From eclipse drawings to the coronagraph and spectroscopy

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

Hardi Peter

MAX-PLANCK-GESELLSCHAFT

MPS

Why the Sun?

- it is *our* Star
- nearest and only star where we might resolve the basic processes on their characteristic temporal and spatial scales
- the Sun is our ultimate source of energy — influences the whole heliosphere
- solar activity can cause failure of space based and terrestrial technical systems
- the Sun influences the Earth's climate

- the Sun is a huge plasma laboratory
- dynamics of a magnetized plasma
- how do stars and galaxies produce magnetic fields?
- basic physical questions: e.g. the (solved) neutrino problem

- the Sun's past: how was the Sun formed and why do we have (8) planets?
- the Sun's future: how will the habitable zone change in the future?

- change of paradigms:

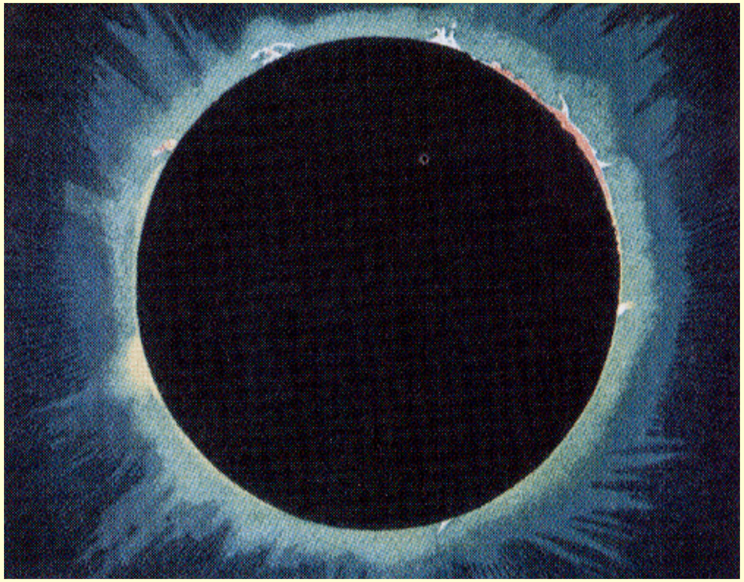
  often: classification (partly) according to instrumental capabilities

visible	—	photosphere
UV	—	chromosphere
EUV/X-ray	—	corona
particles	—	heliosphere

↪ but: strong coupling between various atmospheric structures **!**

Challenge: close interaction between modeling and observations: models are needed for interpretation of increasingly complex models

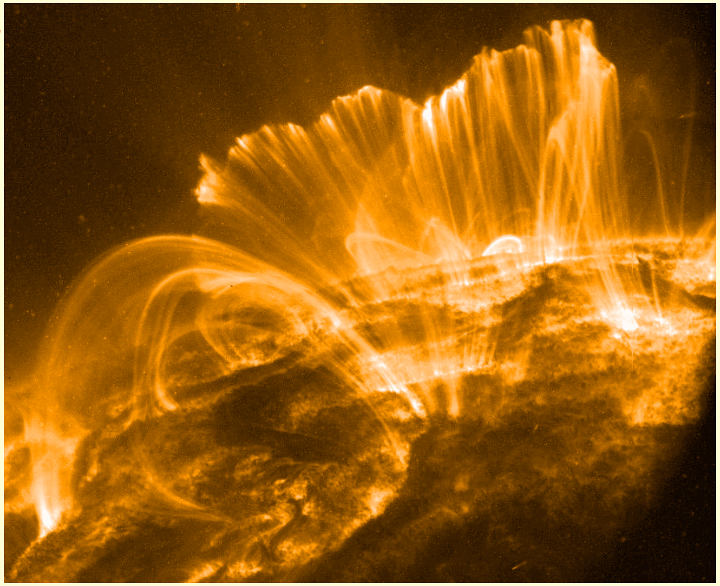
... and the Sun (and its corona) is fascinating



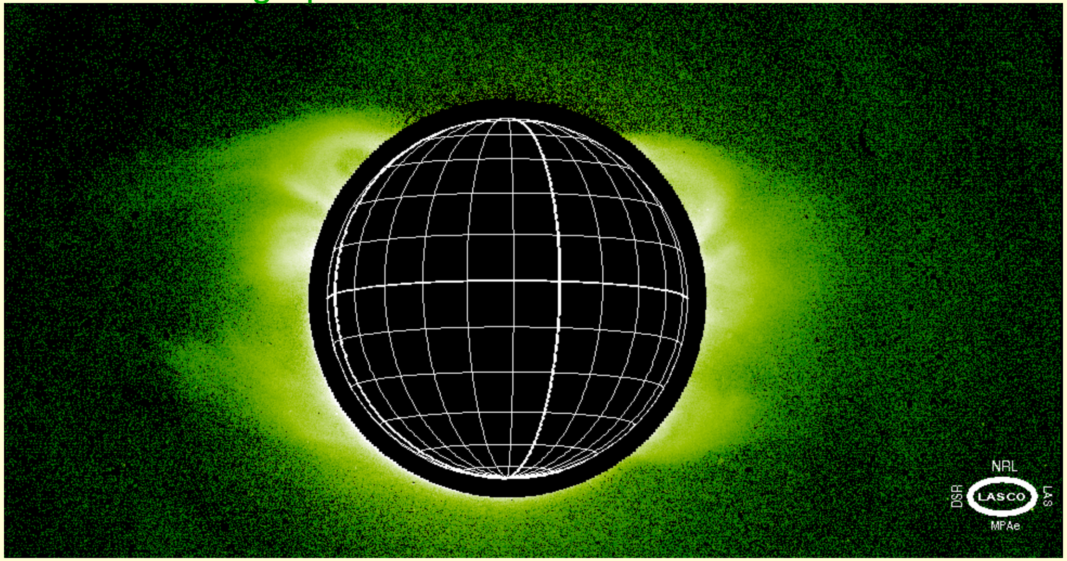
Eclipse drawing, 1860

amateur photography

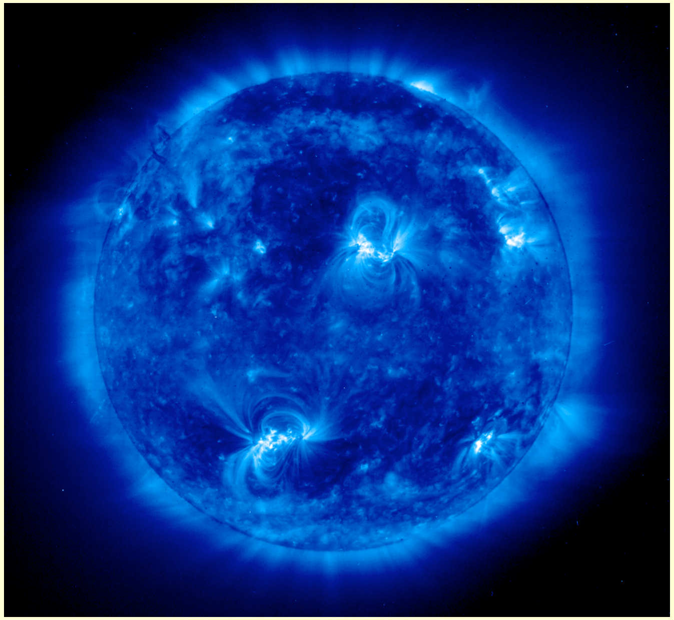
fine loops in the corona



modern coronagraph



the solar corona



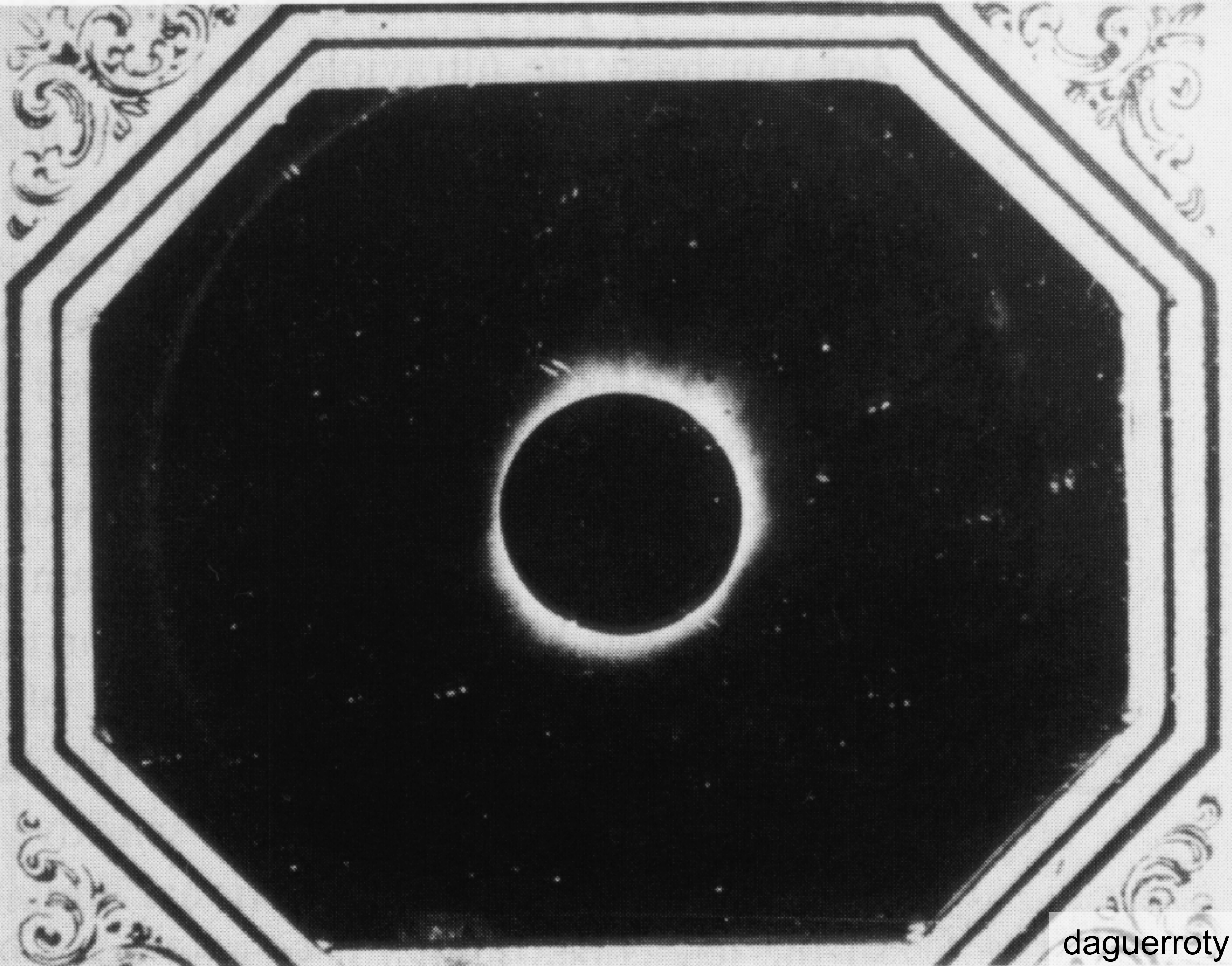
Outline

1. From eclipse drawings to the coronagraph and spectroscopy
2. The solar atmosphere and magnetic field
3. Modern observational techniques
4. Coronal heating and energetics
5. Closed magnetic structures – loops
6. Open magnetic structures – coronal holes and the solar wind
7. Stellar coronae
8. The microstate of the solar corona and the solar wind
9. Space weather and solar–terrestrial relations
10. Structures, waves and turbulence in the heliosphere

the solar chromosphere, just before totality

Duckmüller / Aniol, eclipse 2006

First eclipse photo: Berkowski, Königsberg, 28.7.1851



daguerrotype

Real adventures … 1898 in India

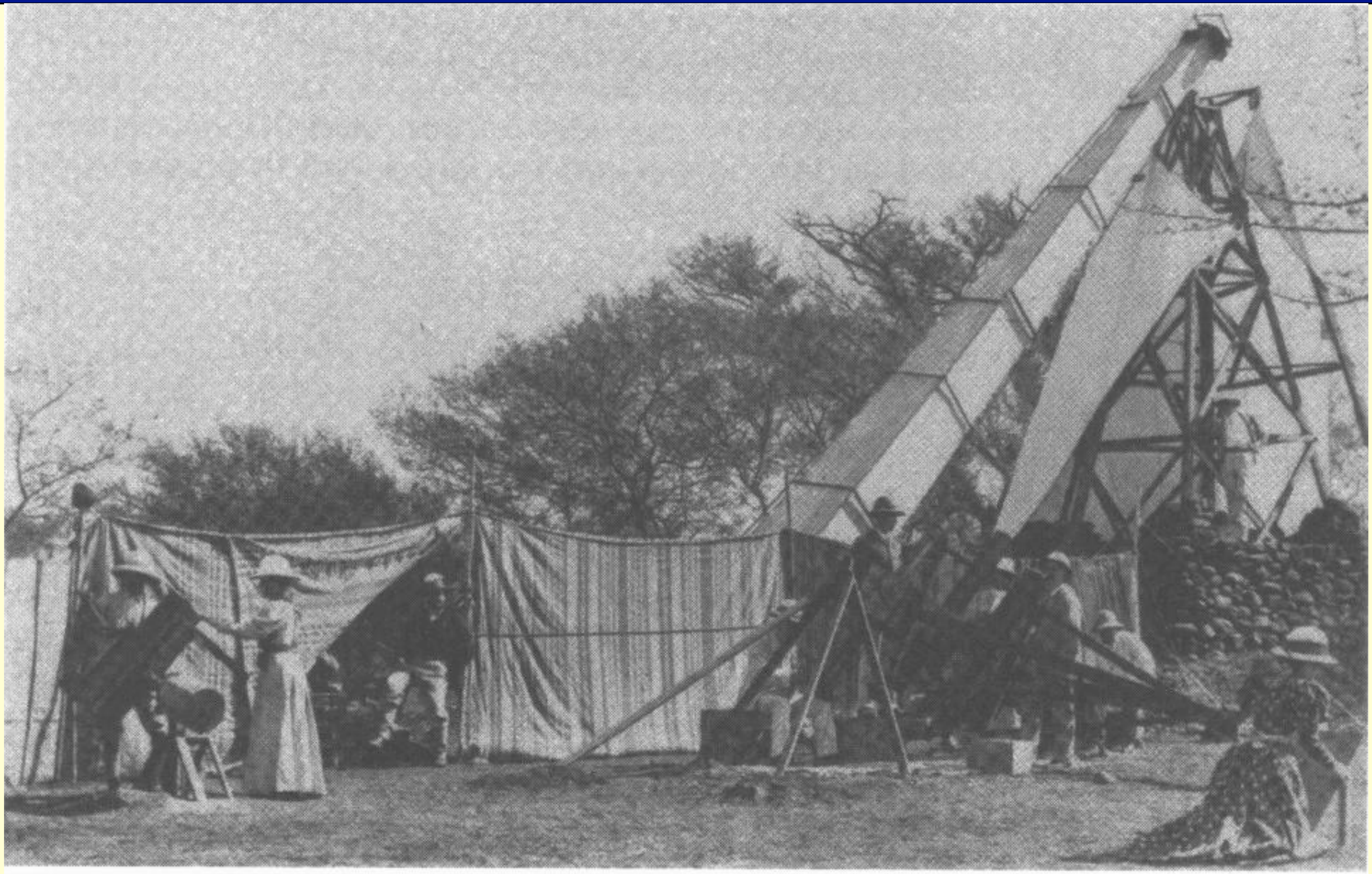
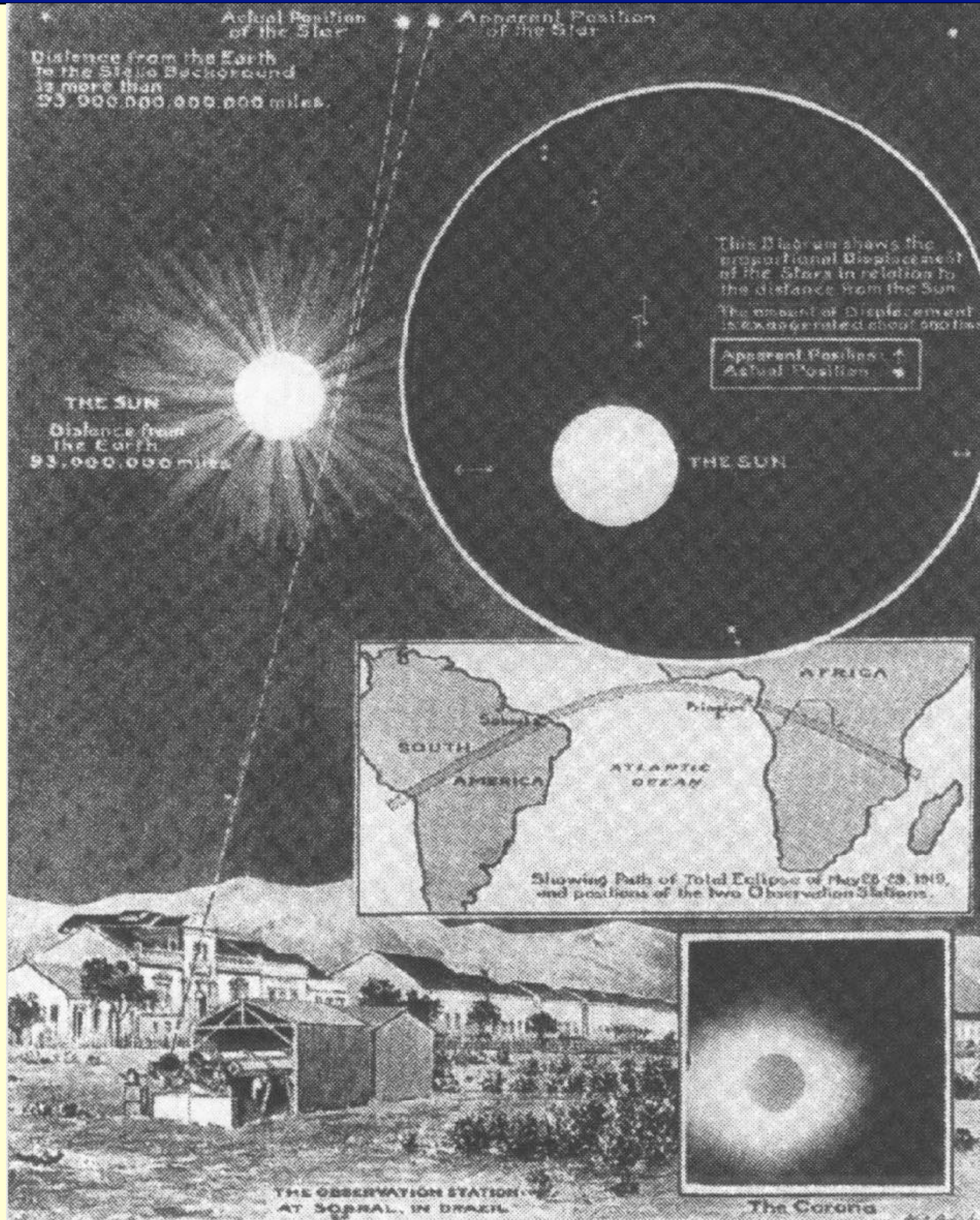
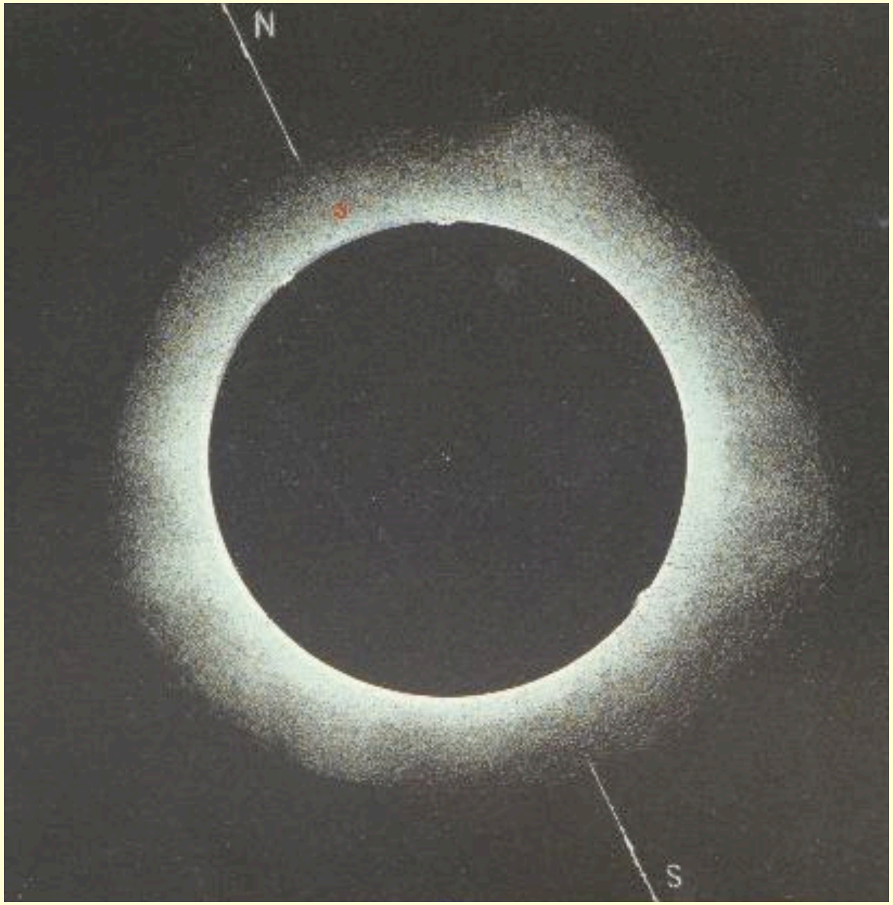


