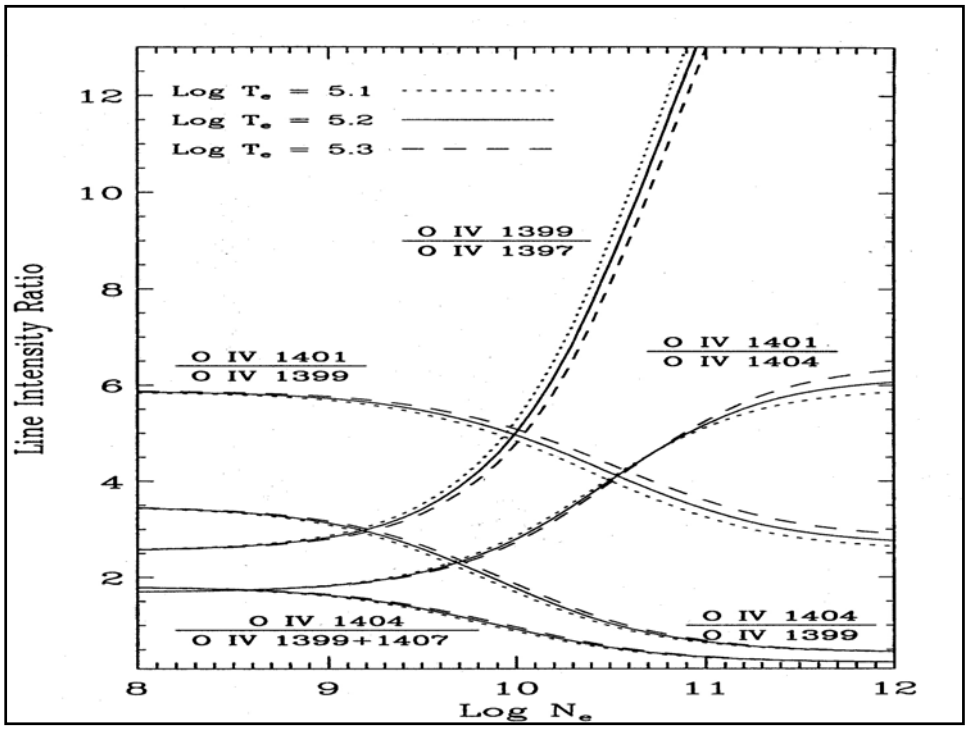
# Line ratios

$P_{ul}(\lambda) \approx N_e^2$

$P_{ul}(\lambda) \approx N_e$ metastable levels

$N_e$ diagnostics

$T_e$ diagnostics




# Historical overview

- 1950 Bragg-crystal spectrometers
- 1962 OSO armada
- 1973 Apollo Telescope Mount
- 1975 HRTS, 8 rocket flights
- 1985 HRTS, Spacelab 2
- 1996 SOHO-CDS
- 1996 SOHO-SUMER
- 2006 Hinode-EIS
- 2015 SO EUS

