Sun, solar activity, and space weather

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TR 24 complex plasmas

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„Plasma Physics in Science and Technology“

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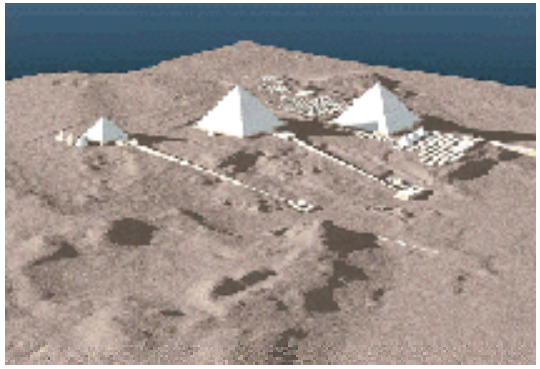
the Sun – our star

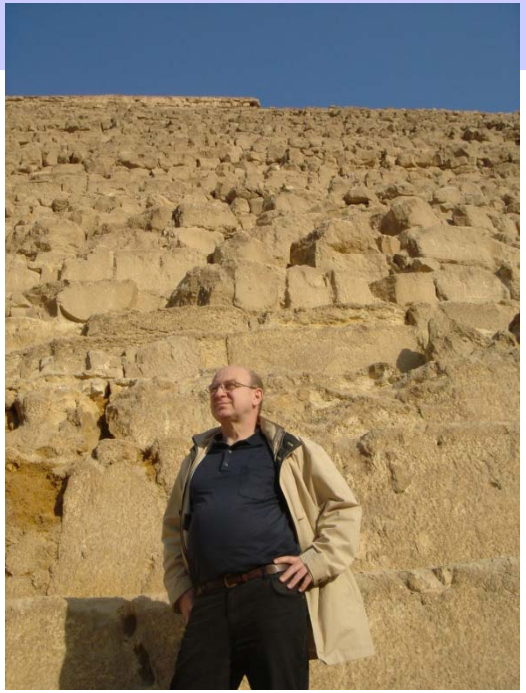
the Sun – our star

- Sun inspired the ***mythology*** of several cultures (Babylon, Egypt, China, Celtics, Azteces ...)
- e.g. important necessety for ***observation of the Sun***

- extraordinary importance of Sun for live, culture and religion
- observation of regular movement and special phenomena, e.g. solistites, equinoxes and eclipses

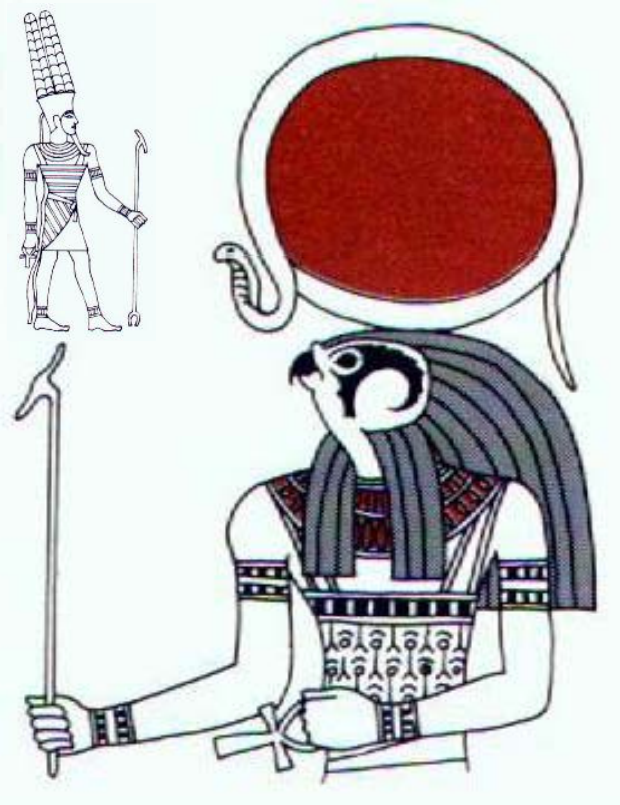
the Sun – our star





pyramids at Giza
(~ 2600 B.C.)
are oriented to Sun

the Sun – our star

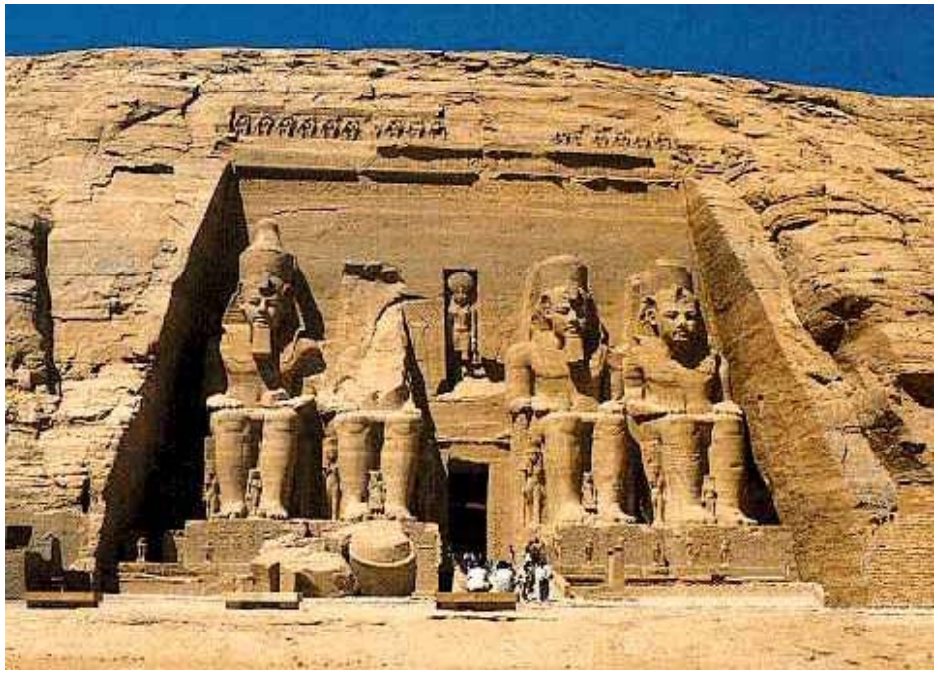


Amun-Ra

God of the Sun: ***Re***

Goddess of the sky: ***Nut***

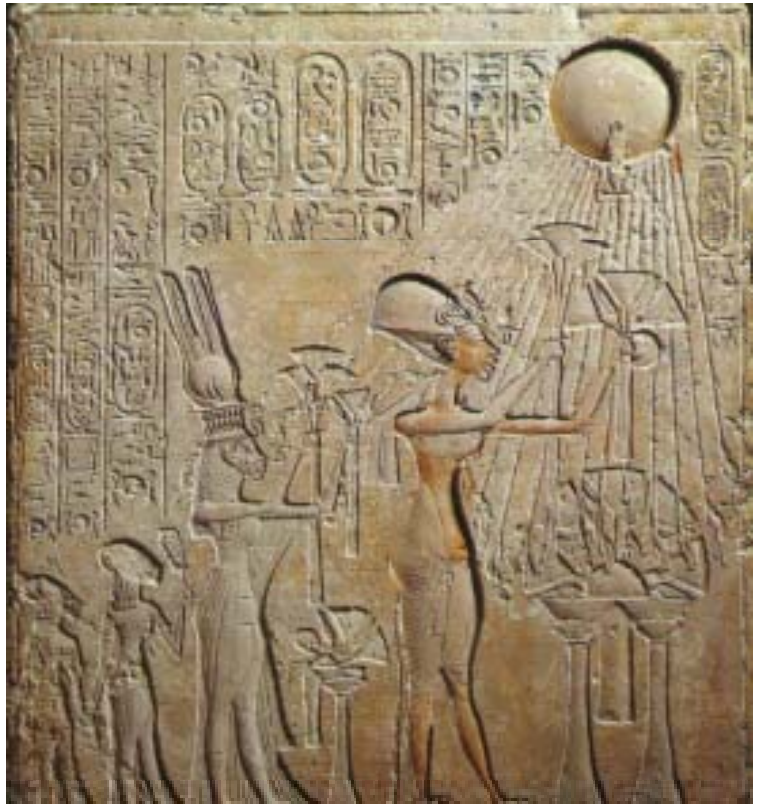
the Sun – our star



temple of Ramses II.
in Abu Simbel
(~1250 B.C.)