Fig. 4.10. The great 40-foot (12-metre) Lick Observatory eclipse camera, set up near Jeur in India for the eclipse of 22 January 1898. This giant instrument – named 'Jumbo' by its creator, J.M. Schaeberle – was transported to every continent, with the exception of Antarctica, for every eclipse from 1893 to 1931. It could not be guided in the normal way (although it had a clock-driven plate-holder), and was aimed at the pre-calculated position of the eclipse. It could provide a dozen photographs per eclipse on 56 × 36-cm glass plates. (High Altitude Observatory collection.)

Fundamental Physics: eclipse 1919



Drawing vs. photography

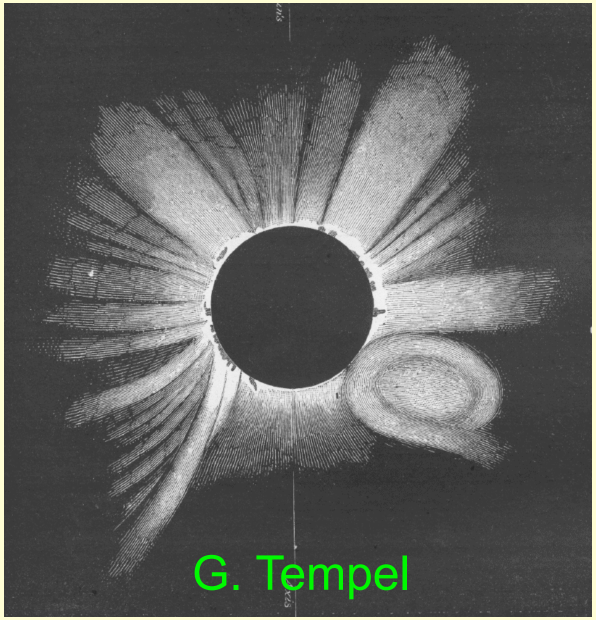


18. July 1860

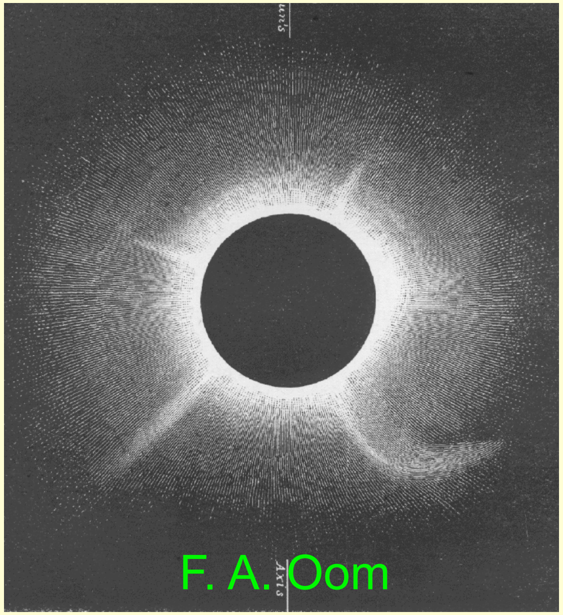
Spain,
drawing following the eclipse,
Warren de la Rue

Desierto, Spain,
40 s exposure time,
Angelo Secchi

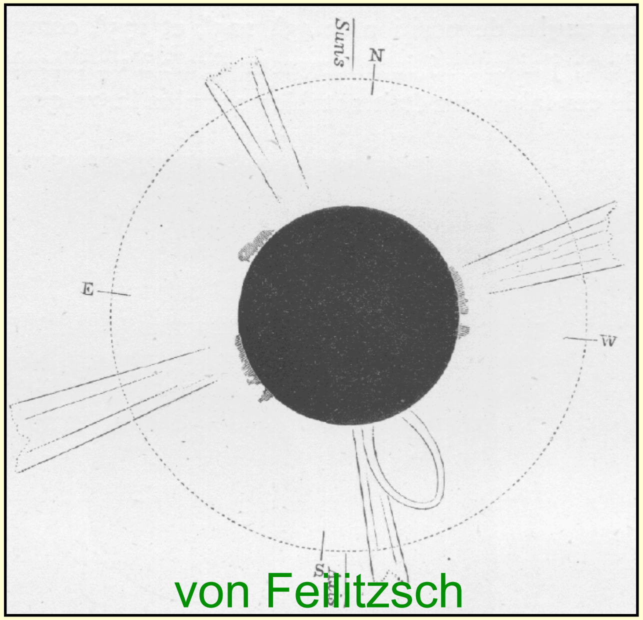
Solar eclipse 18.7.1860: more drawings



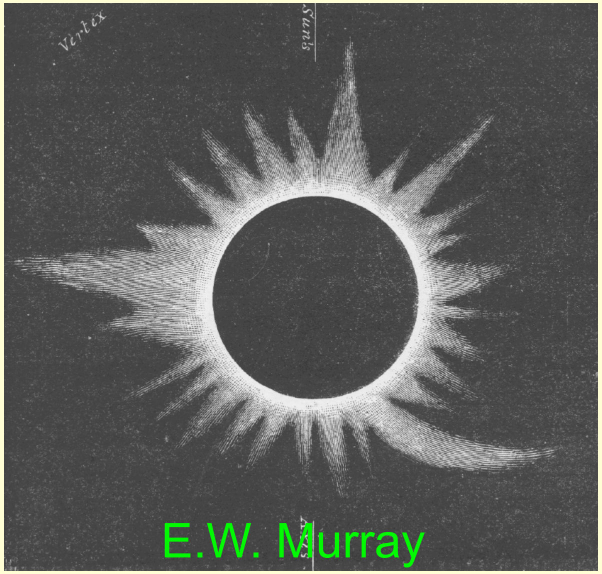
G. Tempel



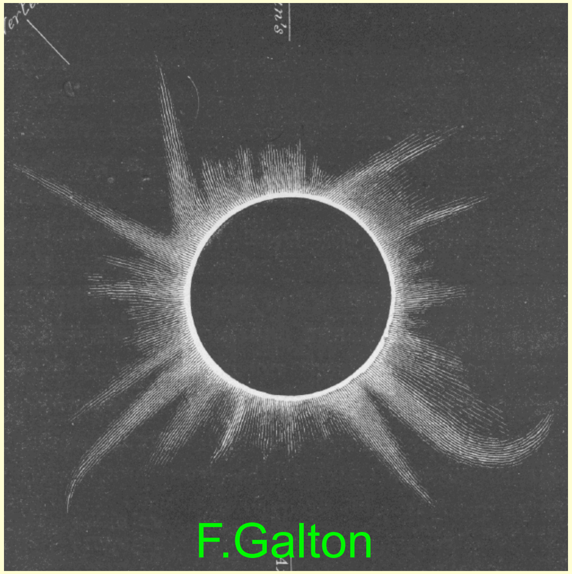
F. A. Oom



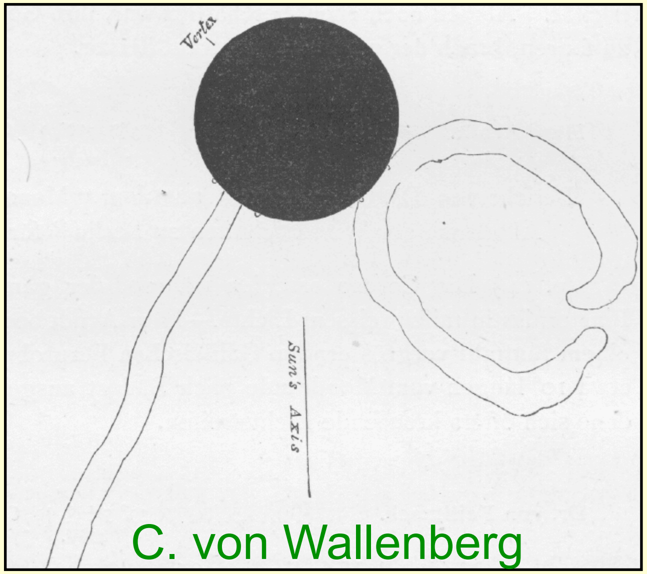
von Feilitzsch



E.W. Murray



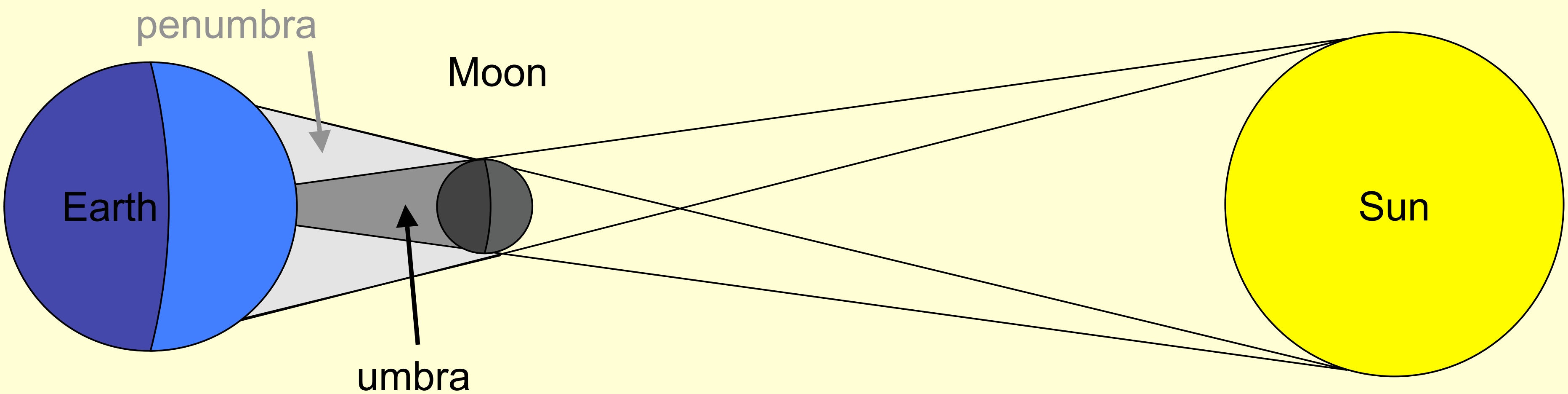
F.Galton



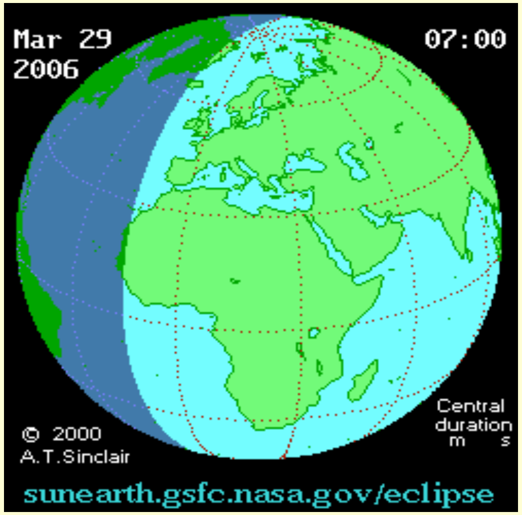
C. von Wallenberg

from: C.A. Ranyard (1879), Mem. Roy. Astron. Soc. 41, 520, Kap. 44.

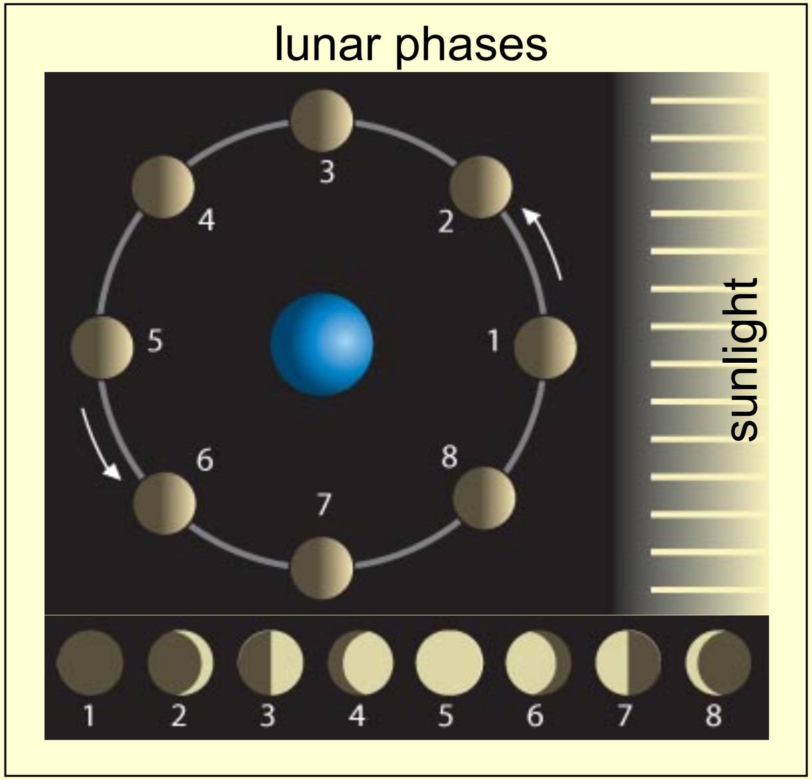
Solar eclipse



A solar eclipse always happens at new moon !