# Performance characteristic

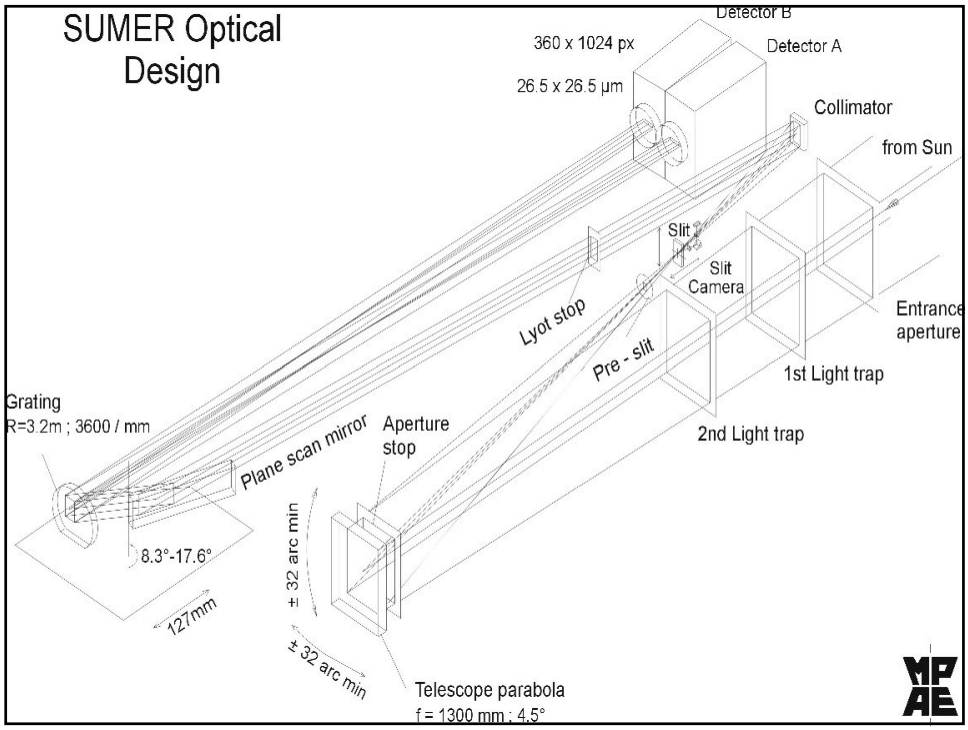
Coronal Diagnostic Spectrograph
Solar Ultraviolet Measurement of Emitted Radiation
EUV Imaging Spectrograph

| | CDS | SUMER | EIS |
|---|---|---|---|
| wavelegth range, Å | 308-381 (NI) | 790-1608 (1) | 180 - 204 (A) |
| | 513-633 | 465-804 (2) | 240 - 290 (B) |
| | 151-221 (GI) | | |
| | 256-338 | | |
| | 393-493 | | |
| | 656-785 | | |
| spatial resolution / ″ | 4 - 8 | 1.2 | 1 |
| spectral ″ / km/s | 10 | 2 | 2-3 |
| temporal ″ / s | 10 | 10 | 1 |



# Instrumental aspects

- Spectroscope:
  - telescope
  - slit
  - dispersive element
  - 2D detector
- infrastructure
  - to bring the instrument into space
  - to bring the data back to Earth




# Telescope primary mirror

- size determines spatial resolution, λ/D
- size ~ photon input ⇒ temporal resolution
- figure defines PSF
- micro roughness defines scattered light level
- needs pointing mechanism
- optical surface:
  - λ > 120 nm ⇒ Al/MgF2
  - λ > 50 nm ⇒ Si C
  - λ < 50 nm grazing incidence (Wolter) or multilayer coating

## Telescope slit

- slit width limits photon input
- slit width limits spectral resolution
- slit: loss of >99% of photons
  - slitless spectroscopes (strong lines, filters)
  - slot spectroscopes (wide slit)
  - raster scans
  - drift scans (low temporal resolution)



## Telescope collimator

- Makes parallel light (classical design)
- defines magnification (pixel adjustment)
- folds the light beam (compactness)

## Spectroscope grating

- Bragg crystal systems
- holographic gratings
- ruled gratings
- variable line space technique (TVLS)
  - future 2 reflection designs



## Instrument detector(s)

- Films
- CCDs
  - back-illuminated CCDs
  - intensified CCDs
- MCP detectors
  - multianode systems (MAMA)
  - time delay systems (XDL)
- APS sensors
- BOLD detectors