Amun-Re
at Abu Simbel

the Sun – our star



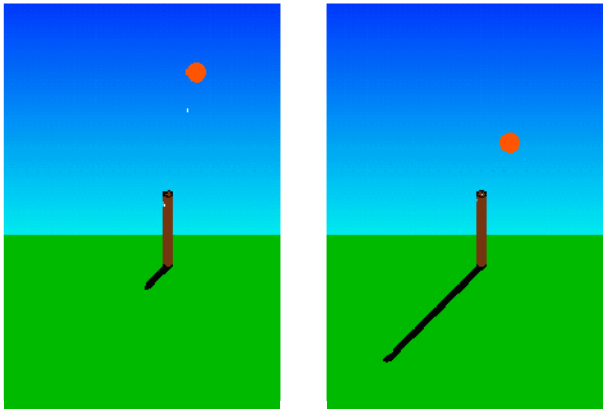
Amenhotep (Amenophis) IV = Echnaton (~1400 B.C.)
Worship of Sun‘s disc (***Aton***)

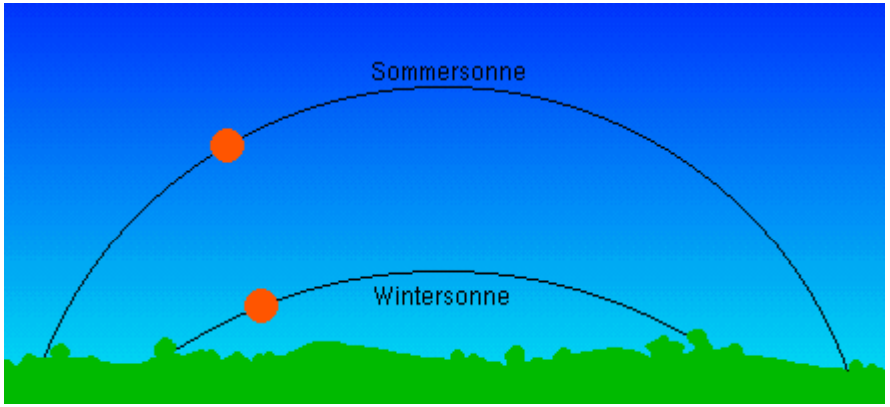
the Sun – our star

Sun set

the Sun – our star

Sun : time and clock





the Sun – our star

Sun eclipse

partial solar eclipse, 10.05.1994

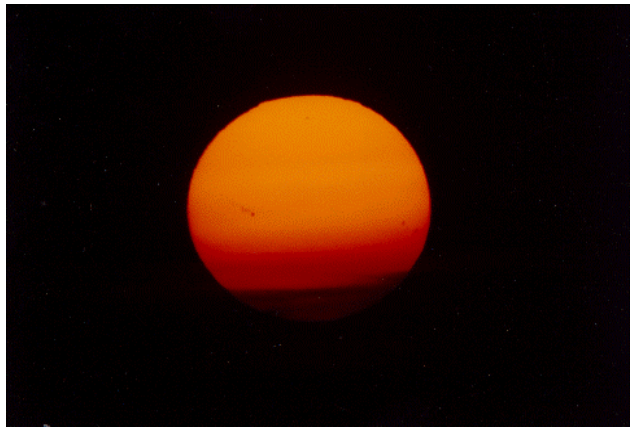
effects due to atmosphere:

- *extinction (scattering, absorption)*
- *refraction*
- *szintillation*

the Sun – our star

• Sun is located in a spiral arm (Orion arm) of our galaxy (milky way), about *30.000 ly* far away from its centre
• solar system rotates around the centre of the galaxy in *225 Mio.* years (*v ~ 230km/s*)
• milky way contains more than *100 Mrd.* stars

• mass of Sun is *333400* times larger than Earth, which is *99,86%* of total mass of the solar system



• Sun consists *78%* hydrogen, *20%* helium and *2%* havier elements

contents

- observation of the Sun's electromagnetic radiation

- interior of the Sun
  - # energy transport in the Sun (radiation, convection)
  - # conversion of nuclear energy by fusion processes in the core
  - # neutrino flux due to fusion

- evolution of the Sun
  - # birth, life and death of stars
  - # state in the HRD and life time of the Sun

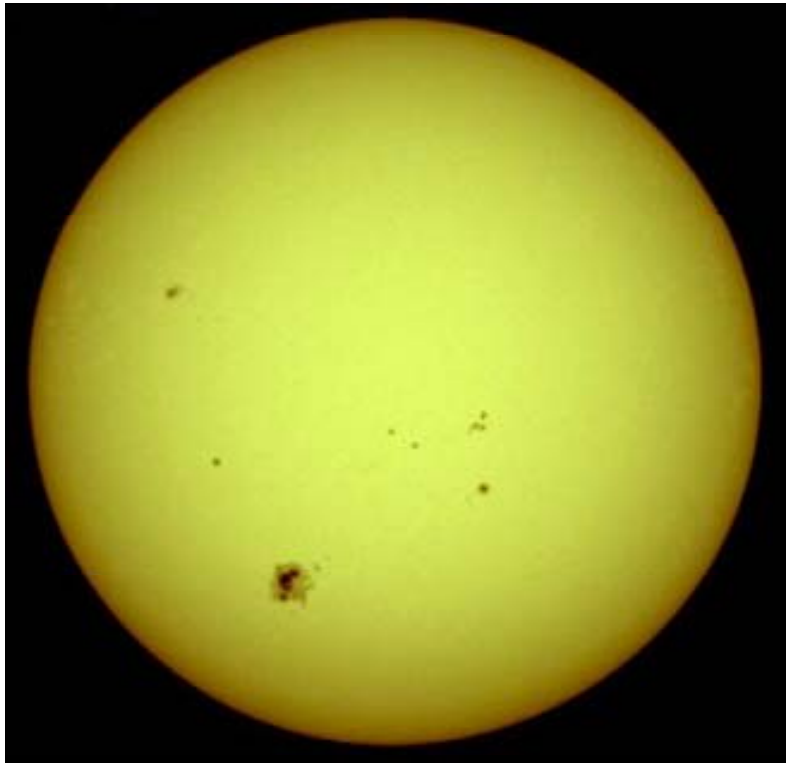
- solar activity
  - # photosphere, chromosphere, corona
  - # Sun spots, solar prominences and the activity cycle

- solar-terrestrial phenomena
  - # solar wind, polar lights and geomagnetic storms
  - # space weather and its impact

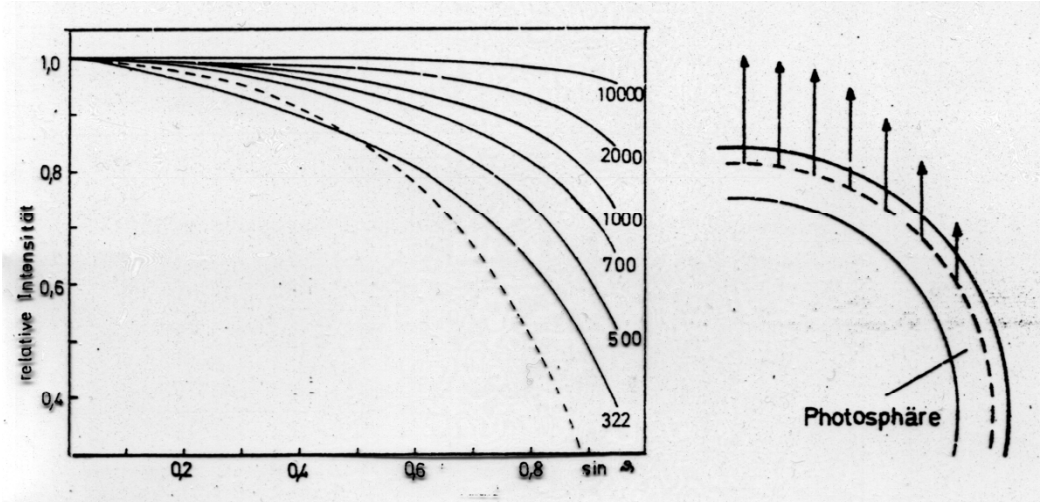
observation of the Sun

observation

photosphere



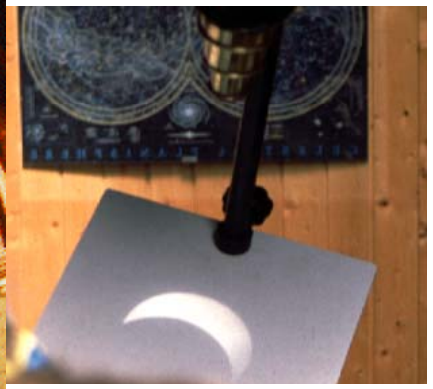
• ← Earth



edge of the Sun (atmosphere of Sun)
= **photosphere**
~100 ... 1000km
temperature ~ *5800K*
darkening of photosphere edge

observation telescope

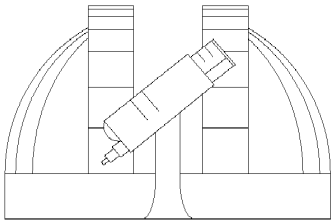
Caution !
Be aware during Sun‘s observation !