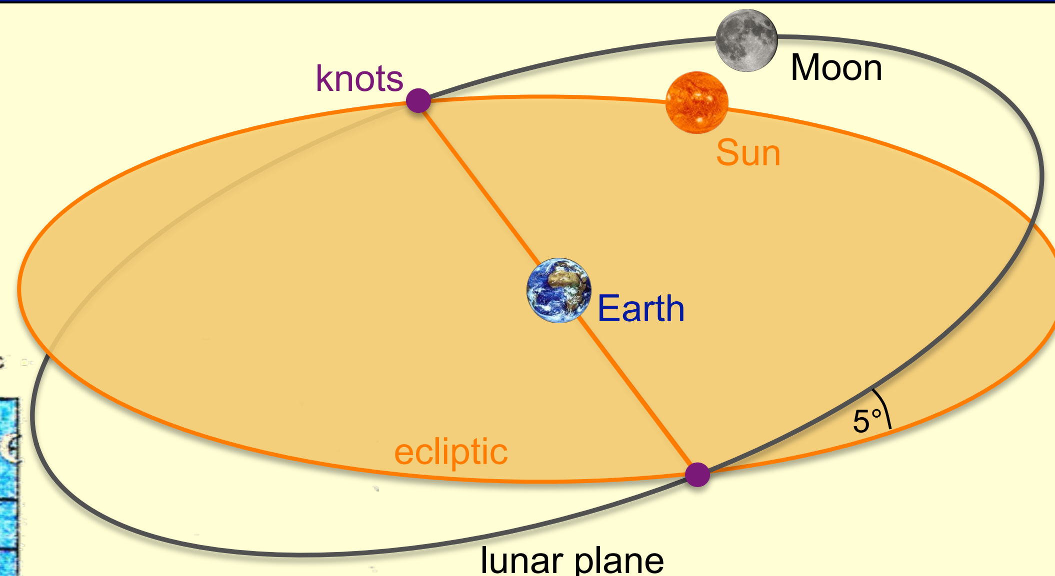


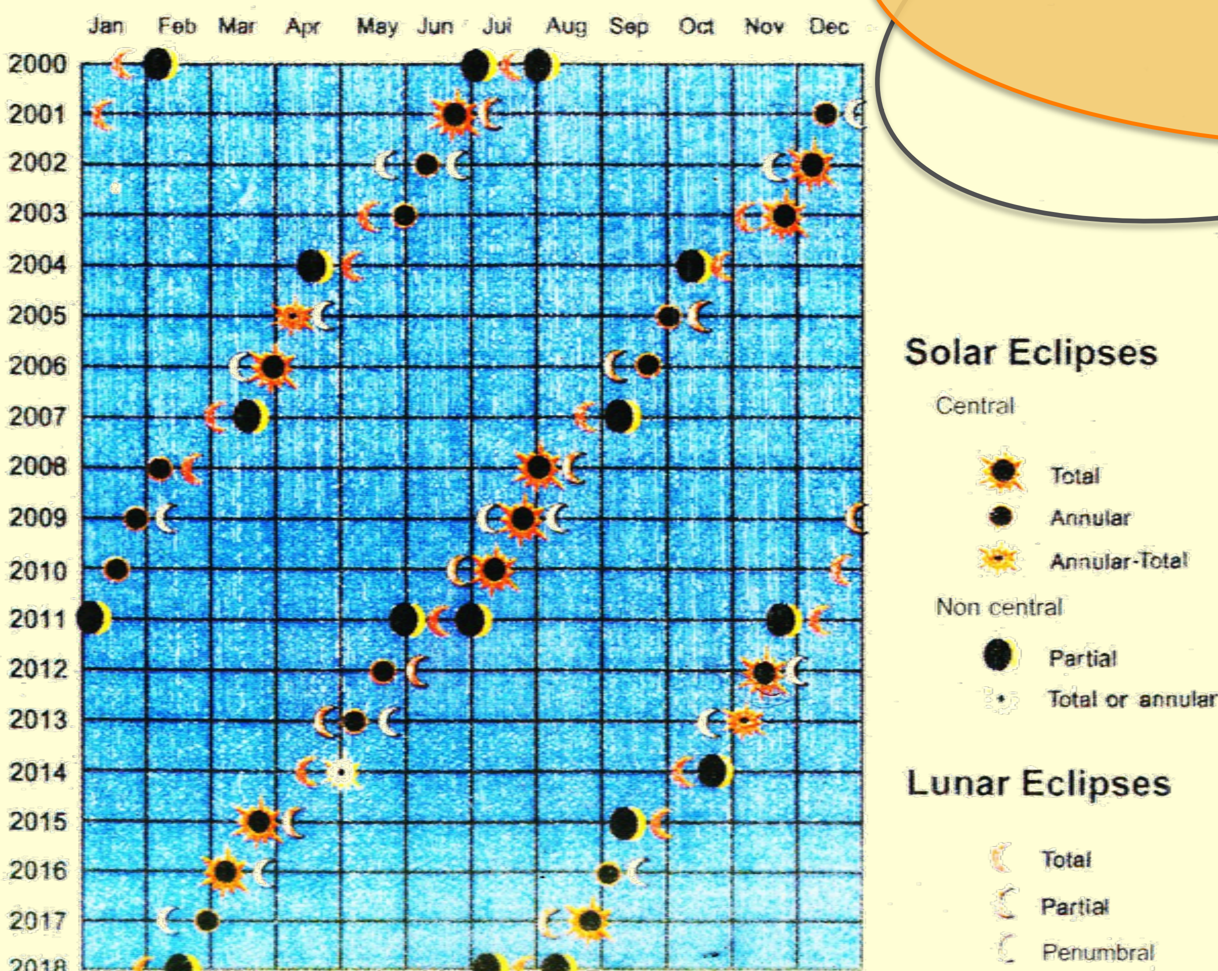
umbra and penumbra on Earth surface during 2006 eclipse



Predicting eclipses / eclipse tables

- ► there are up to 5 eclipses per year (lunar or solar)
- ► pattern in month vs. year diagram
  → phenomenological prediction





Sun:
knot → knot: 173 d

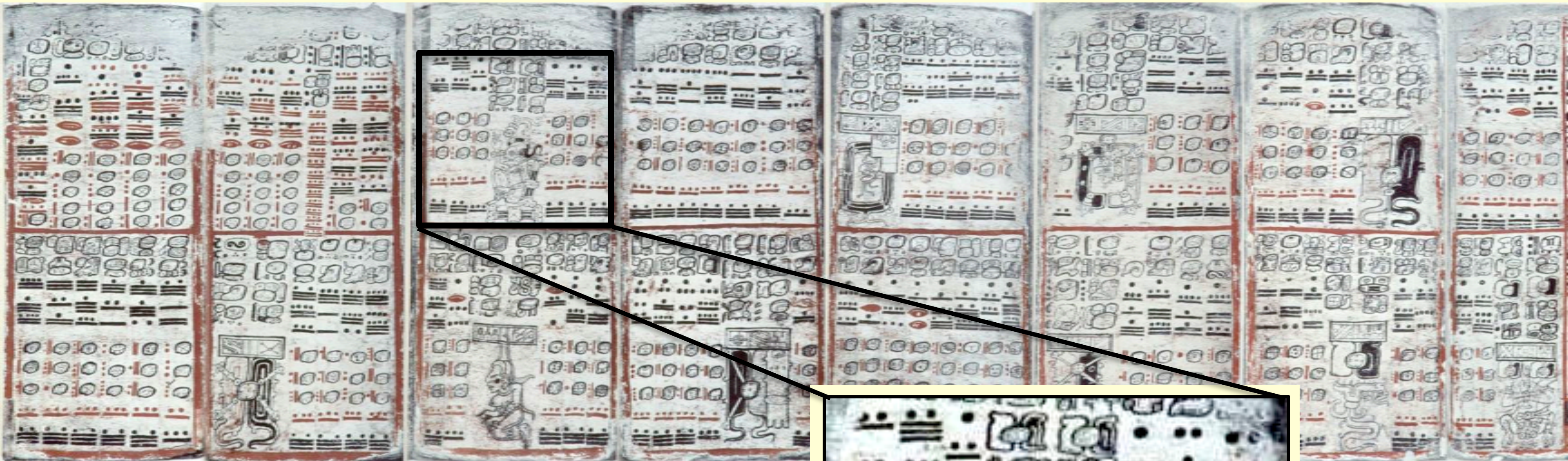
Moon:
6 lunations: 177 d

(< ½ year)

→ 2 – 3 eclipse seasons per year

Eclipse tables in Mayan Codex

Dresden Codex: one of four Mayan hieroglyphic books, showing eclipse tables on 8 pages



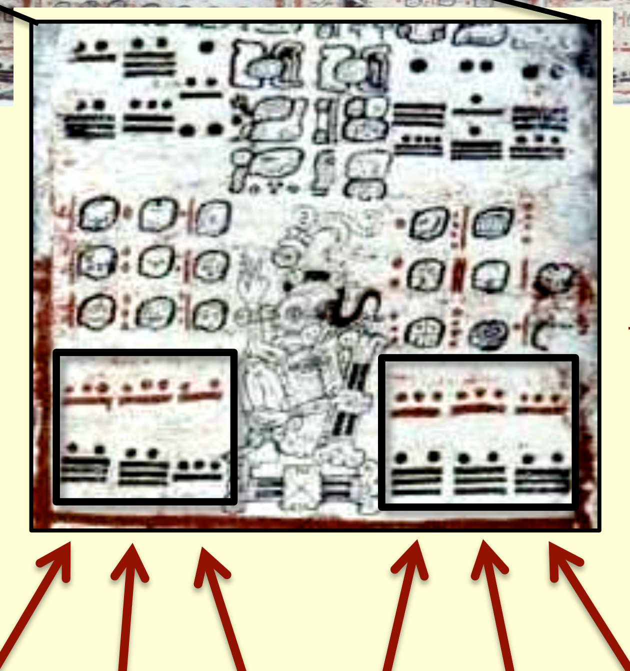
minimum time between eclipses:

time Sun needs from knot to knot = 173 d

time between 6 lunations: 177 d
(5 lunations: 148 d)

→ after 177 d next possible eclipse

→ this (and much else) seems to be noted in Codex



• = 1

— = 5

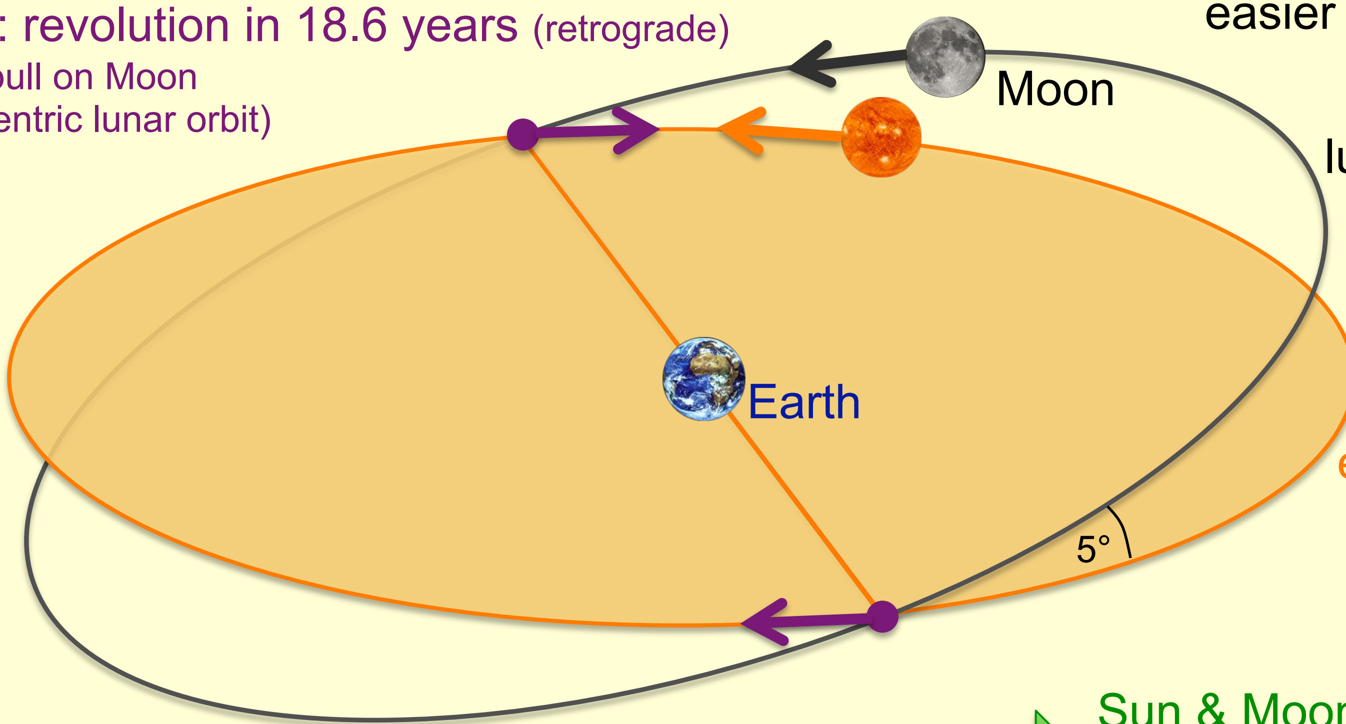
numbers written vertically in powers of 20

(3+5)*20 + (2+3*5)*1 = 177 177 148 177 177 177

more precisely…

knots: revolution in 18.6 years (retrograde)
(grav. pull on Moon
on eccentric lunar orbit)

easier in geocentric view…



sidereal year:	365.2425 d		
nodical year:	346.6 d	x 19	= 6585.8 d
synodical month:	29.53 d	x 223	= 6585.3 d
nodical month:	27.21 d	x 242	= 6585.4 d
anomalistic month:	27.55 d	x 239	= 6585.5 d

Sun & Moon in knot, full moon:
(total) eclipse !!

1/3 d: visiblity on Earth
shifted by 120° longitude

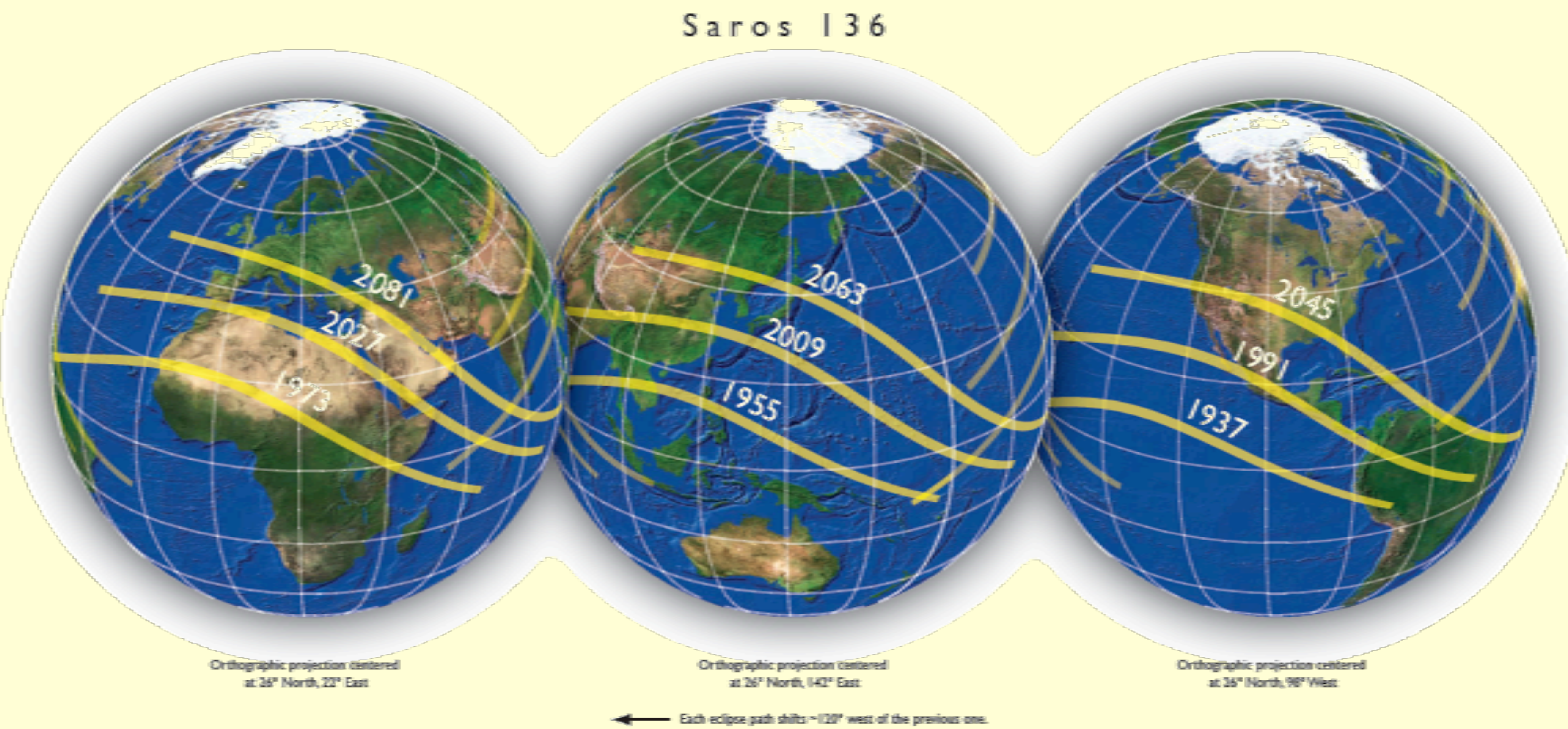
Δt≈0.4 d: small drift from knot
shift in latitude !

same distance Earth – Moon:
→ same type/length of eclipse

Saros cycle

- ► two eclipses of the same “Saros” about 18 years apart
- ► of same type / length
- ► seen 120° separated in longitude
- ► slow migration towards North / South

→ **one Saros cycle lasts 1244 – 1514 years**

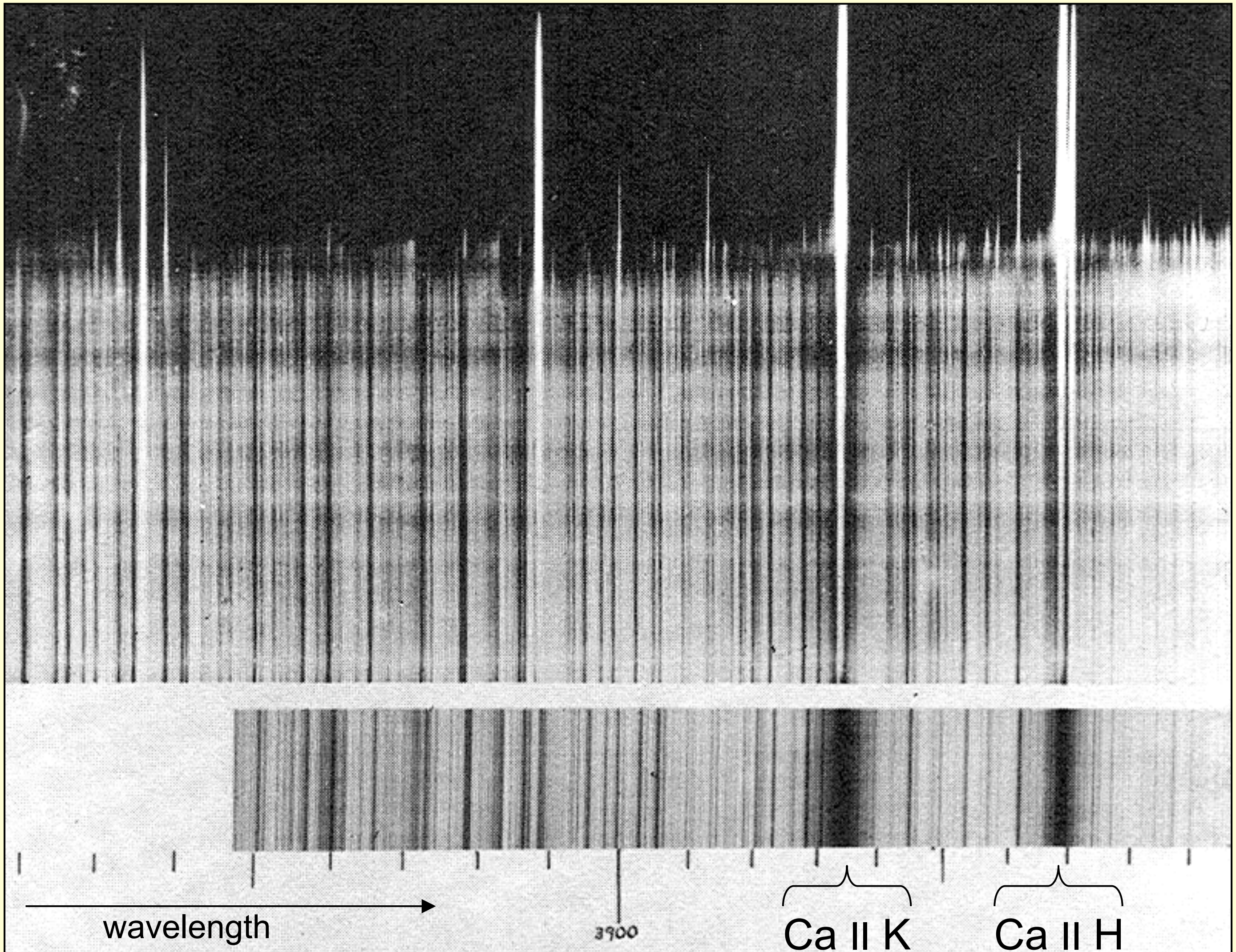


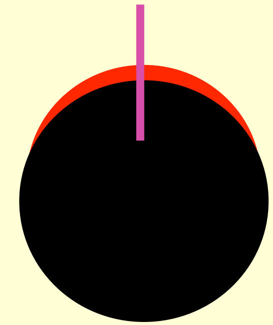
Michael Zeiler / Xavier Jubier / Fred Espenak