# Telemetry issues

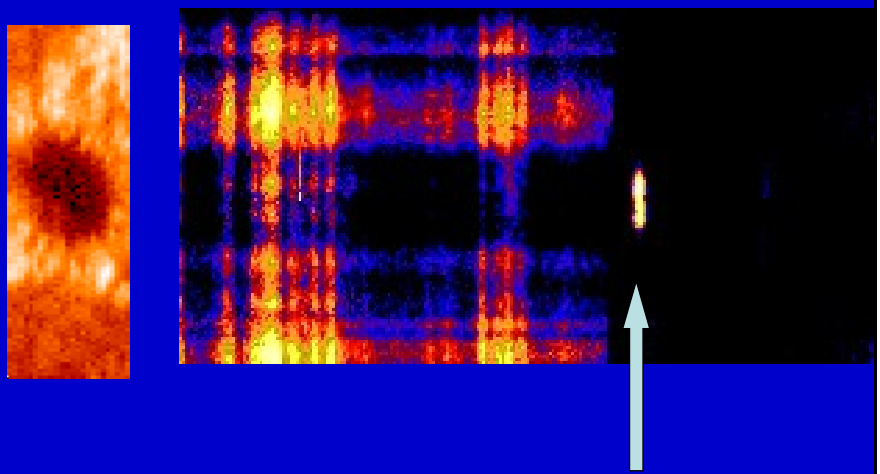
| | |
|---|---|
| 16 bit pixels | dynamical range |
| 1 k x 1k | small and numerous |
| 10 s | good time resolution |

Example SUMER: $\frac{16 \text{ bit/px} \times 400\,000 \text{ bit}}{10 \text{ s}}$ ≈500 kbit/s

| | |
|---|---|
| Data selection | windows, binning |
| Data compression | sqrt, JPEG, MPEG |
| Data reduction | moments |