projection of the Sun

observation

telescope

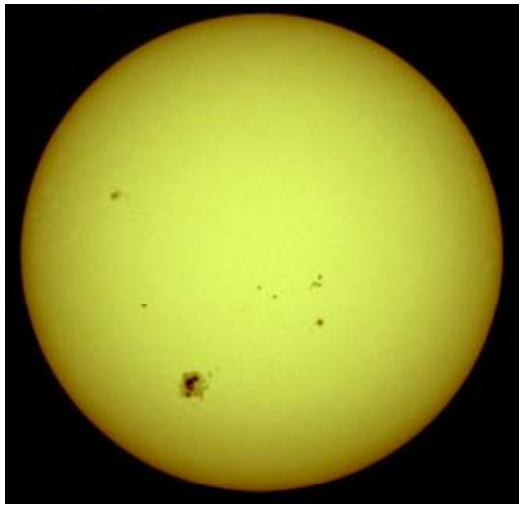


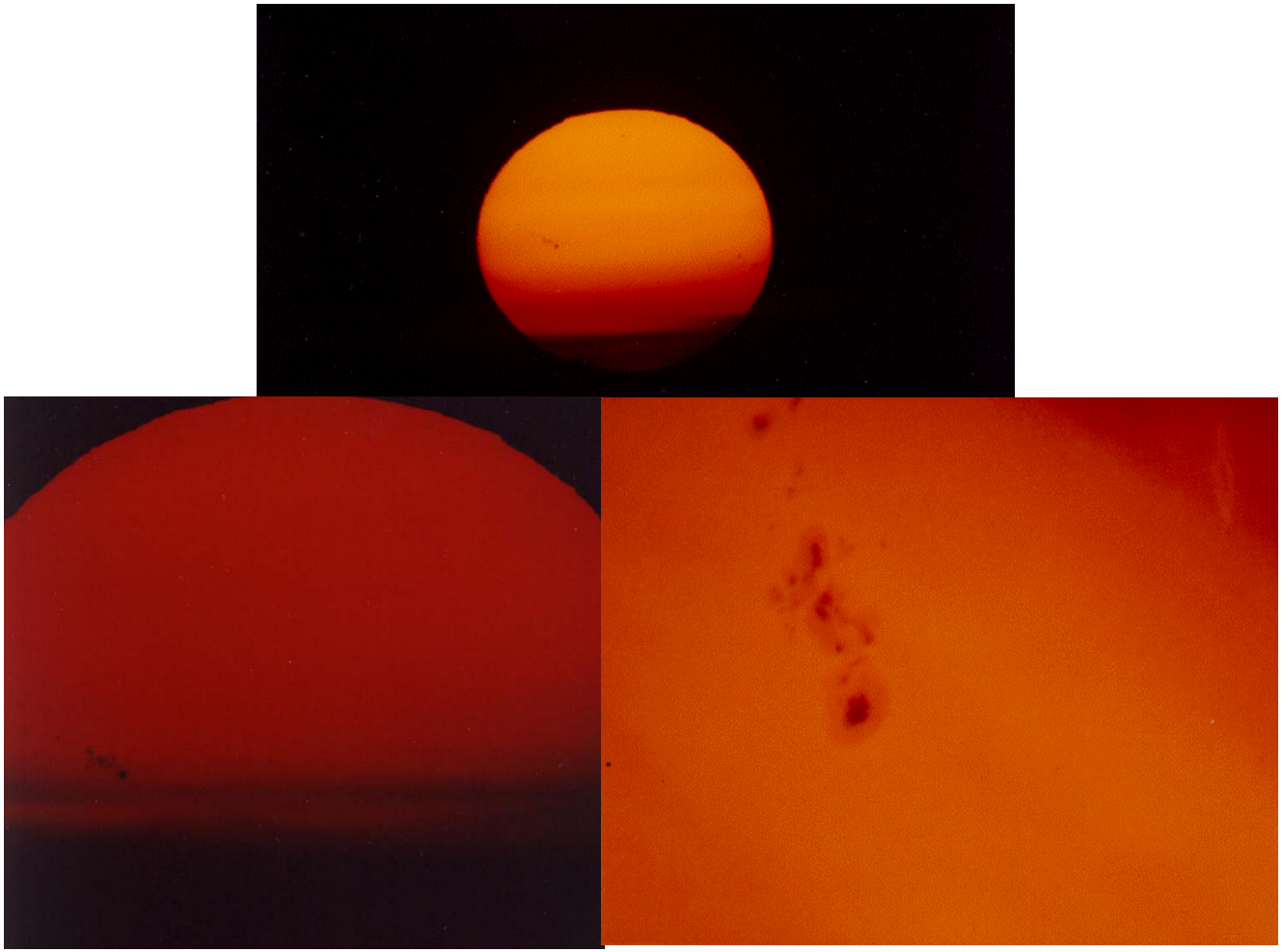
Observatory Greifswald

observation

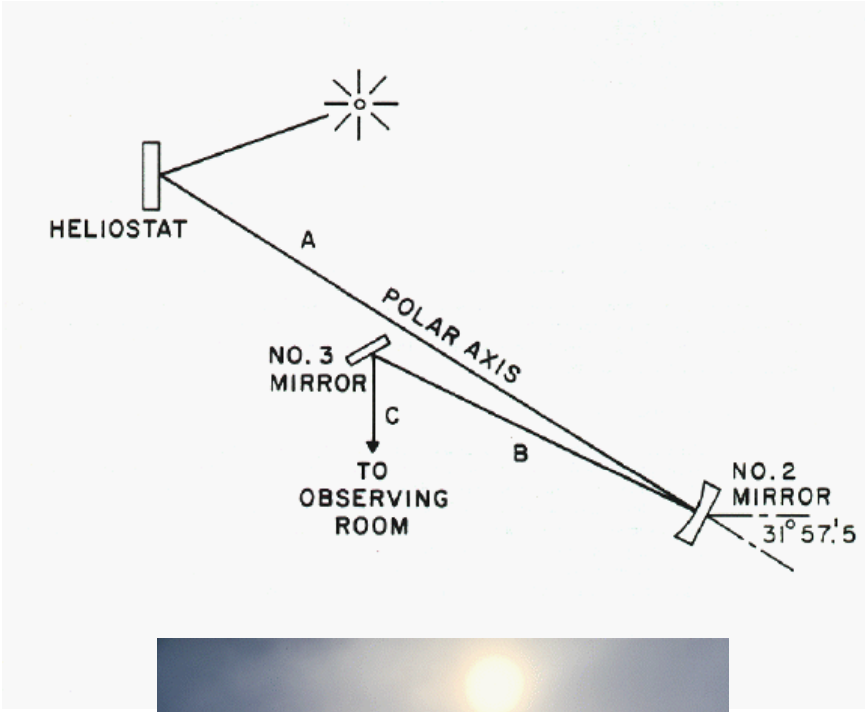
Sun spots

= most flashy phenomena at Sun‘s surface





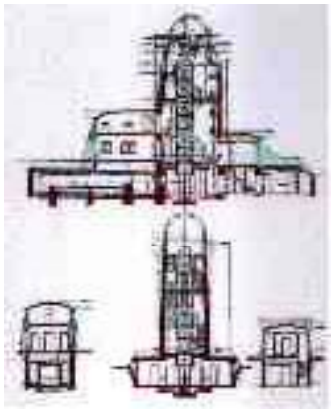
observation telescope



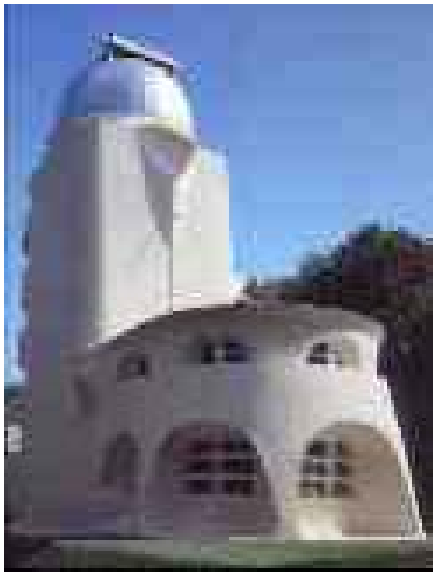
McMath solar telescope (Heliostat)
at Kitt Peak (USA)