Emission line spectrum of the chromosphere

- slit perpendicular to limb
- take spectrum just when moon covers photosphere but NOT chromosphere

  ➡ only a short instance ➡ ***flash spectrum***

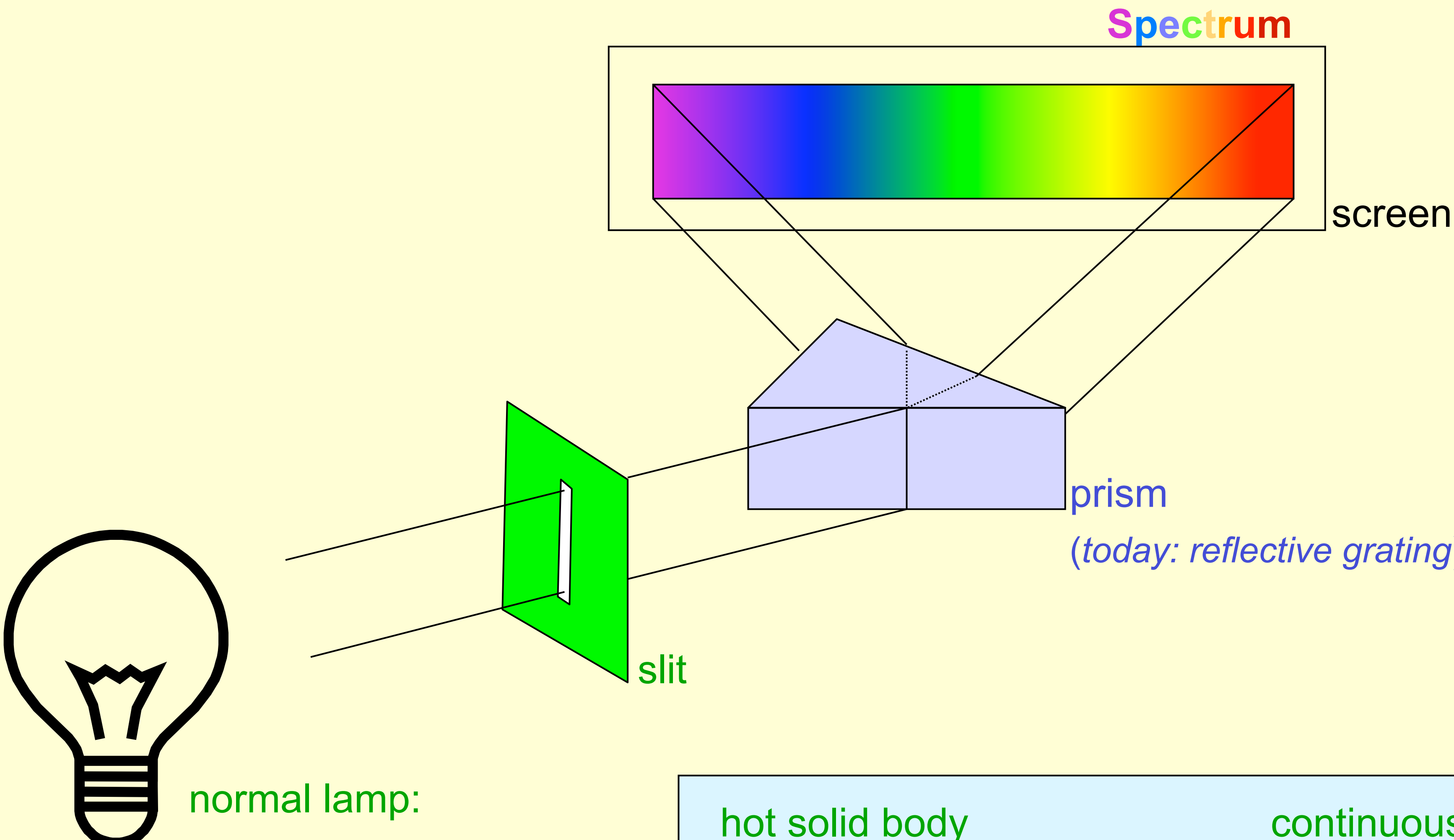




chromosphere:
flash spectrum

"normal" photospheric spectrum with absorption lines

… astrophysics … — spectroscopy



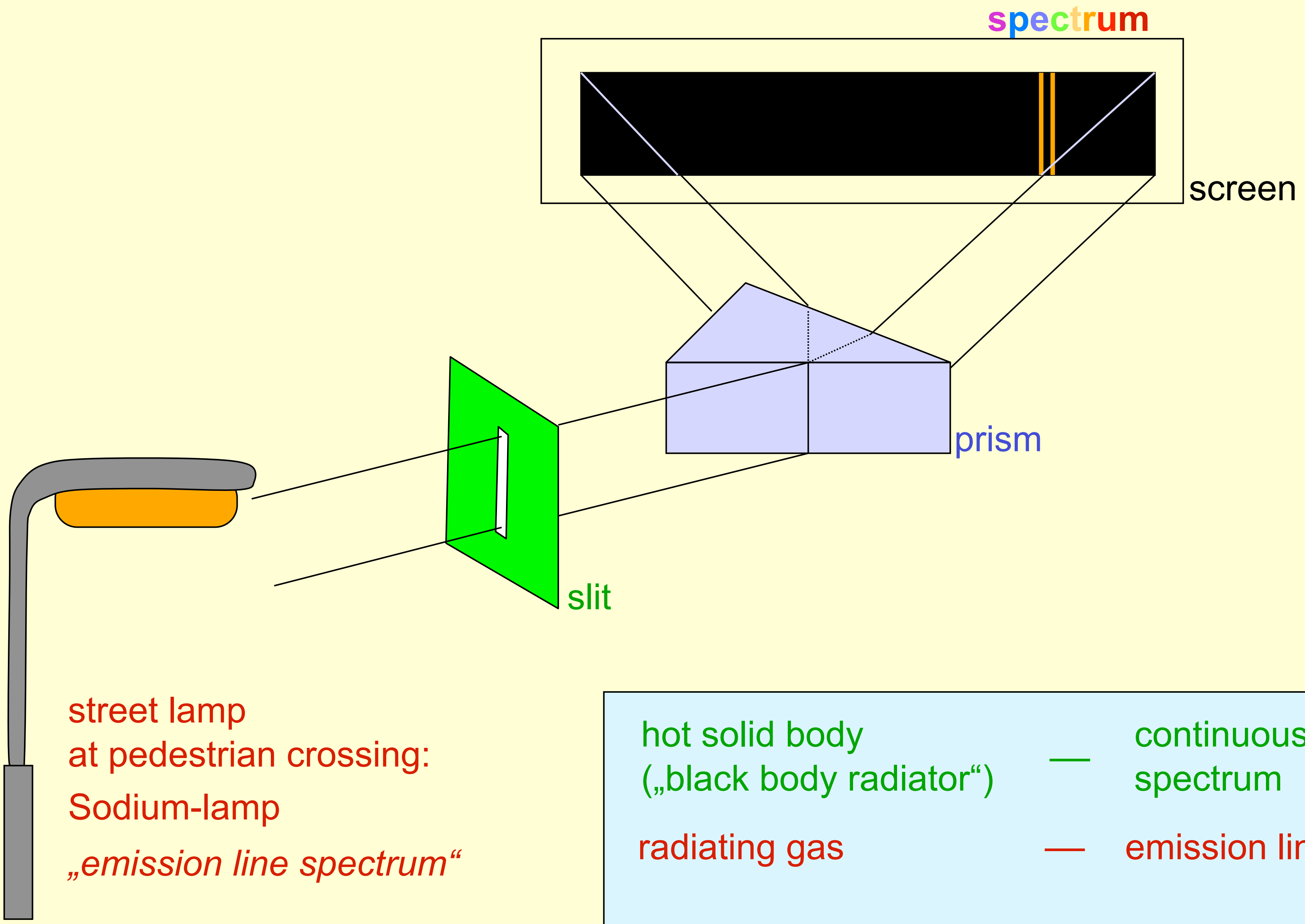
normal lamp:

solid state
(Wolfram-spiral)

black body continuum

hot solid body („black body radiator“) — continuous spectrum

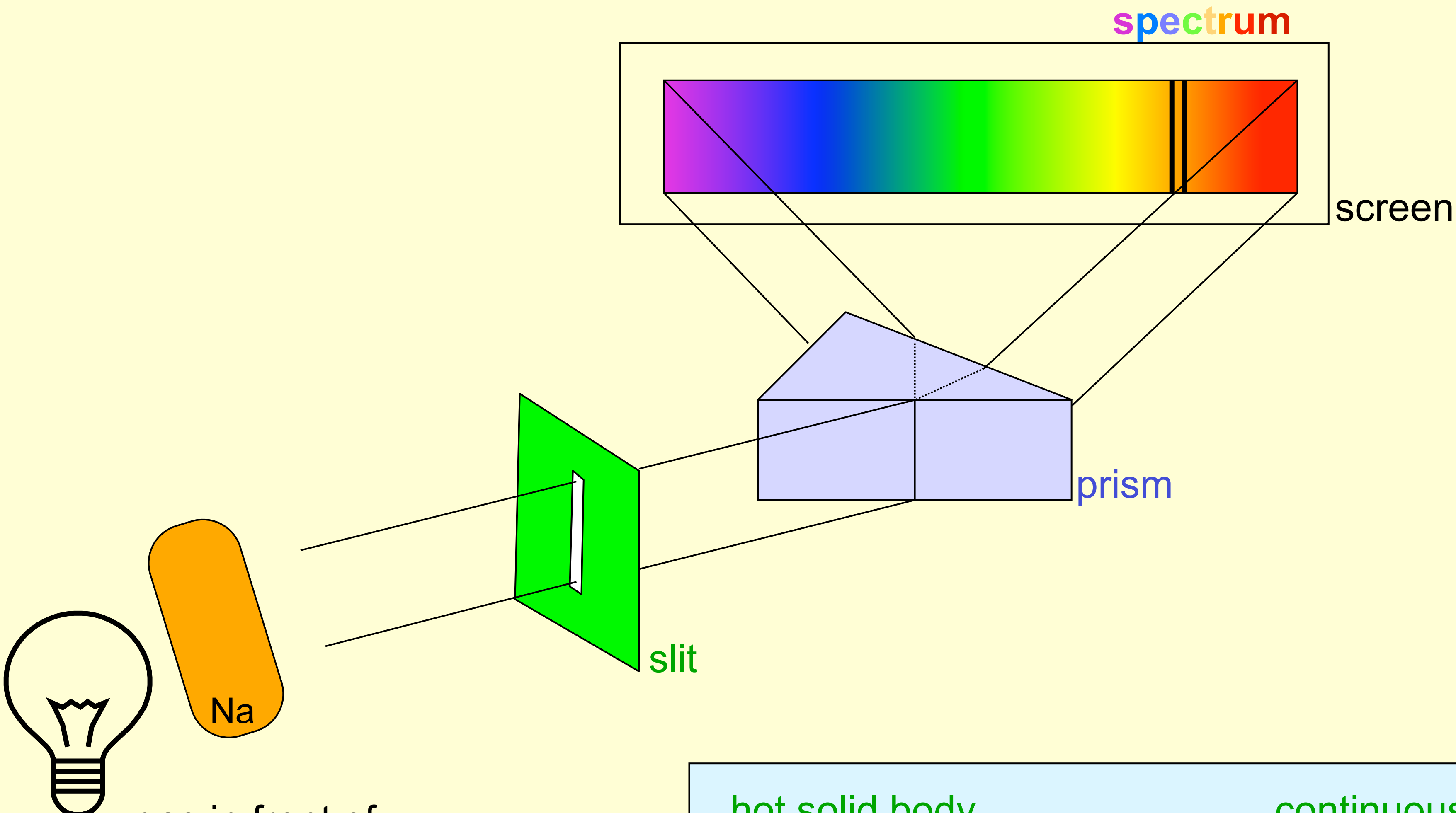
… astrophysics … — spectroscopy



street lamp
at pedestrian crossing:
Sodium-lamp
„emission line spectrum“

hot solid body („black body radiator“)	—	continuous spectrum
radiating gas	—	emission lines

… astrophysics … — spectroscopy

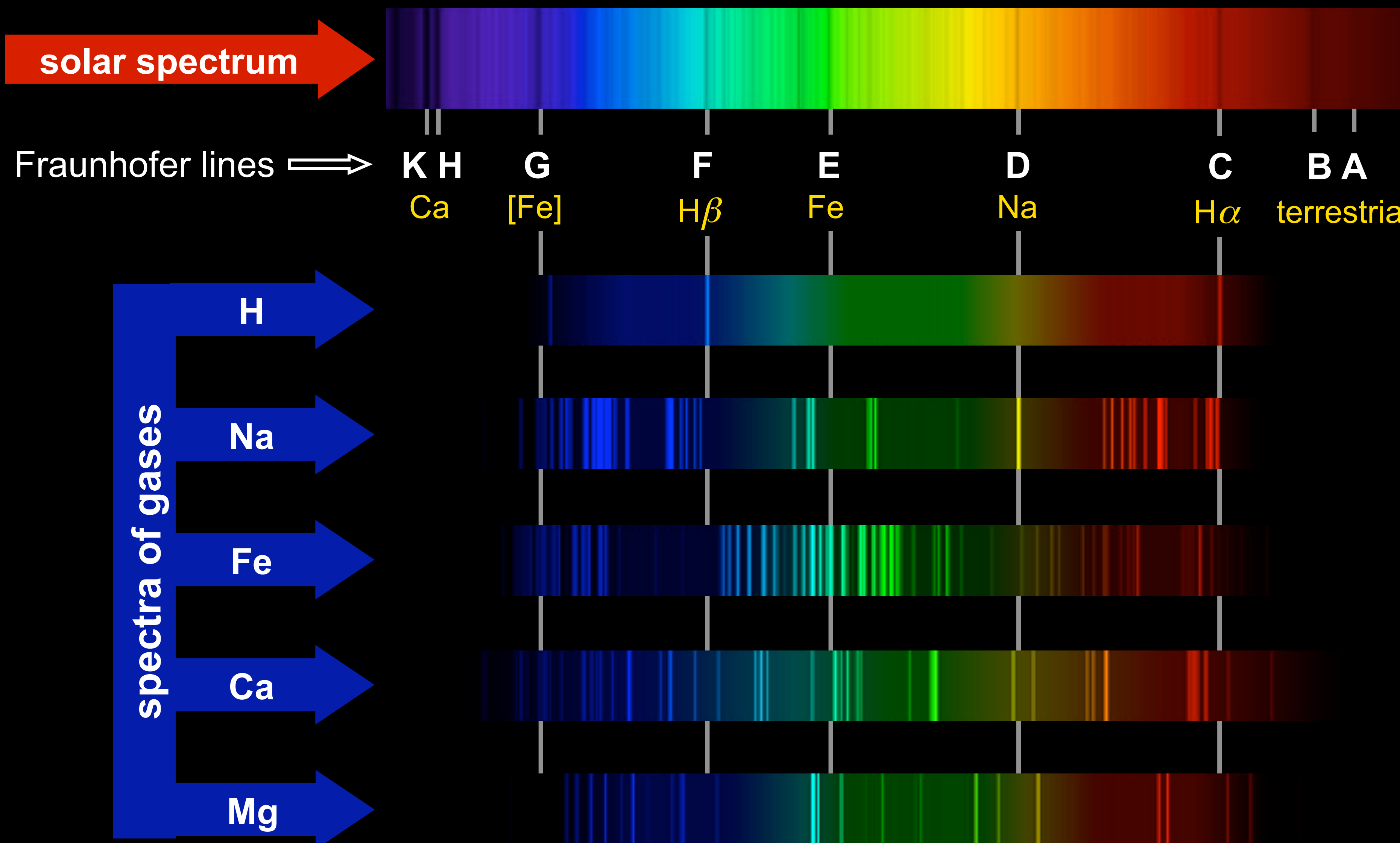


gas in front of
continuous radiator

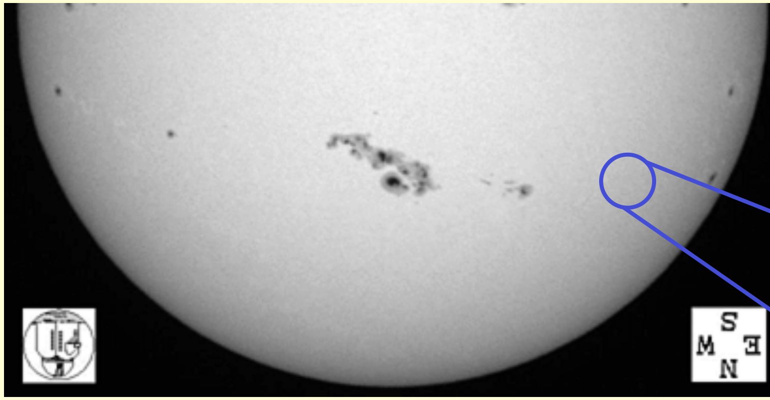
„absorption lines"

hot solid body („black body radiator")	—	continuous spectrum
radiating gas	—	emission lines
gas absorbing radiation	—	absorption lines