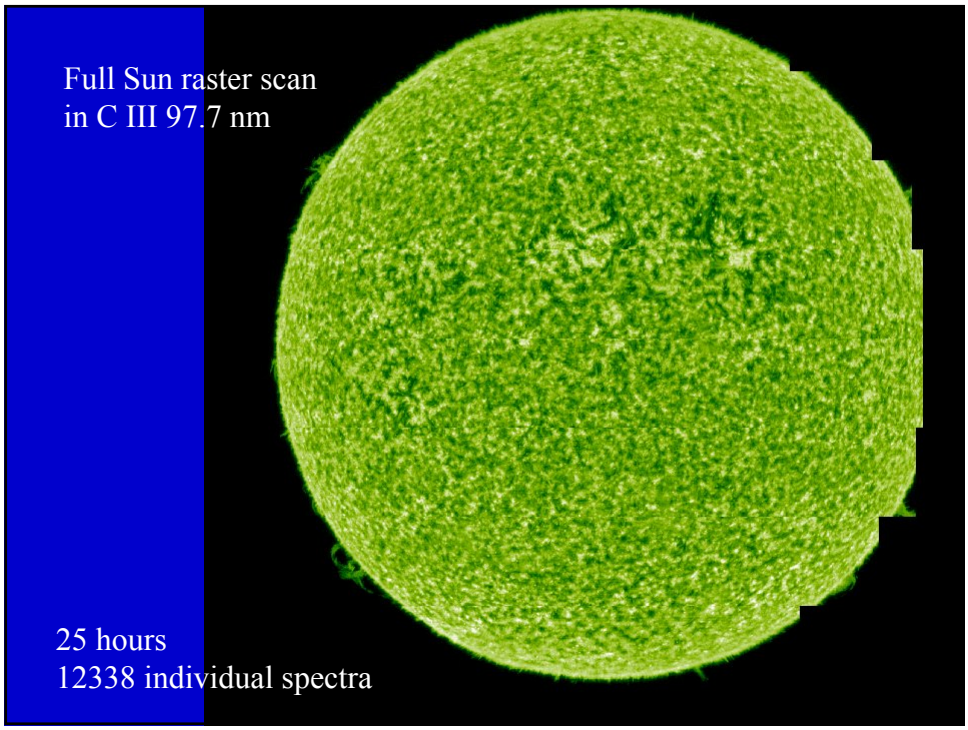


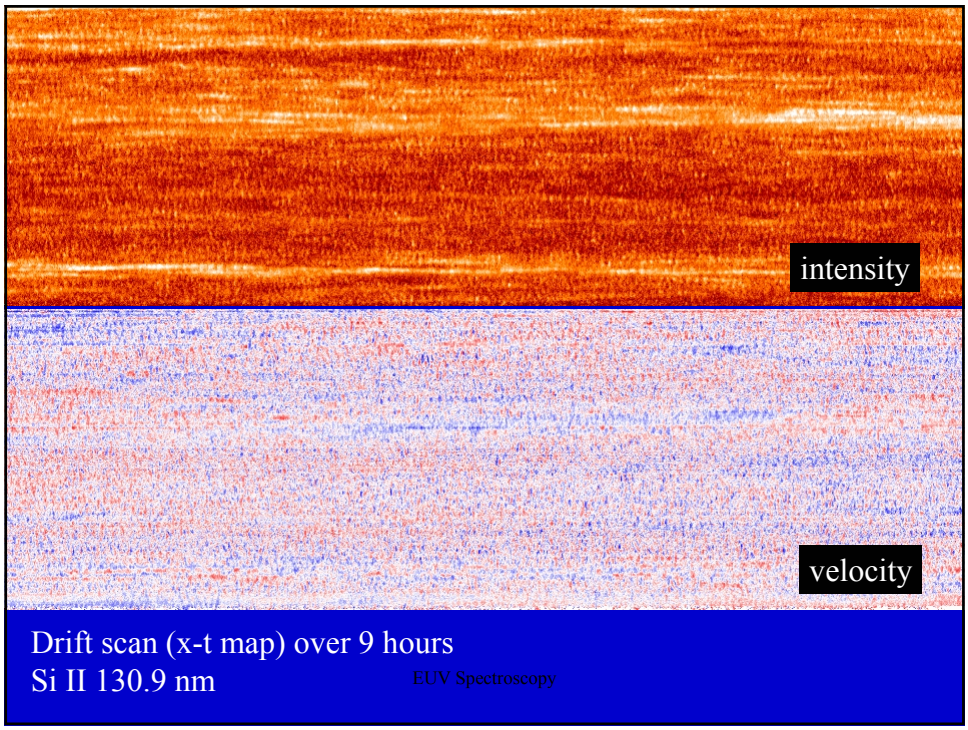
Sunspot onbserved on Mar 18, 1999

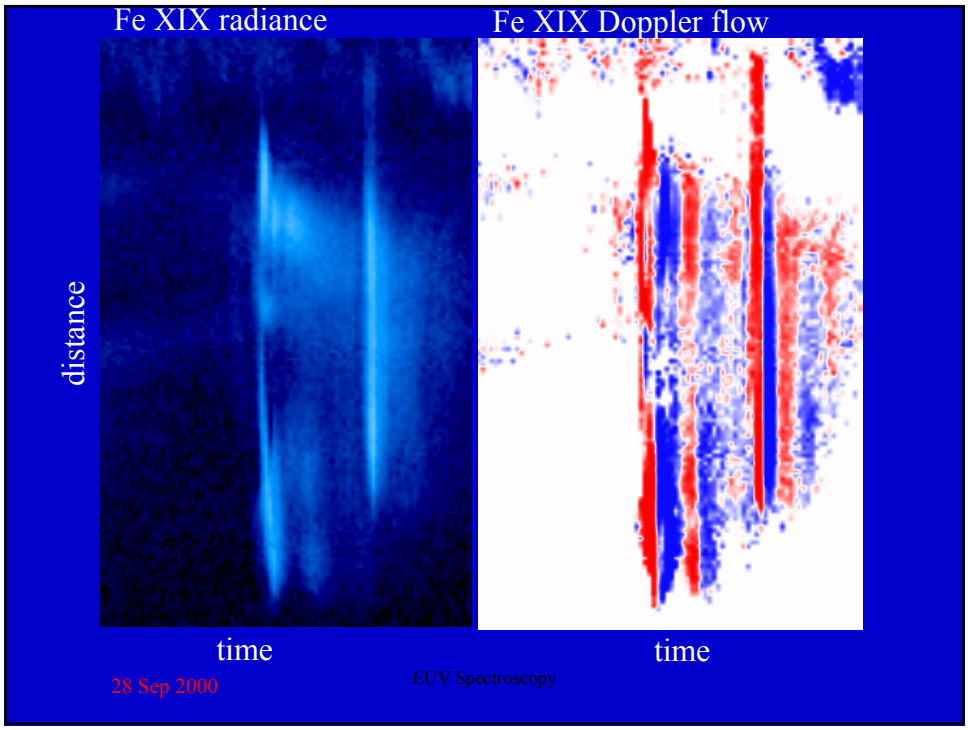


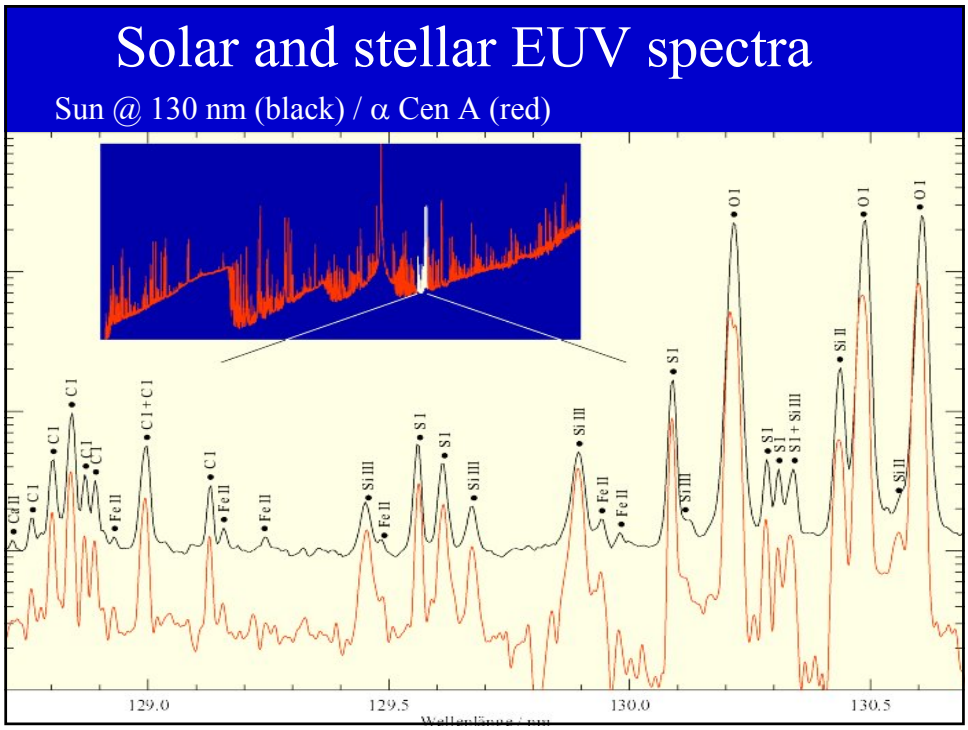
Raster scan in the continuum @ 1478 Å

Spectrum around 1163 Å with strong $H_2$ fluorescence emision


Full Sun raster scan
in C III 97.7 nm
25 hours
12338 individual spectra


intensity
velocity
Drift scan (x-t map) over 9 hours
Si II 130.9 nm
EUV Spectroscopy


Fe XIX radiance
Fe XIX Doppler flow
distance
time
time
28 Sep 2000
EUV Spectroscopy


Solar and stellar EUV spectra
Sun @ 130 nm (black) / α Cen A (red)
129.0
129.5
130.0
130.5

# Outlook

- SUMER and CDS still in operation
- HINODE EIS
- Solar orbiter EUS