observation

telescope



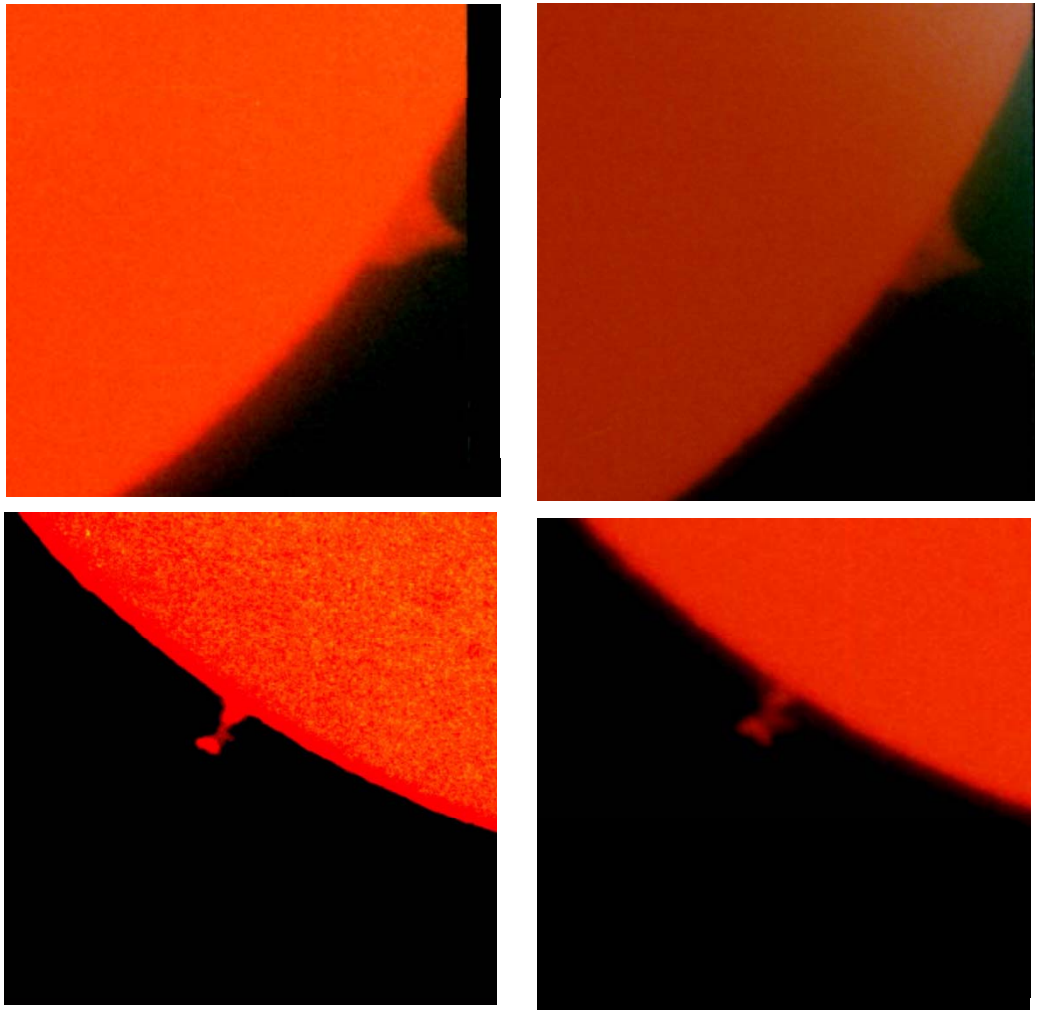
Einstein tower
in Potsdam
(with Heliostat)