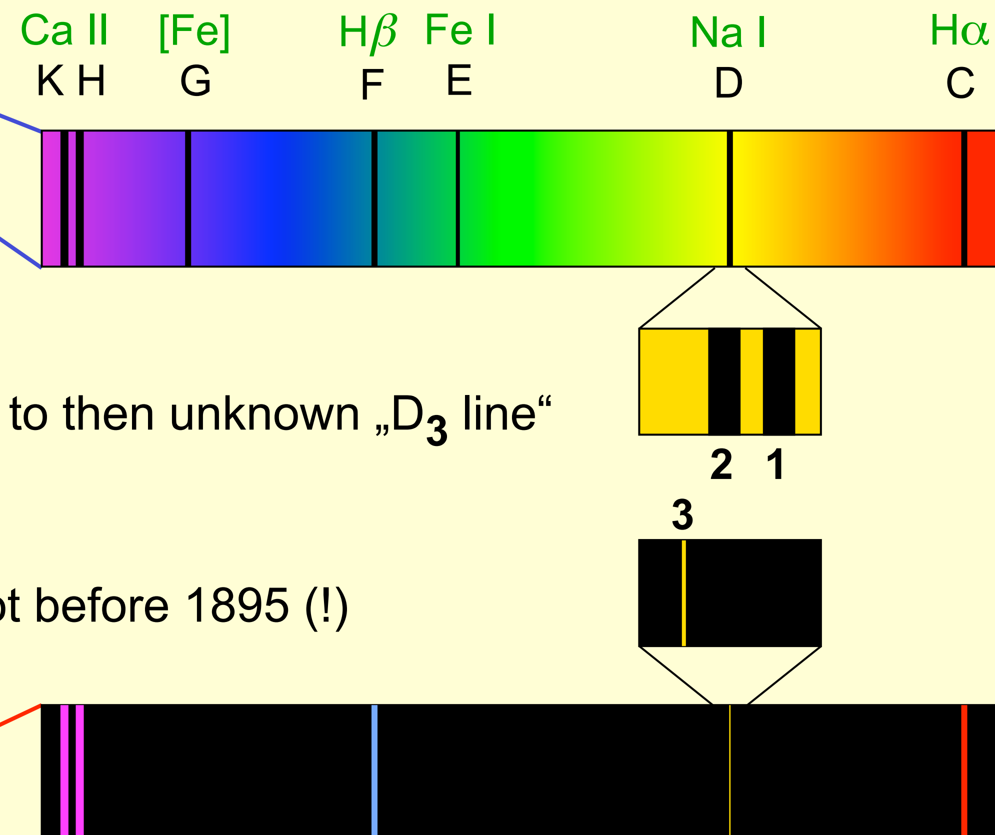
Fingerprints of the elements



A new element: *Helium*



absorption lines in the photosphere



solar eclipse 1868:
Janssen and Lockyer identify the up to then unknown „D_3 line"

→ *new element*: ***Helium***

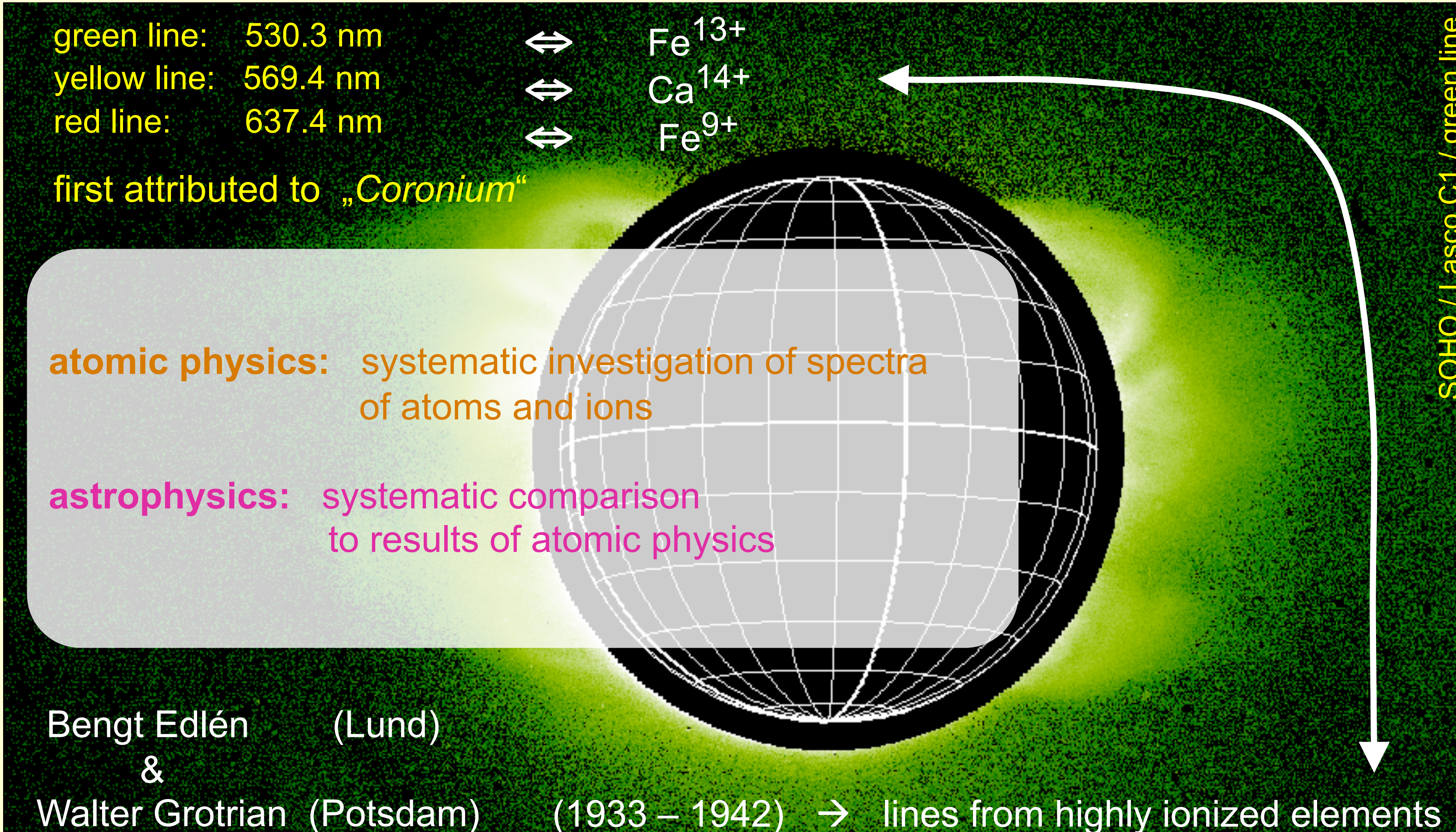
discovered in Earth's atmosphere not before 1895 (!)

emission line spectrum of the chromosphere during a solar eclipse

Even more new elements ?

emission lines in planetary nebula ➡ Nebulium ?? …

more than 100 „corona lines“ identified in the visible:
The strongest ones:



green line: 530.3 nm ⇔ Fe^{13+}
yellow line: 569.4 nm ⇔ Ca^{14+}
red line: 637.4 nm ⇔ Fe^{9+}

first attributed to „*Coronium*“

atomic physics: systematic investigation of spectra of atoms and ions

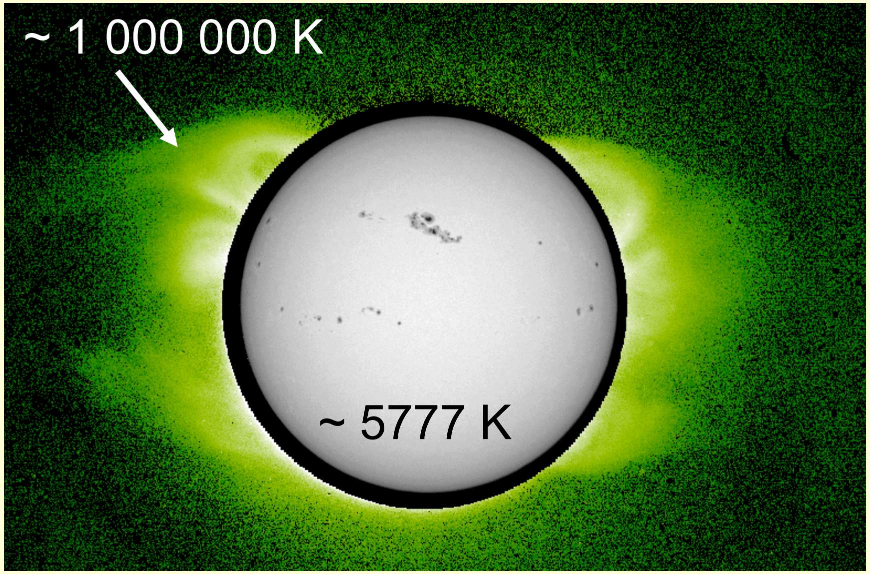
astrophysics: systematic comparison to results of atomic physics

Bengt Edlén (Lund)
&
Walter Grotrian (Potsdam) (1933 – 1942) → lines from highly ionized elements

The corona is hot !!!

temperature of the corona:

– ca 10^6 K
– more than 100 x hotter than surface



energy required to heat corona:

flux ~ 100 W/m² at photosphere

➡ no problem!
(less than 10^{-6} of luminosity)

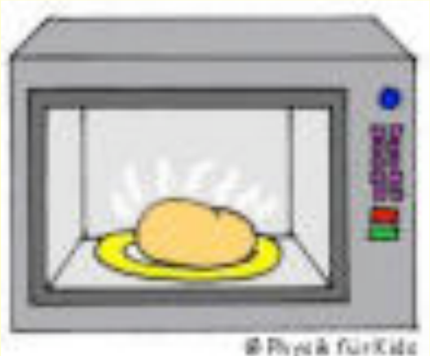
Problem:

How does a cold body (surface)
heats a warmer body ?? (corona)

contradiction to laws of thermodynamics?

➡ energy transport e.g. through waves

e.g. microwave oven



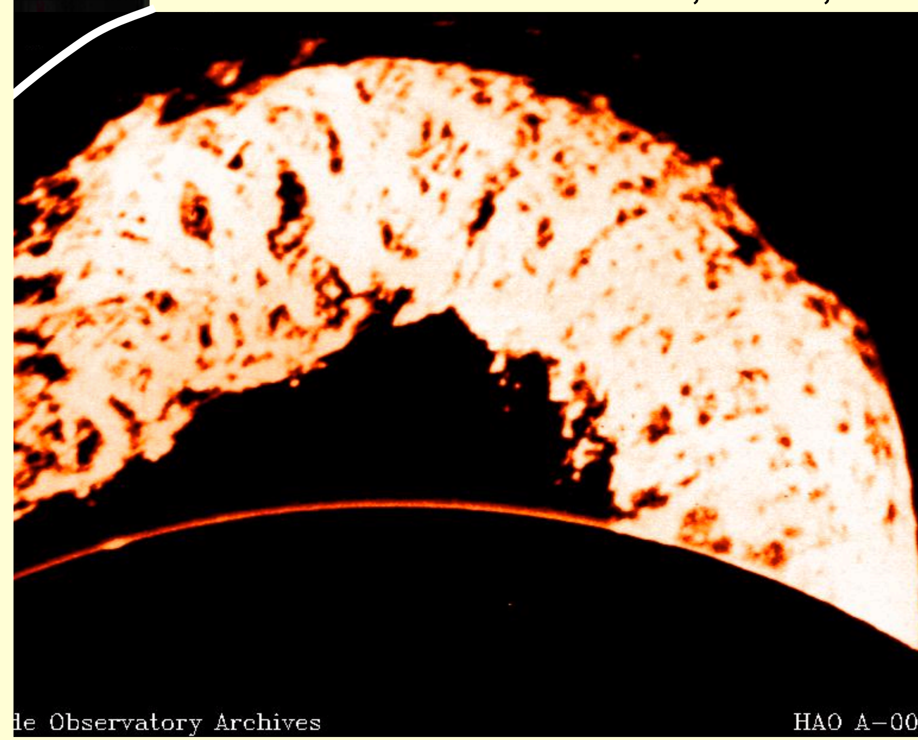
in the solar corona:

magnetic field is the "energy agent"
➡ magneto-acoustic waves
➡ induced currents

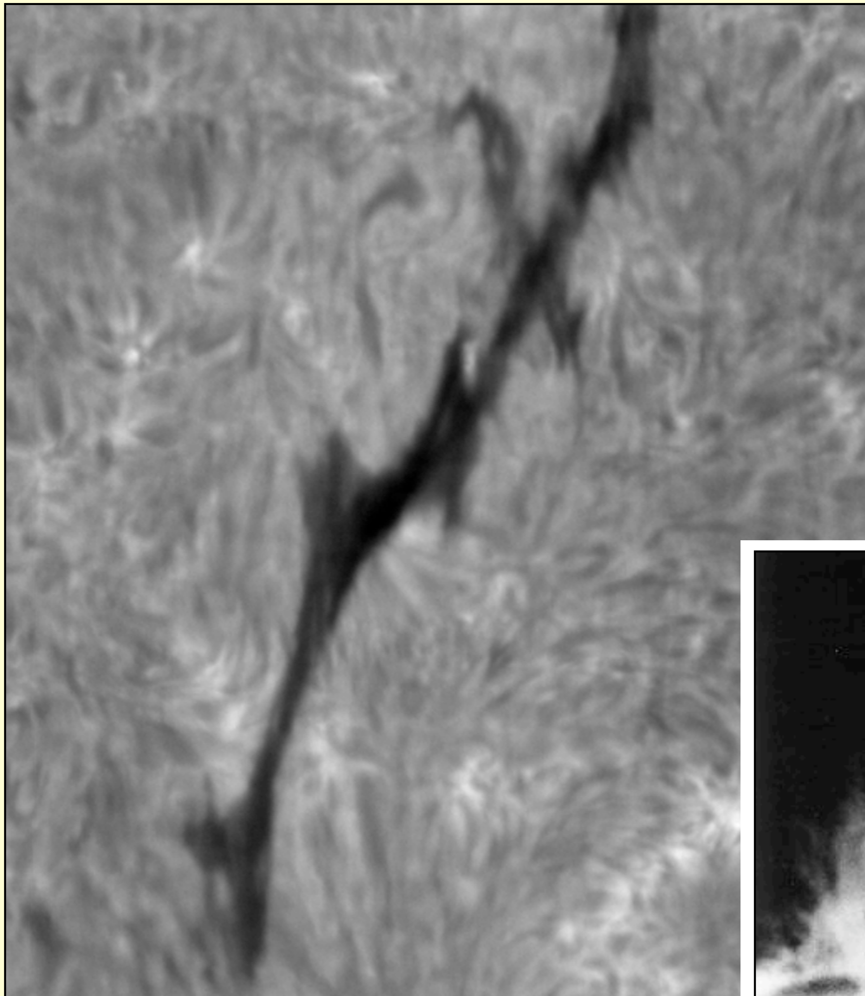
Prominences: cool structures in the hot corona

Prominence observed on Skylab, 1973, He II (304 Å)

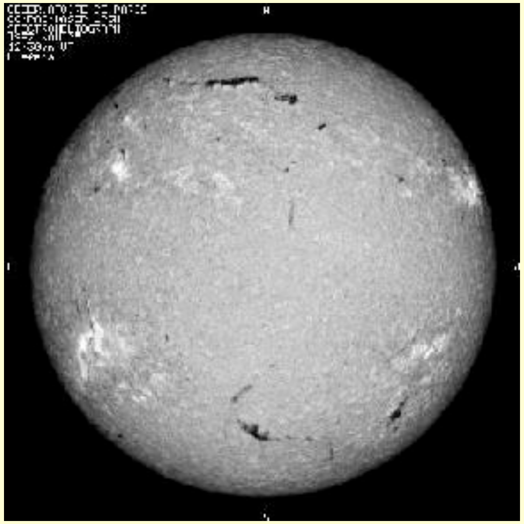
Grande Daddy prominence
4. June 1946, HAO, Hα



Prominences and filaments



on the disk:
filament.
absorption of
light from the
photosphere



full Sun in Hα
(Meudon)

above the limb: prominence.
„grande curtain“

Prominences through spectroscopy outside eclipses

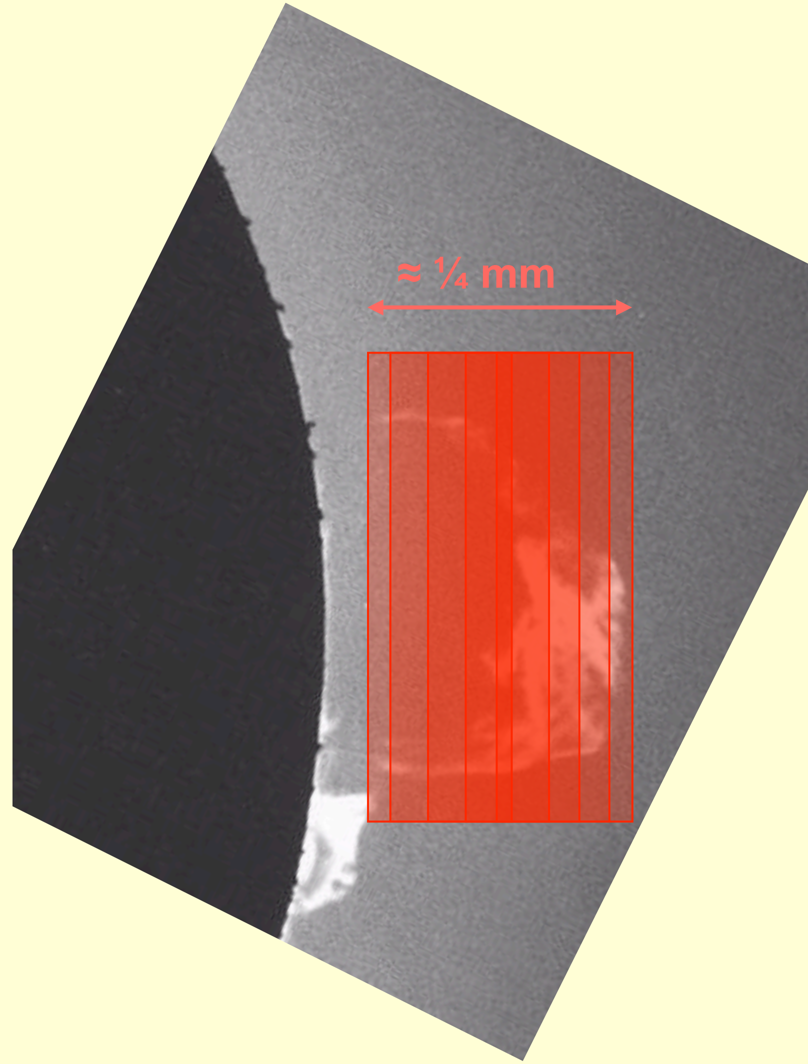
1860s observations:

– use prime focus of single lens (stray light)

– f ¼ 2 m ➡ diameter of solar image: ~20 mm

procedure to observe above the limb
(following Secchi/Schellen, 1872)

1. place slit parallel to limb
2. now slowly increase width of slit
   up to ¼ to ½ mm
3. take care that the slit
   "is not touching the disk"



this works only for strong isolated lines
e.g. Hα ("slitless spectrograph")

today: narrow band filtergraphs:

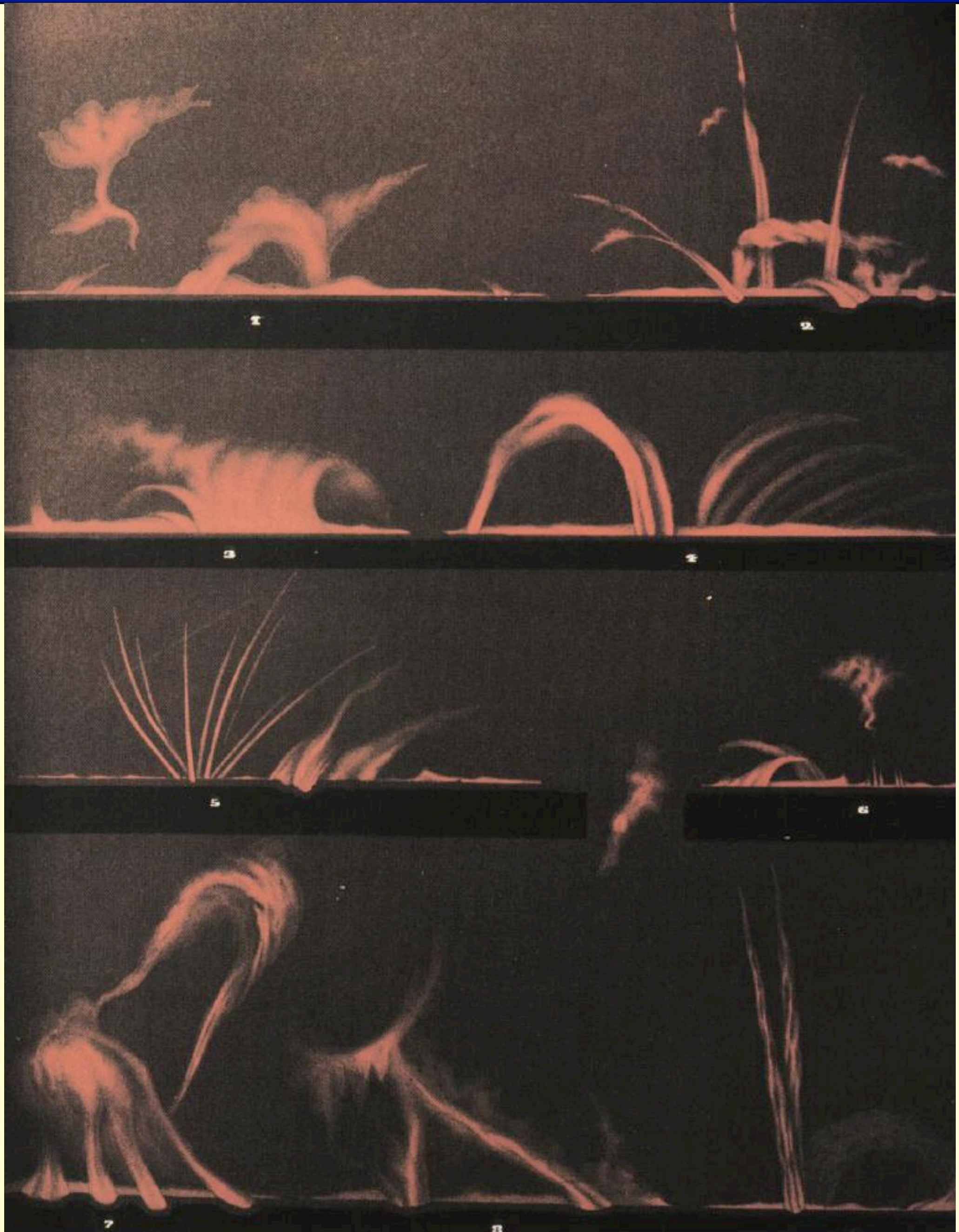
– visible: Lyot filter, Fabry-Perot and Michelson interferometers
– VUV: FPI (?)
– EUV-X-ray: foils, multi-layer coating

Drawings of structures above the limb

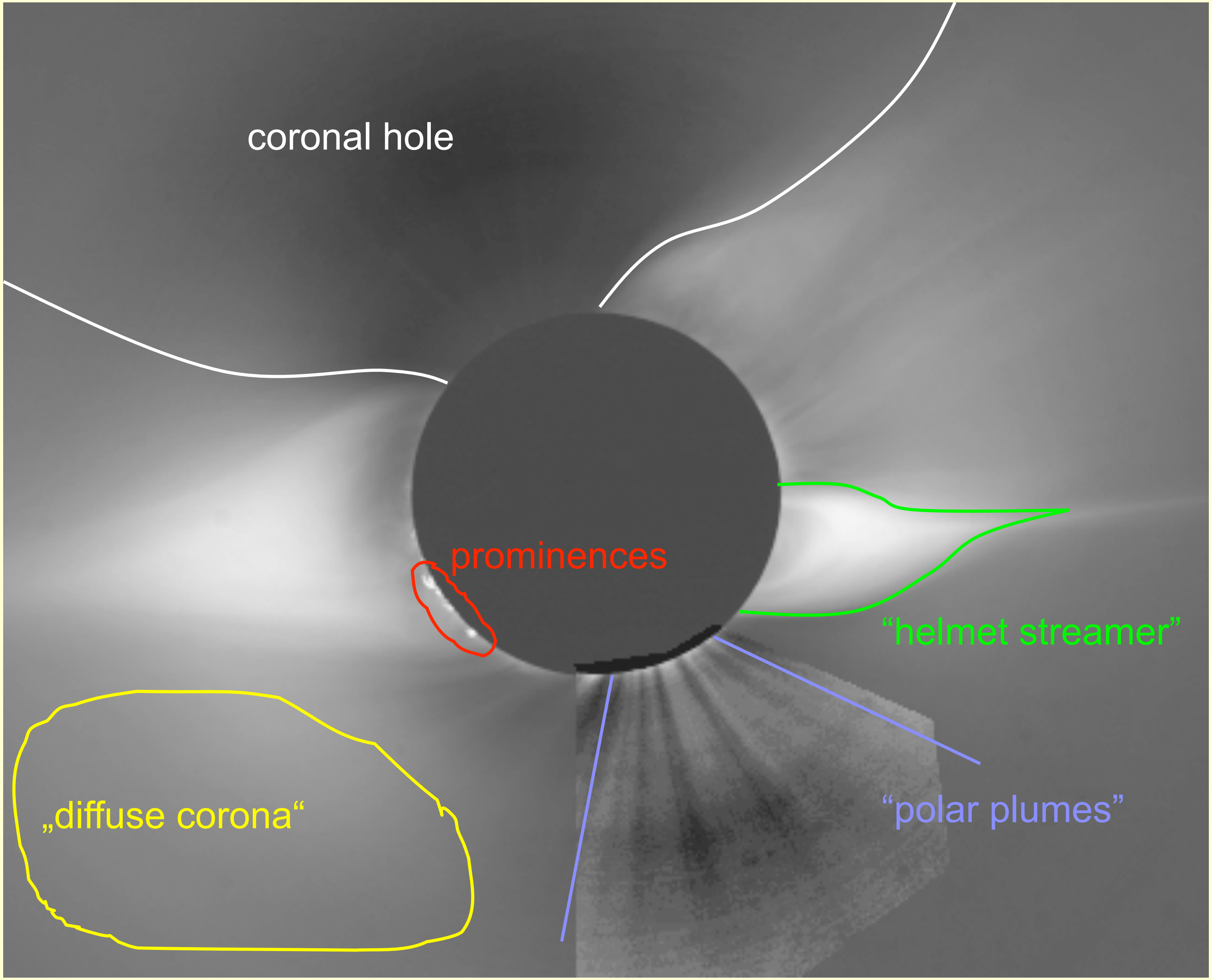
using spectroscopic methods outside eclipses

by **Etienne Trouvelot (1827-95)**

➡ he was one of the most skilled scientific artists of the pre-photographic era



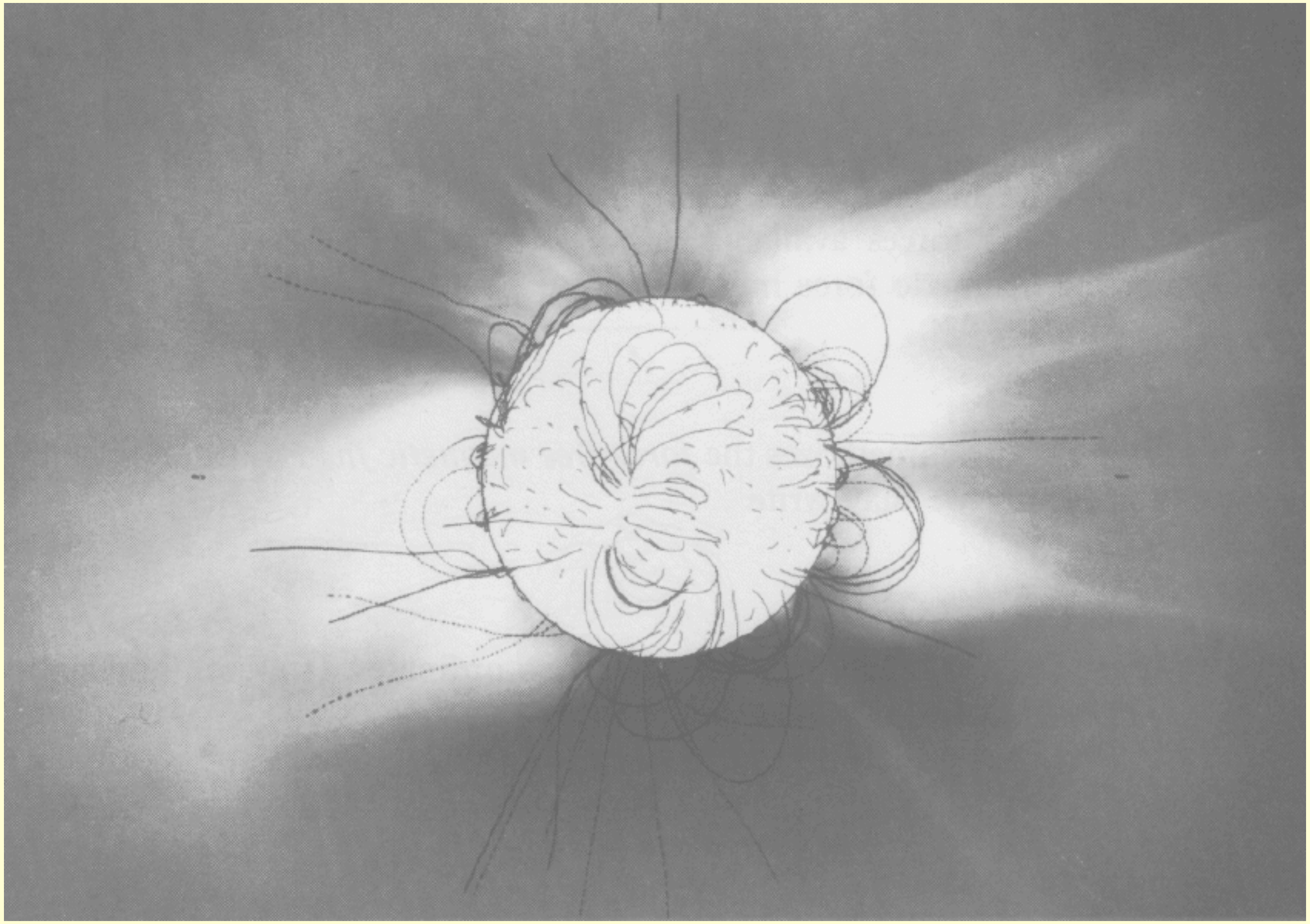
Structures in the corona: minimum of solar activity



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

The magnetic field structuring the corona

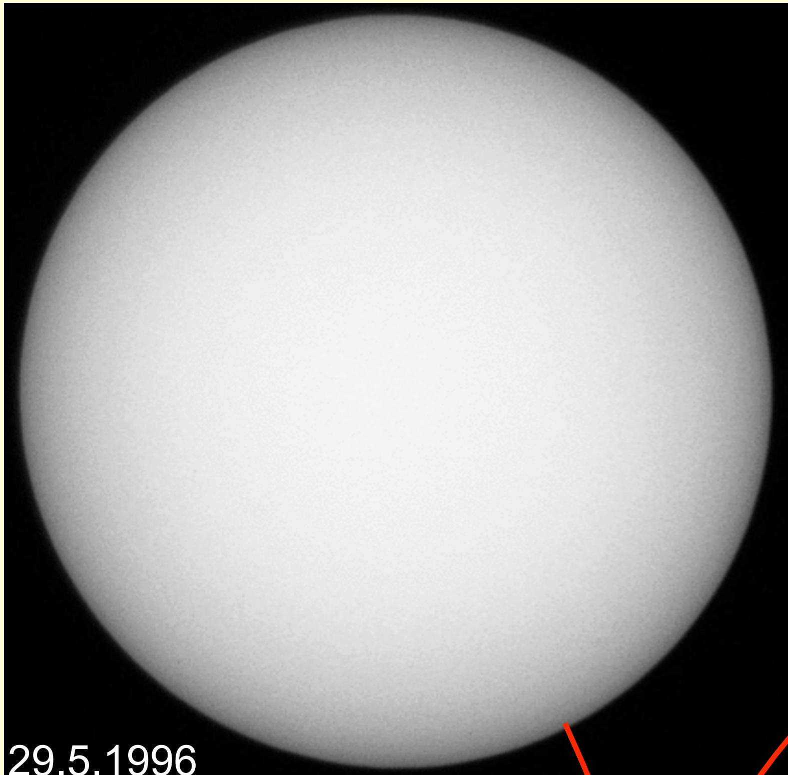
1. magnetic field map of the photosphere ("solar surface") → Zeeman effect
2. potential field extrapolation (or better)
3. compare to structures in the corona

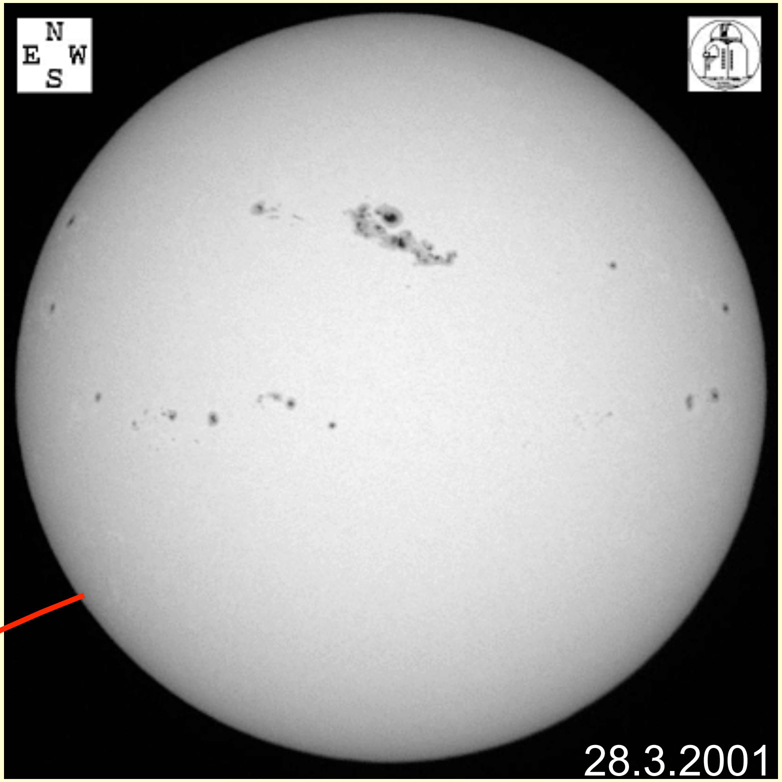


solar eclipse, 30.June 1973, photograph by Serge Koutchmy
potential field extrapolation: Altschuler at al. (1977) Solar Physics 51, 345

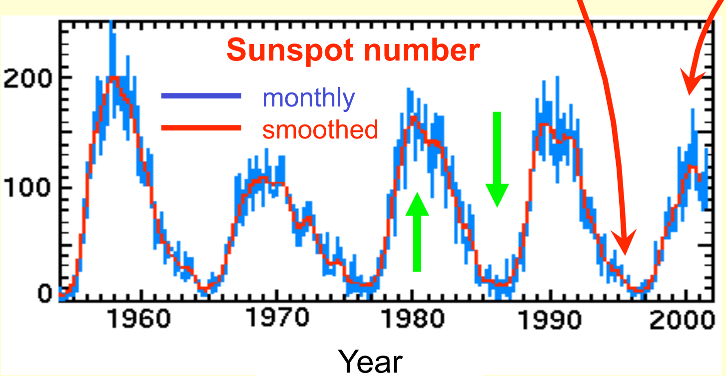
The activity cycle of the Sun

minimum — the Sun in white light — **maximum**





Big Bear Solar Observatory



11 year cycle of the Sun:

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

basic mechanism:

⇨ dynamo generating magnetic field

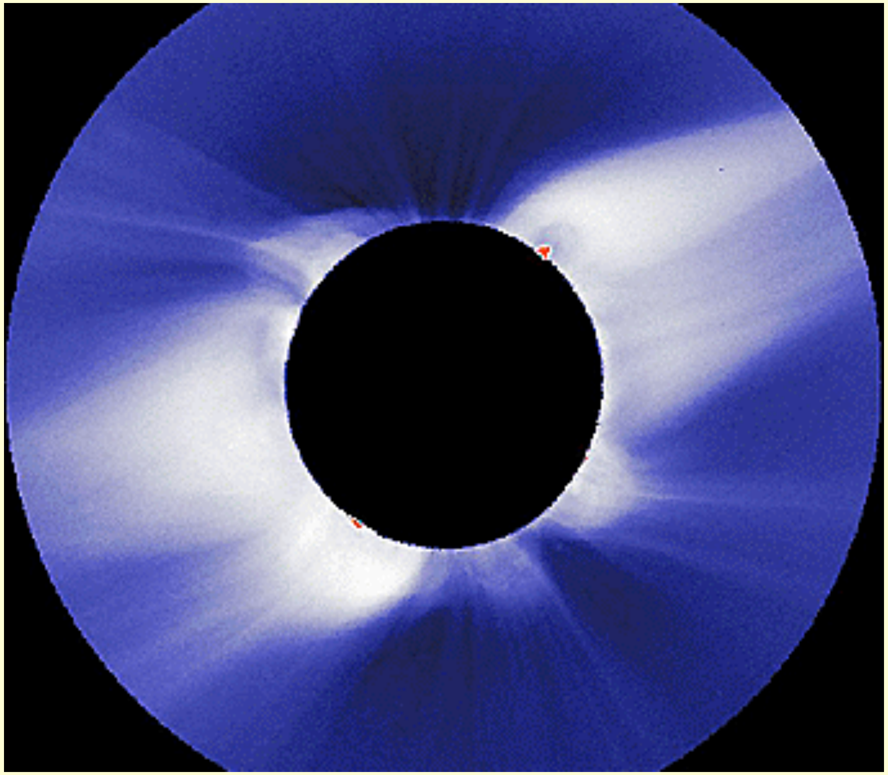
The corona: maximum vs. minimum

Minimum

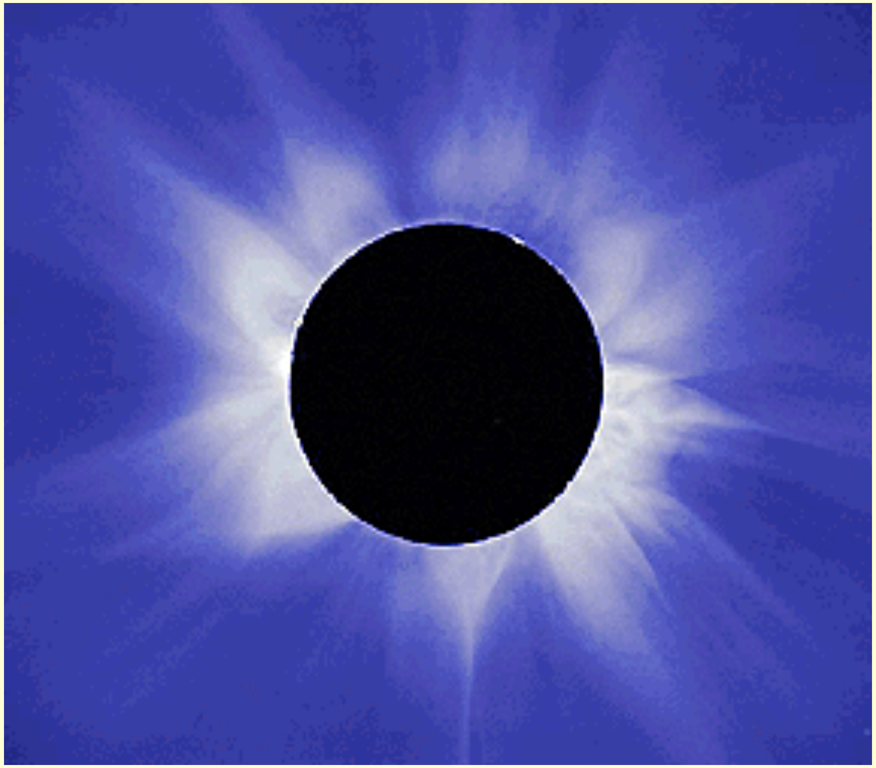
- "simple" dipolar structure
- few active regions (sunspots)
- prominent coronal holes
- "helmet streamer" only at equator

Maximum

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



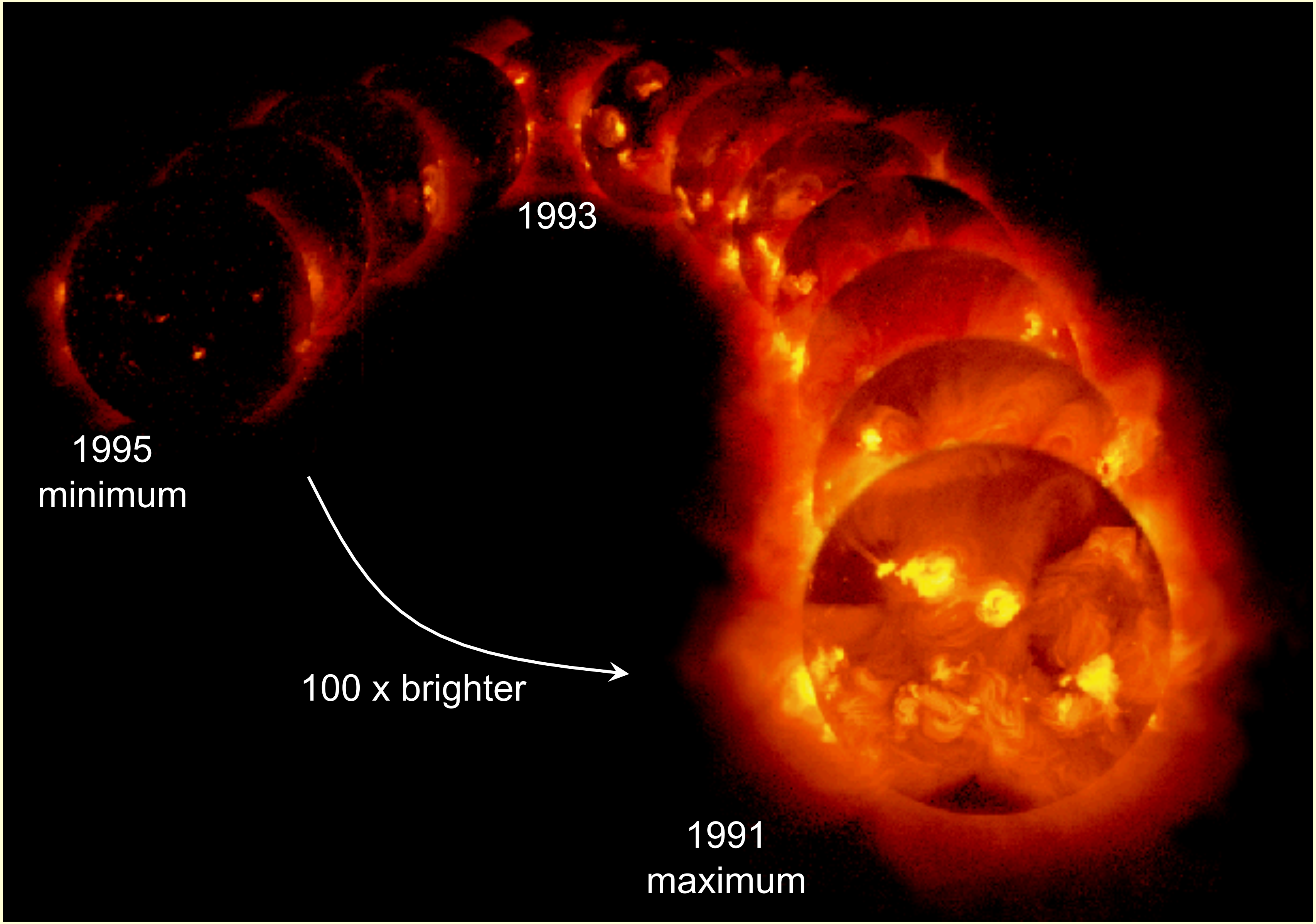
18. 3. 1988, Philippines



16. 2. 1980, India

High Altitude Observatory - NCAR

The X-ray corona in the solar cycle



Yohkoh Soft X-ray Telescope (SXT), X-ray emission at about 1 nm

The corona outside eclipses: Lyot's coronagraph

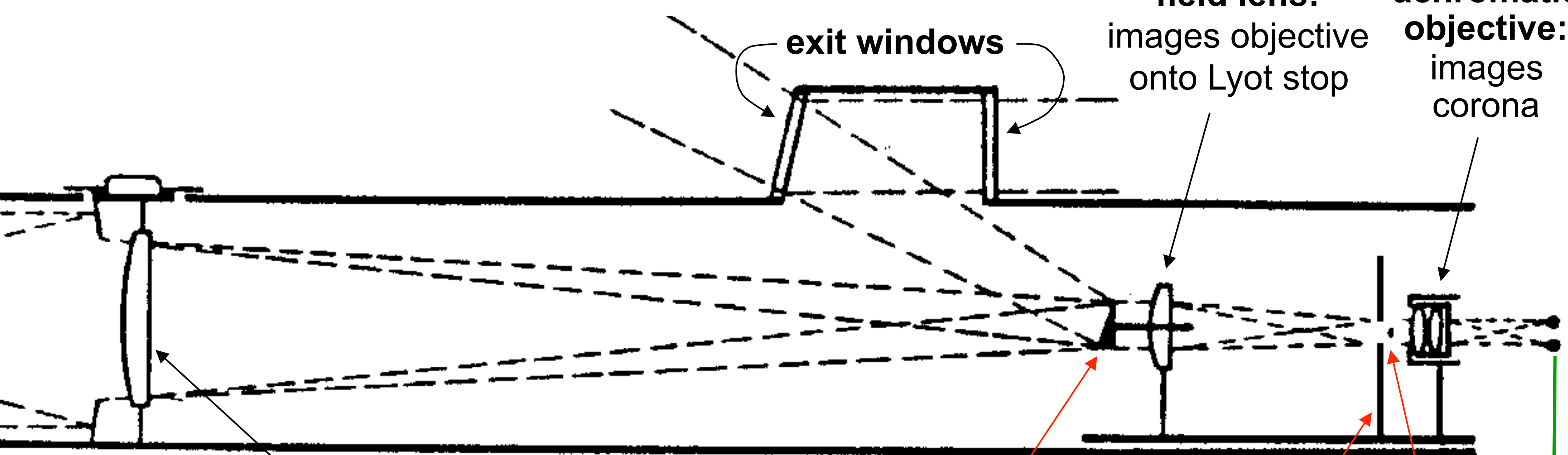
essentials of the coronagraph: get stray light down to < $10^{-7} – 10^{-8}$!!

occulting surface: light from solar disk reflected out of window

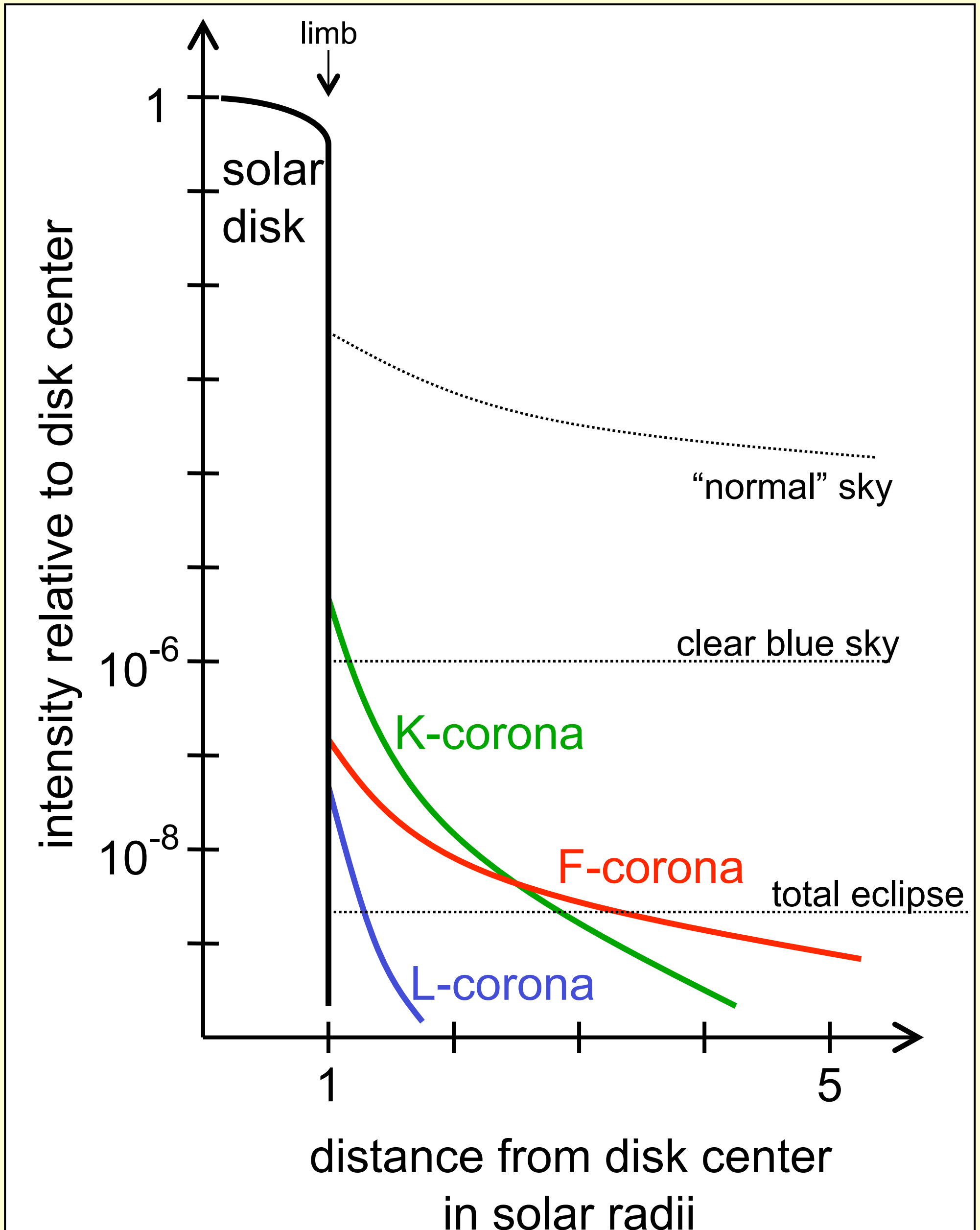
Lyot stop: blocks light diffracted at entrance pupil / edges of objective

Lyot dot: stops light from secondary reflections within objective

Lyot (1932), Z. Astrophys. 5, 73



What is seen during an eclipse?



- **(K) continuum corona**
  - no absorption lines
  - polarised: free electron scattering
- **Fraunhofer corona**
  - absorption lines visible
  - not polarized: dusk scattering
  - Zodiac light…
- **Line corona**
  - emission lines: e.g.: "green coronal line"
  - *emission of atoms / ions:* new elements? helium, coronium

The Zodiac light

The corona is hot!

- **intensity scale height:** $0.1\ R_\odot$ (around 1900; Schwarzschild 1906 Astron. Mitt. d. Sternwarte Göttingen 13, 63)

$$H = \frac{k_B T}{mg} \quad \Longrightarrow \quad T_{corona} \approx 1.2 \cdot 10^6\ \mathrm{K}$$

- **K-corona: free electron scattering:**
  thermal speed of electrons: $v_{th}^2 = 3\,\frac{k_B T}{m}$

  most narrow spectral features: 6 nm (Grotrian 1931; ZA 3, 199)

  6 nm @ 500 nm ⇔ 4000 km/s ⇔ $1.2 \cdot 10^6$ K *(electron temperature)*

- **Emission lines of highly ionised species** (Edlén & Grotian 1939-42)

  green line: Fe XIV (530.3 nm)

  yellow line: Ca XV (569.4 nm)

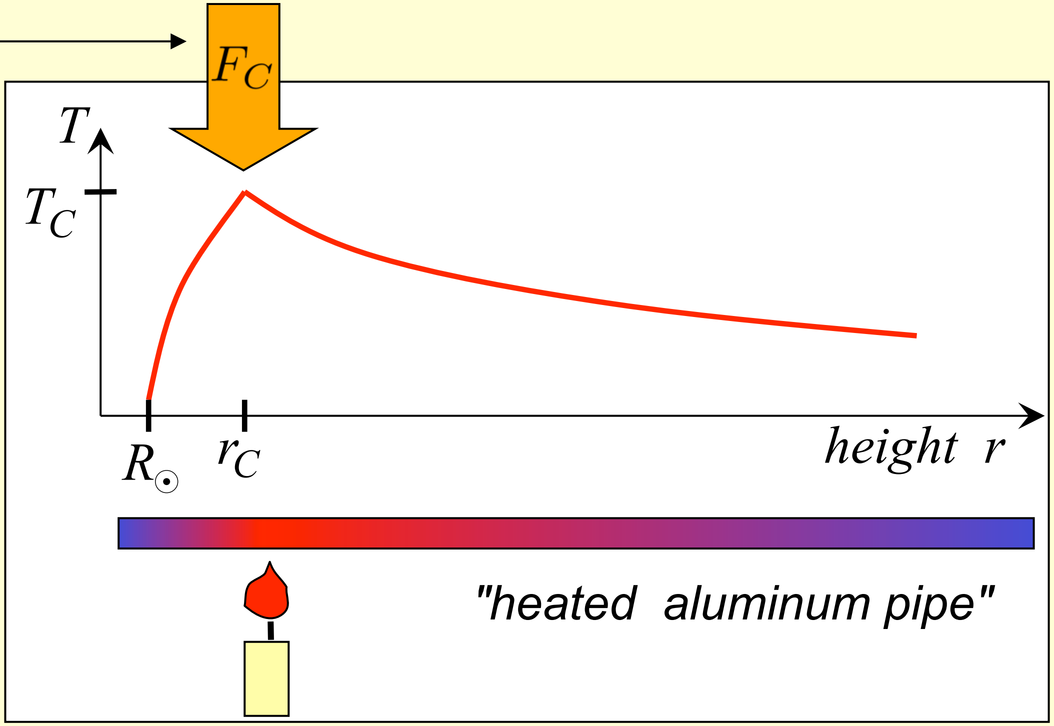
  red line: Fe X (637.4 nm) → these ions exist only at > 10^6 K

- **L-corona: line width of emission lines:** green line: 0.08 nm

  0.08 nm @ 530 nm ⇔ 45 km/s ⇔ $4 \cdot 10^6$ K *(ion temperature)*

A static heat conduction corona: temperature

heating at the “base” of the corona:



$$F_C = 4\pi\, r_C^2\, f_C = 4\pi\, R_\odot^2\, f_0$$

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

below base: $R_\odot < r < r_C$

➢ **equilibrium of heat conduction and heating:**

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

conductive heat flux: $q = -\kappa\, T^{5/2}\, \frac{\partial T}{\partial r}$

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

Integration in: $R_\odot \rightarrow r_C$ $\Longrightarrow$

$$T_C = \left(\frac{7}{2}\, \frac{f_0}{\kappa_0}\, \frac{r_C - R_\odot}{r_C / R_\odot} \right)^{2/7}$$

following Unsöld (~1960)