coronograph

observation

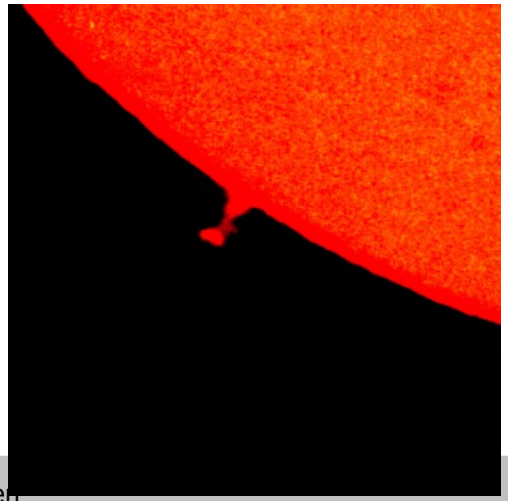
telescope



prominences
Hα filter

Protuberanzen

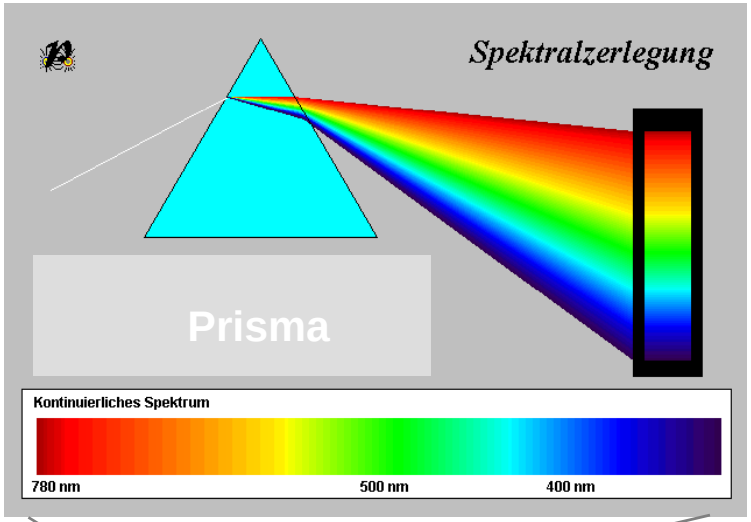
flächenförmig

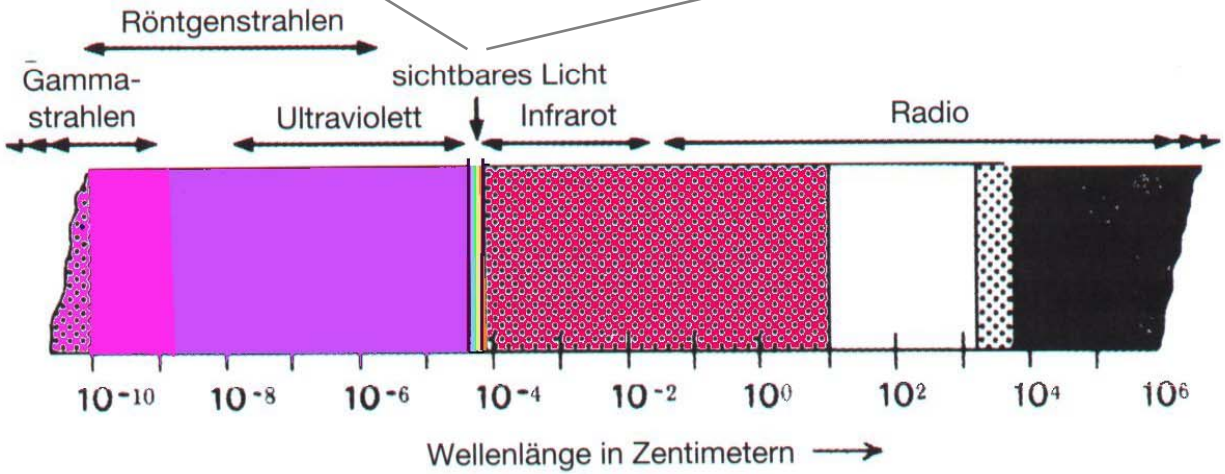


stabförmig

observation spectroscopy

electromagnetic spectrum



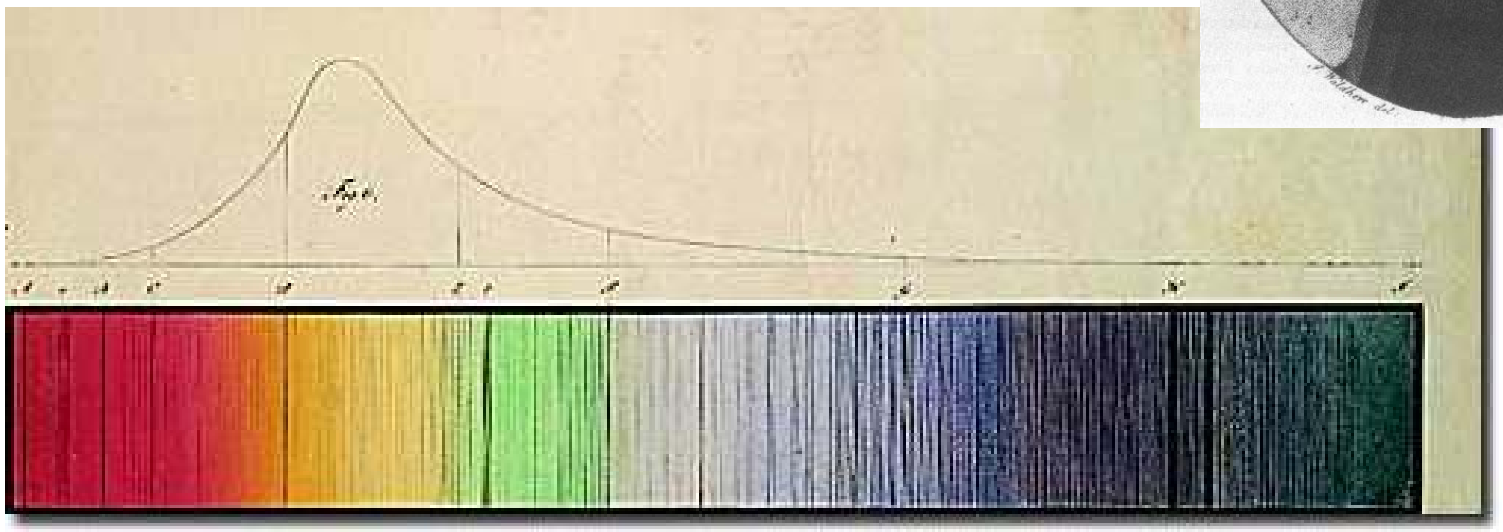


observation spectroscopy

observation spectroscopy

Joseph von Fraunhofer (1787-1826)

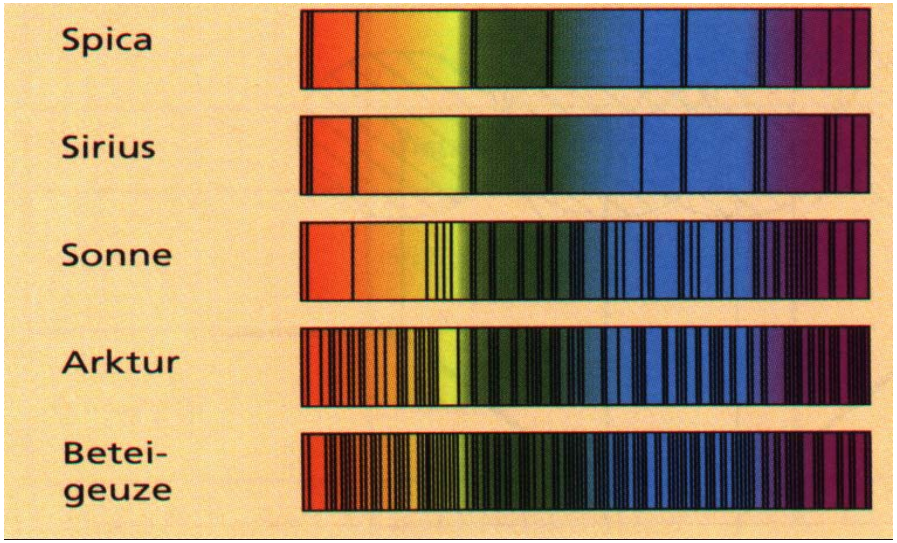
pioneer in optics and spectroscopy

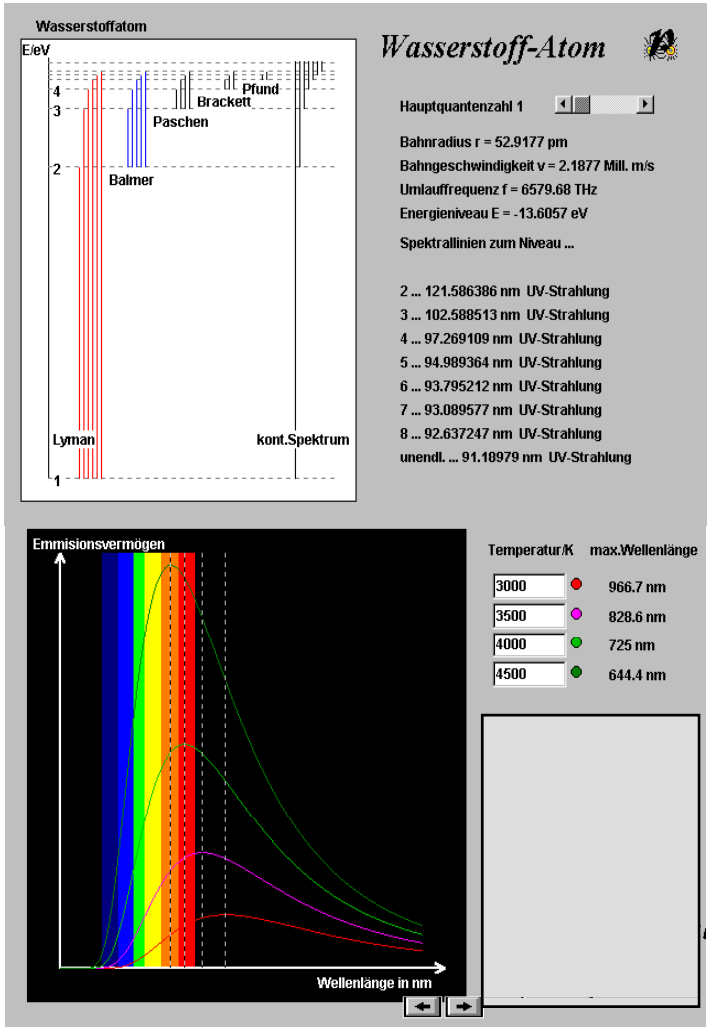


observation spectroscopy

most important information sources,
by spectral analysis one obtains information on

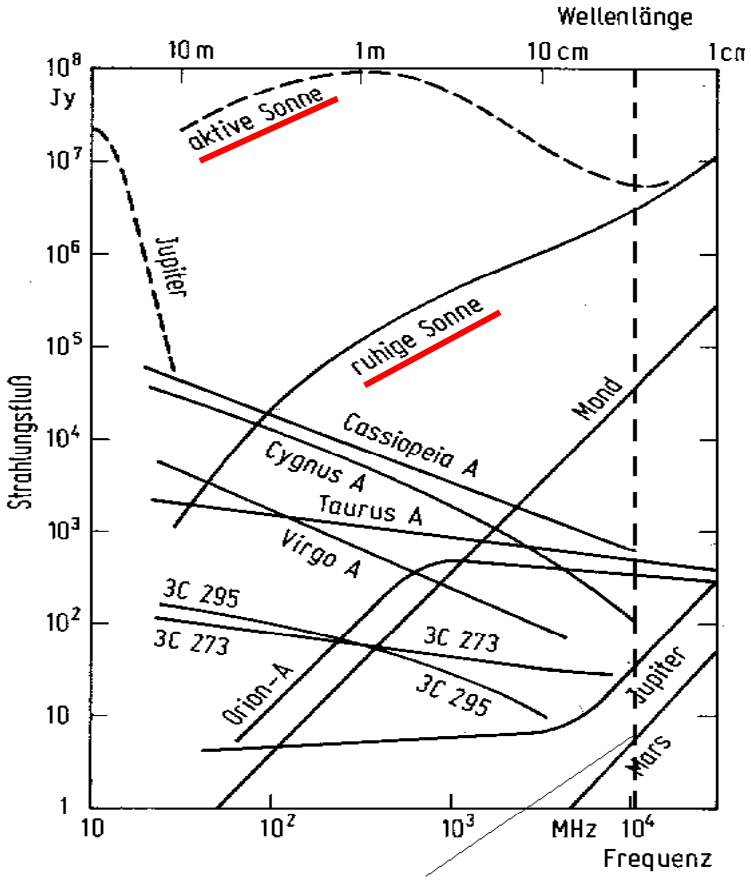
- classification
- changes in spectral lines
- radial velocities
- colour temperature
- equivalent width and line profiles
- state
- chemical composition





observation

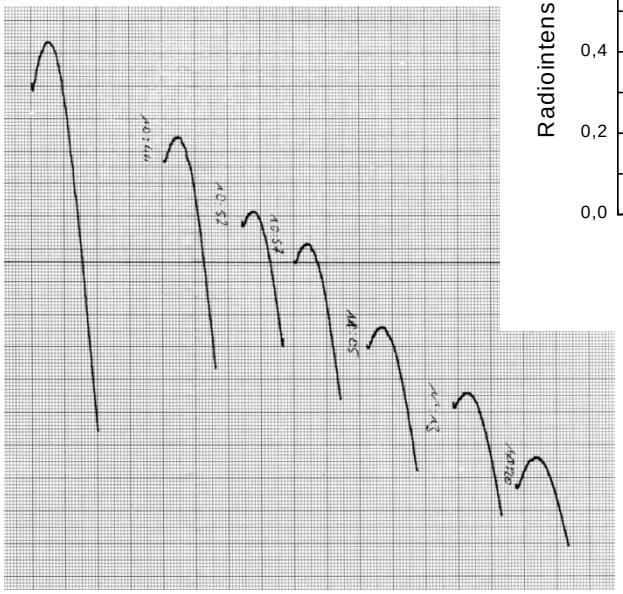
radio telescopes

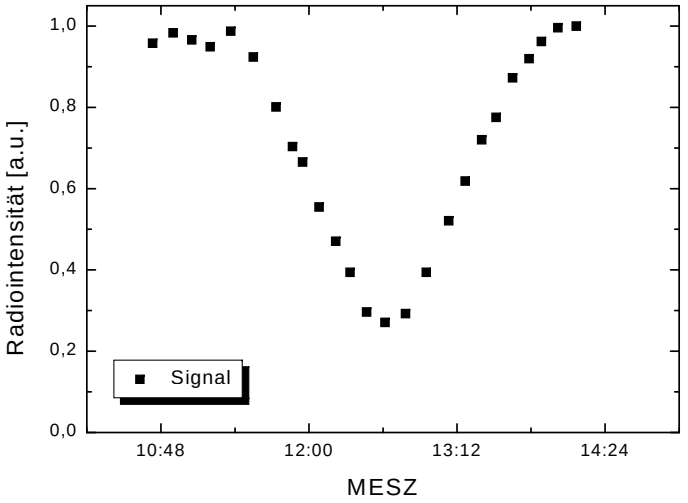


observation

radio telescopes

radio intensity at ~10 GHz

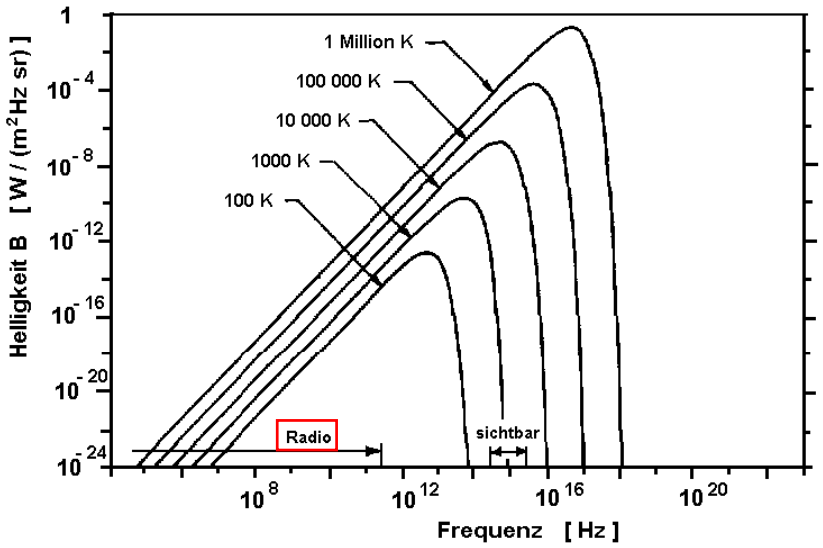




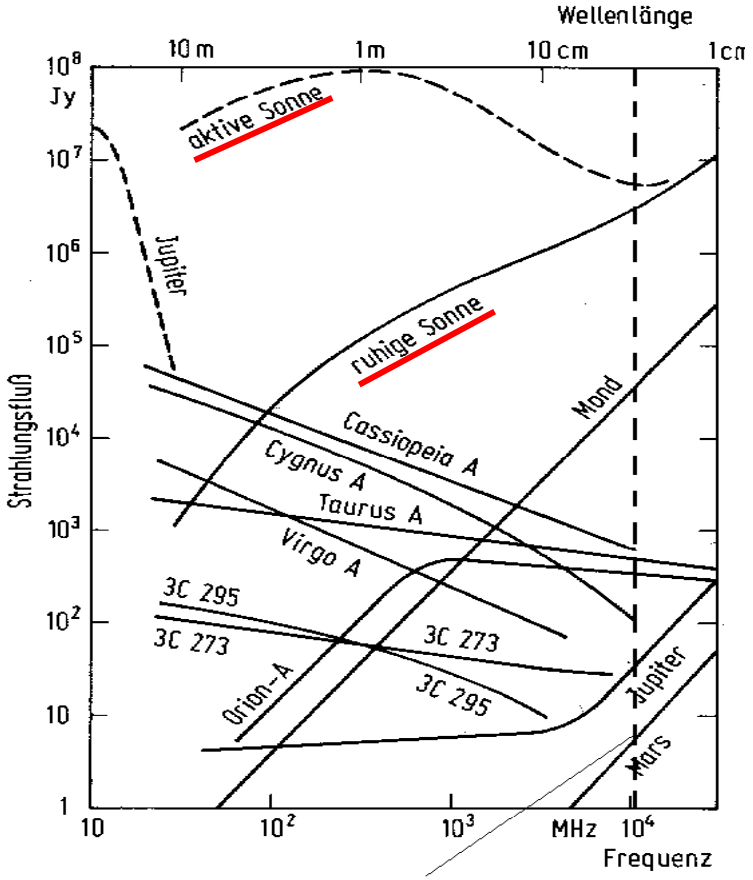
during solar eclipse, 11.08.1999

observation

radio telescopes



Schwarzkörperspekrum bei verschiedenen Temperaturen des Strahlers



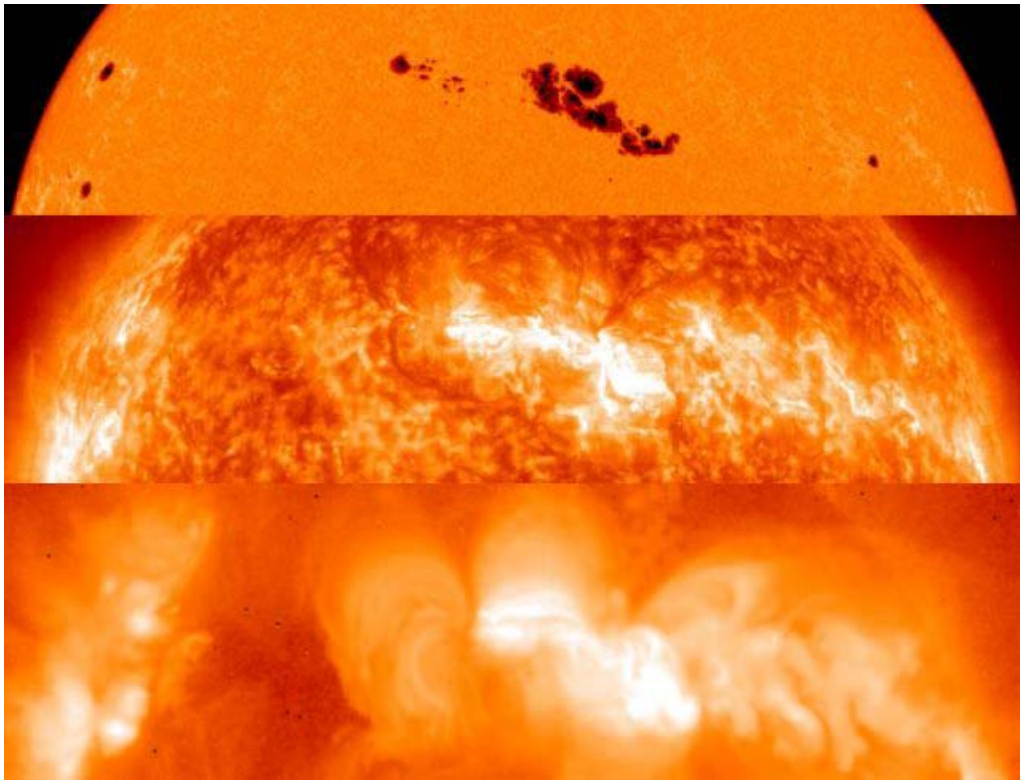
observation

X-ray telescopes

visual light

UV (Soho)