Why 10^6 K ? – a coronal thermostat

- **thermal conductivity:**

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

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

- more heating → T-increase
  → more efficient heat conduction
  → only small net T-increase
- same for less heating…

changing the heating rate f_0 by orders of magnitude results only in a small change of the coronal temperature

f_0 [W/m^2]	T_C [10^6 K]	
17600	5.0	
370	3.0	← "solar like"
0.29	0.5	

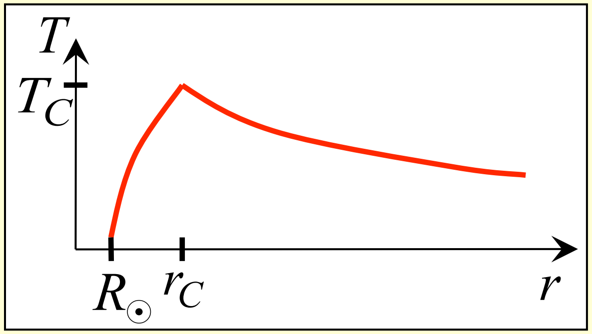
(Leer 1998)

- **solar wind**
  - magnetically open regions: 90% of the energy input powers solar wind
  - more heating → even more losses due to wind
    → less energy to heat corona

Pressure of a static heat conduction corona

heat flux in a fully ionized plasma (Spitzer 1956):

$$q = \kappa_0 T^{5/2} \nabla T$$



idea: carry away energy to Sun and infinity
by heat conduction (spherical coordinates):

$$\nabla \cdot q = 0 \quad \Rightarrow \quad \partial_r \left(r^2 \kappa_0 T^{5/2} \partial_r T \right) = 0 \quad \Rightarrow \quad r > r_C : \quad T(r) = T_C \left(\frac{r}{r_C} \right)^{-2/7}$$

solve hydrostatic equilibrium in outer part: $r_C \rightarrow r > r_C$

$$\frac{\partial p}{\partial r} = -\rho \frac{G M_\odot}{r^2} \quad \xrightarrow{p = 2 n k_B T} \quad p(r) = p_C \exp\left(-\frac{G M_\odot m}{2 k_B} \int_{r_C}^{r} \frac{d\tilde{r}}{\tilde{r}^2 T(\tilde{r})} \right)$$

pressure at infinity
does not vanish !

$$p_\infty = \lim_{r \to \infty} p = p_C \exp\left(-\frac{7}{10} \frac{G M_\odot m}{k_B T_C r_C} \right) > 0 \quad (!)$$

Can a static corona exist ?

Compare pressure of static corona to interstellar medium (ISM)

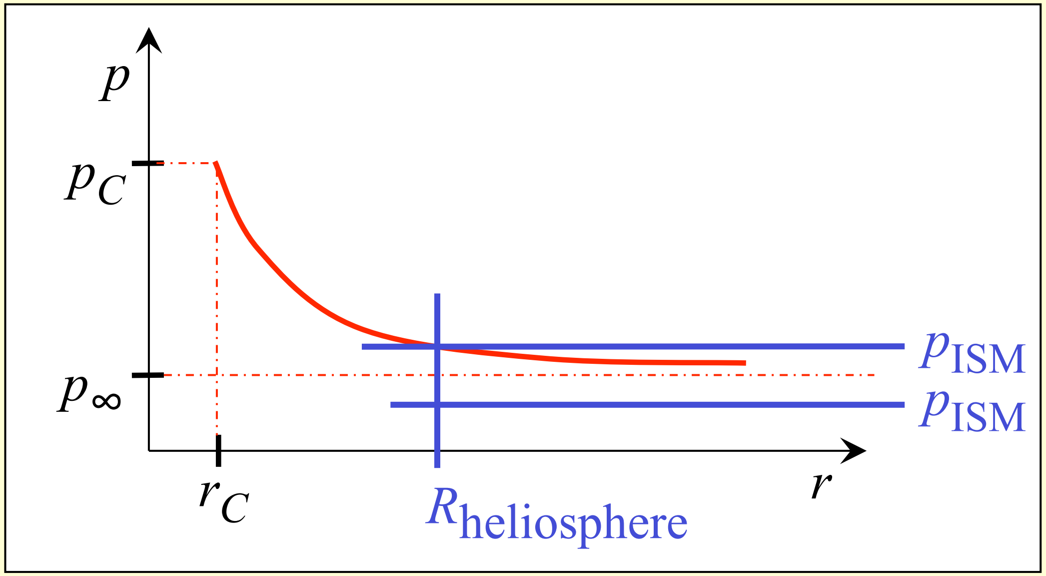
$$p_\infty = p_C \underbrace{\exp\left(-\frac{7}{10}\frac{G\,M_\odot\,m}{k_\mathrm{B}\,T_C\,r_C}\right)}_{=\,\Gamma}$$

ISM:
$T_{\mathrm{ISM}} \approx 100$ K
$n_{\mathrm{ISM}} \approx 10$ cm^{-3}
$p_{\mathrm{ISM}} \approx 1000$ K cm^{-3}

The Sun: $T_C \approx 10^6$ K
$n_C \approx 10^8$ cm^{-3}
$r_C \approx 2\, R_{\mathrm{Sun}}$

➡ $p_C \approx 10^{14}$ K cm^{-3}
➡ $\Gamma \approx 10^{-5}$

➡ $p_\infty \approx 10^9$ K cm^{-3} >> p_{ISM}



Corona has to expand!
➡ coronal wind
➡ thermally driven
➡ pressure (gradient) driven

However: Stars with cool outer atmospheres
T_C 10^4 K ➡ p_∞ < p_{ISM}
➡ **no wind !!**

Continuous corpuscular radiation: solar wind

tails of comets:

two-part structure:

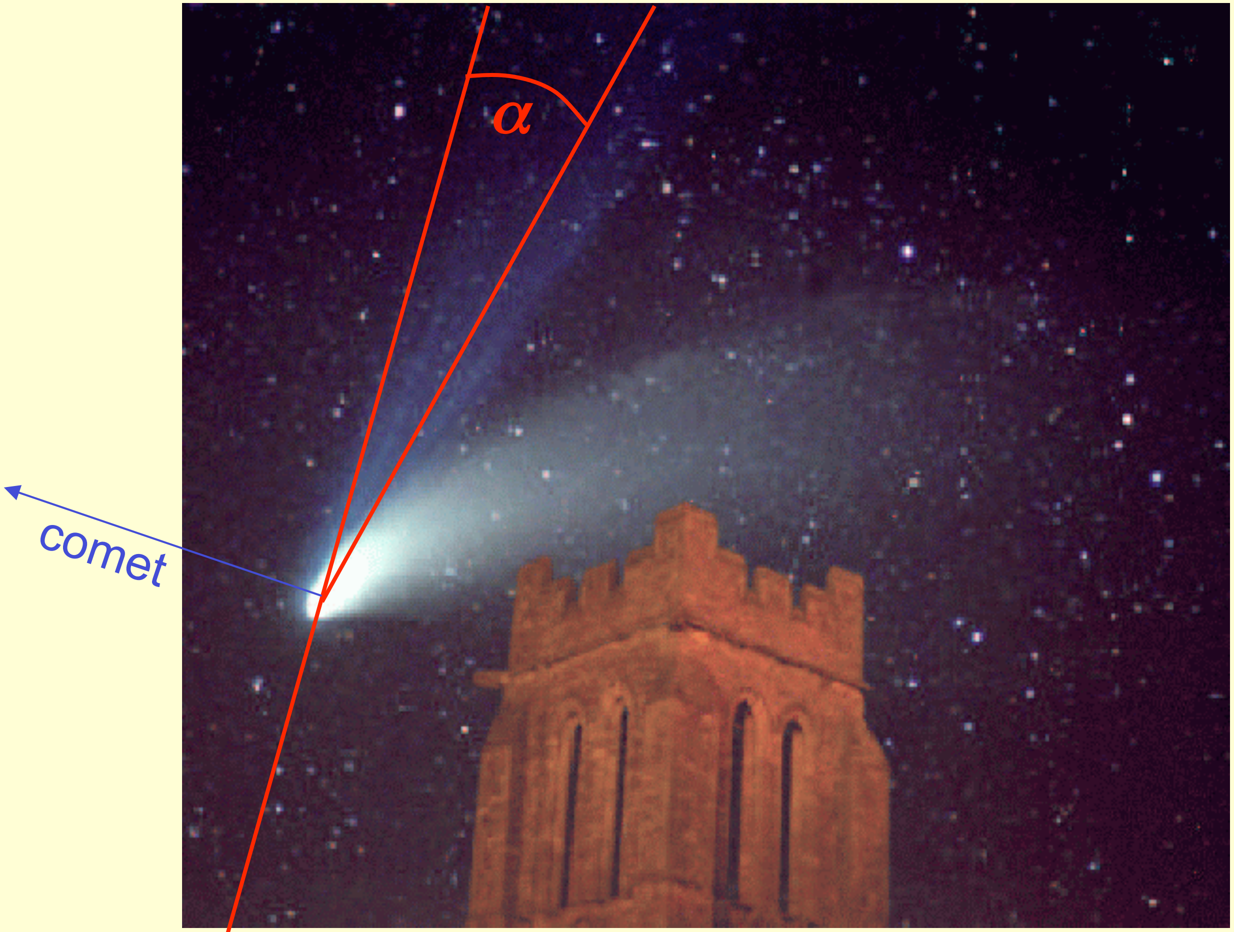
- **dust tail:**
  controlled through
  radiation pressure

- **ion tail**
  (→ polarized light)
  interaction of
  ionized particles
  in cometary tail
  with solar wind

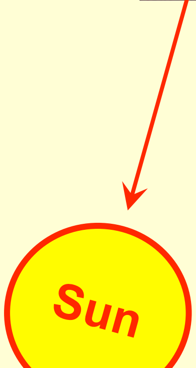
→ ***solar wind***

(Biermann ~1941)

angle α:
➡ wind speed
~ 1000 km/s



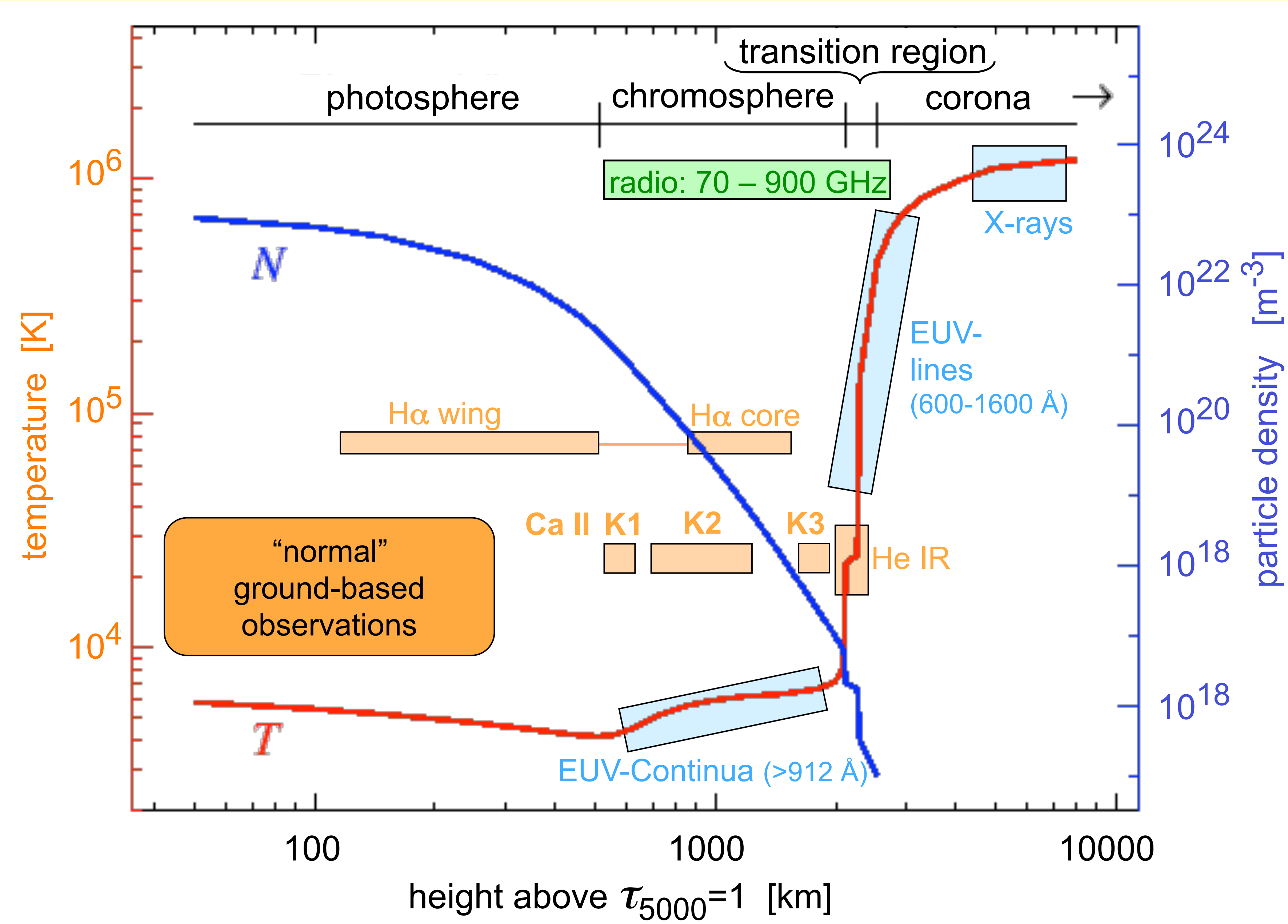
comet Hale-Bopp



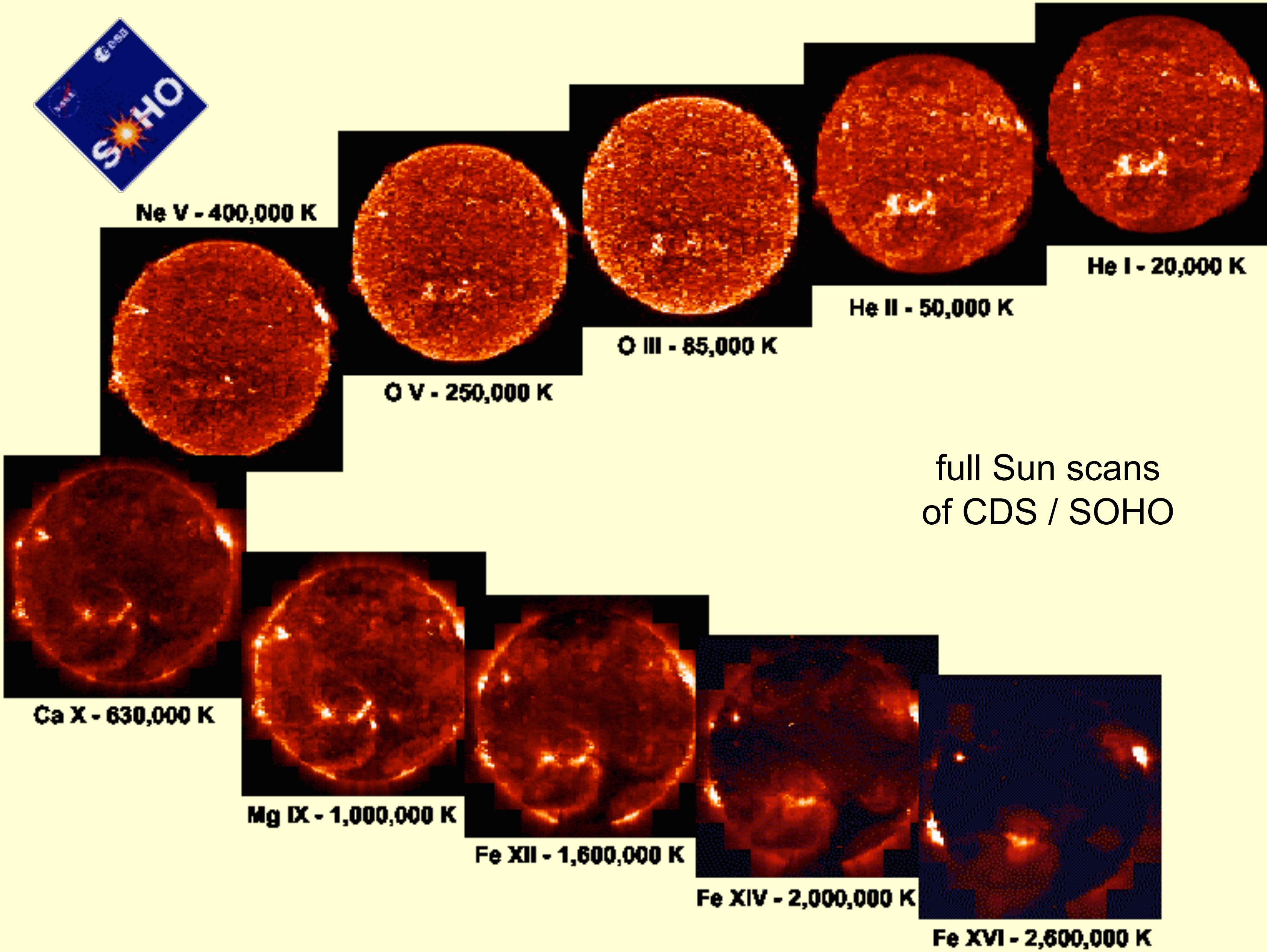
solar wind at Earth:

velocity:	400 – 800 km/s
density:	1 – 10 protons / cm^3
temperature:	100 000 K

Observing the solar atmosphere



From the upper chromosphere to the hot corona



full Sun scans
of CDS / SOHO

Summary / lessons learnt

~ 1850: first systematic "modern" eclipse observations

~ 1870: introduction of spectroscopy into coronal physics

~ 1930: invention of coronagraph

~ 1940: coronal lines are from highly ionized species ➡ the corona ~10^6 K

~ 1970: first advanced X-ray observations

- the corona is magnetically structured
- the appearance of the corona changes with solar activity cycle
- 10^6 K is "quite natural": heat conduction acts as thermostat
- a static hot corona cannot exist ➡ expansion
- appearance the solar atmosphere changes dramatically with temperature