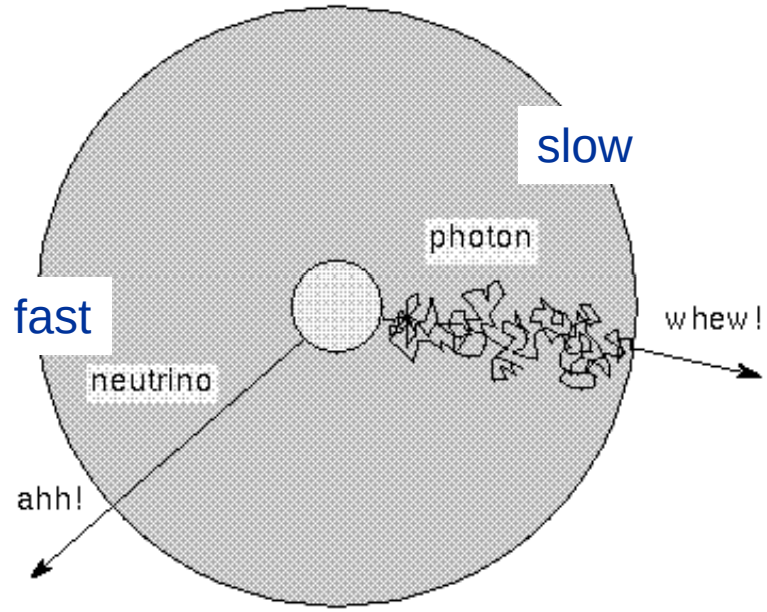
X-ray (Yohkoh)



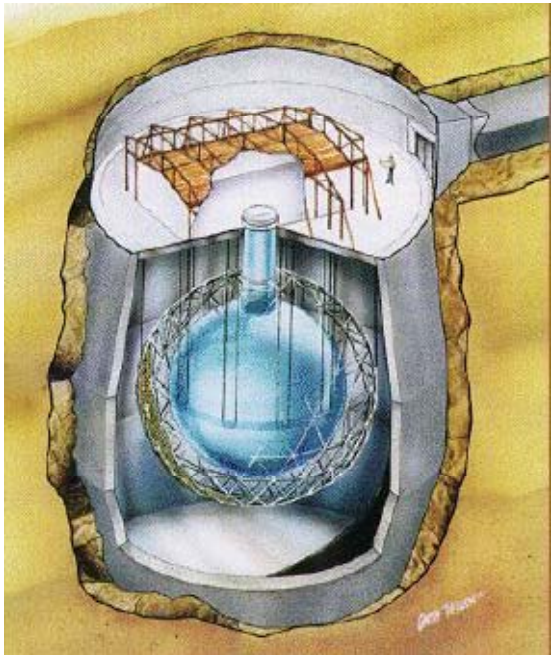
- 0.1 .... 100keV (~10 ... 0.001nm)
- X-ray astronomy
  only from extraterrestric telescopes
  (ROSAT, XMM, AXAF, CHANDRA)

- *X-ray mirror telescopes* (WOLTER type)

observation neutrinos



Photons take tortuous paths out of the Sun's interior.
Neutrinos pass right on through in just two seconds.



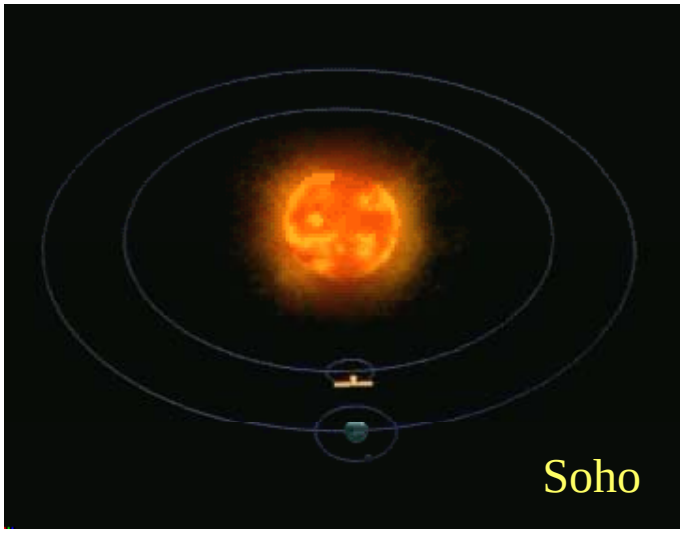
R.Davies (1964)

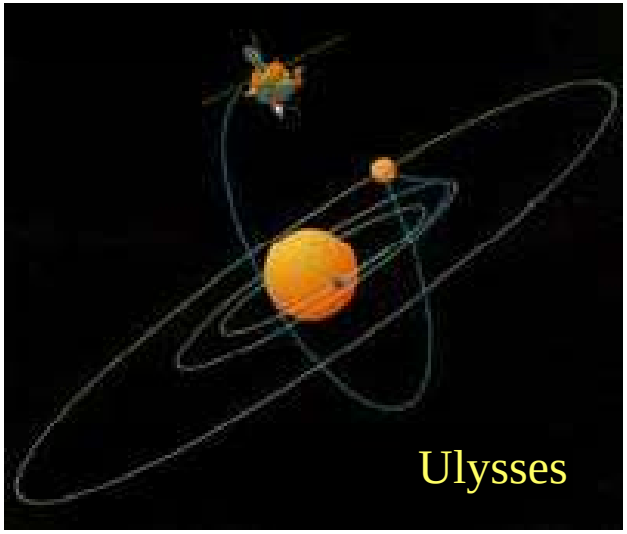
detection of neutrinos is very difficult

neutrino problem ?

observation

probes in space



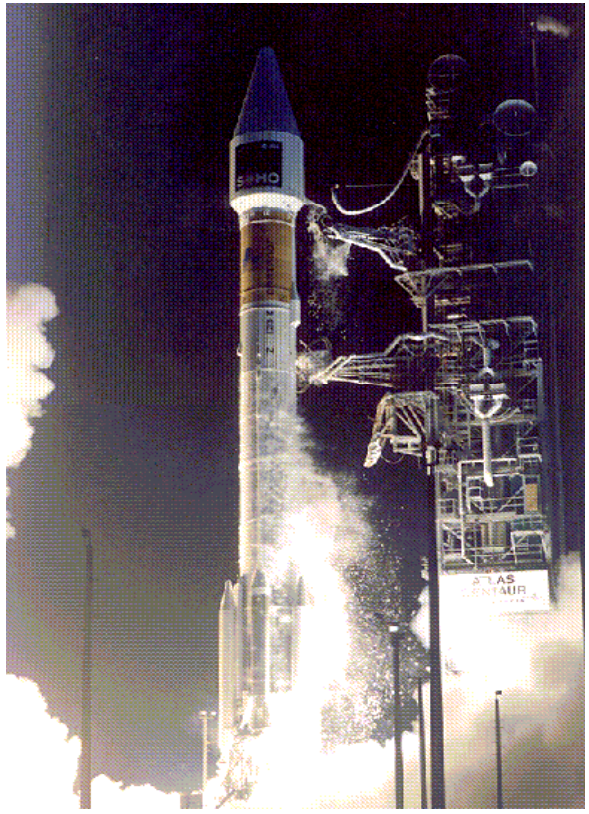


- probes in orbit of Earth (Yokoh)
- probes in orbit of Sun
  - ecliptical (Soho)
  - polar (Ulysses)

observation probes in space

SOHO

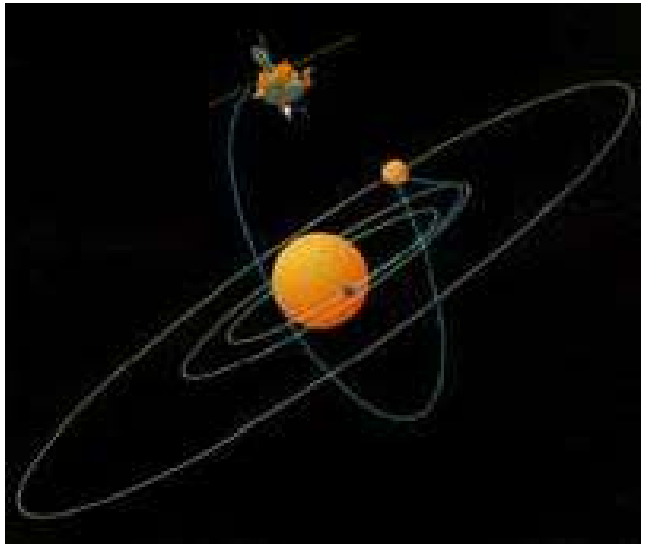
- joint project between ESA (9) und NASA (3)
- ESA : construction, integration, tests
- NASA : start and mission control

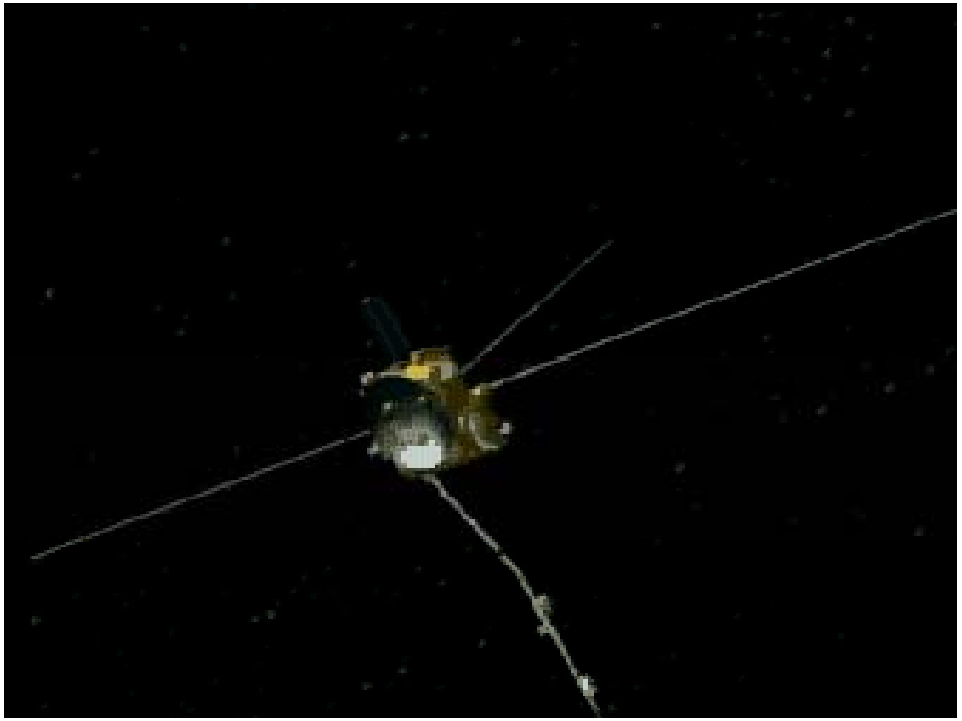


start on 02.12.1995

observation

probes in space

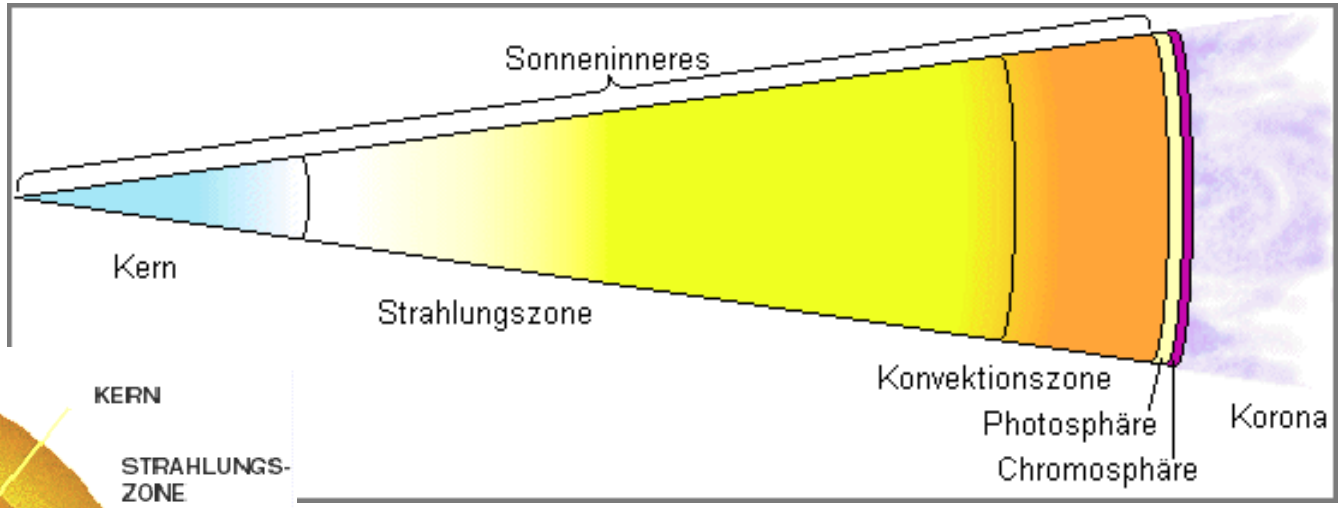


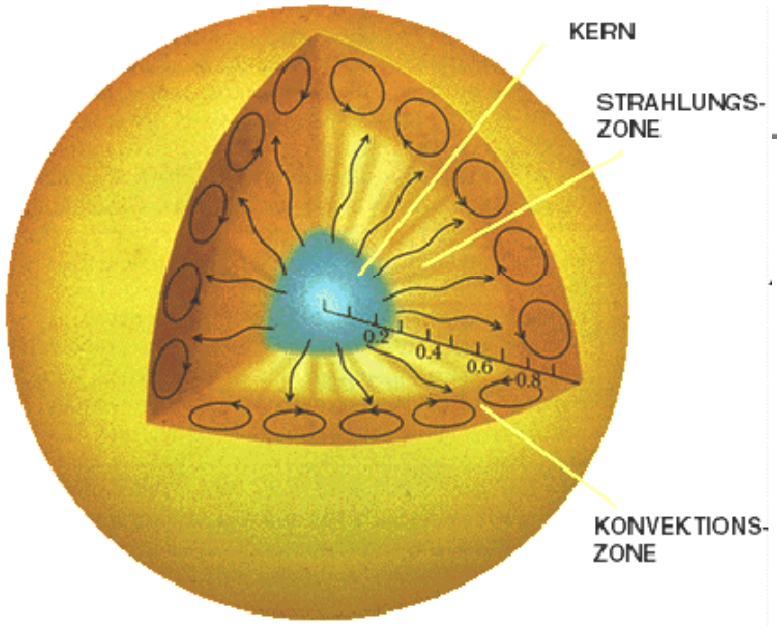


interior of the Sun

interior

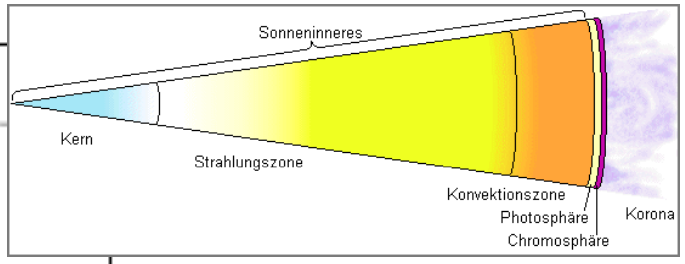
shell structure

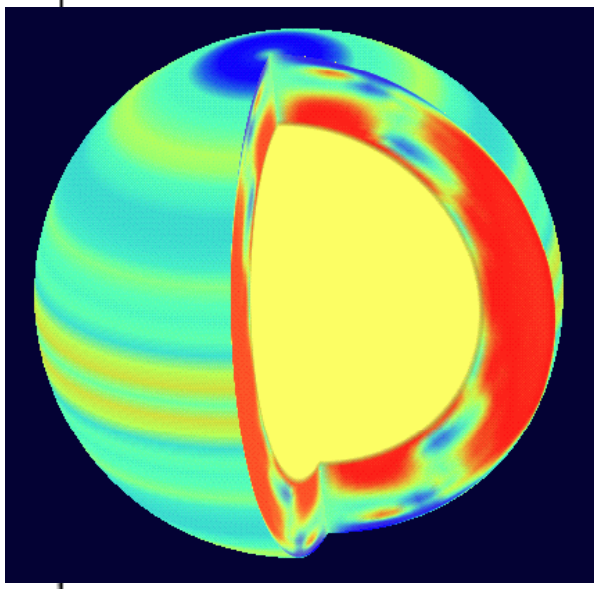




interior

shell structure





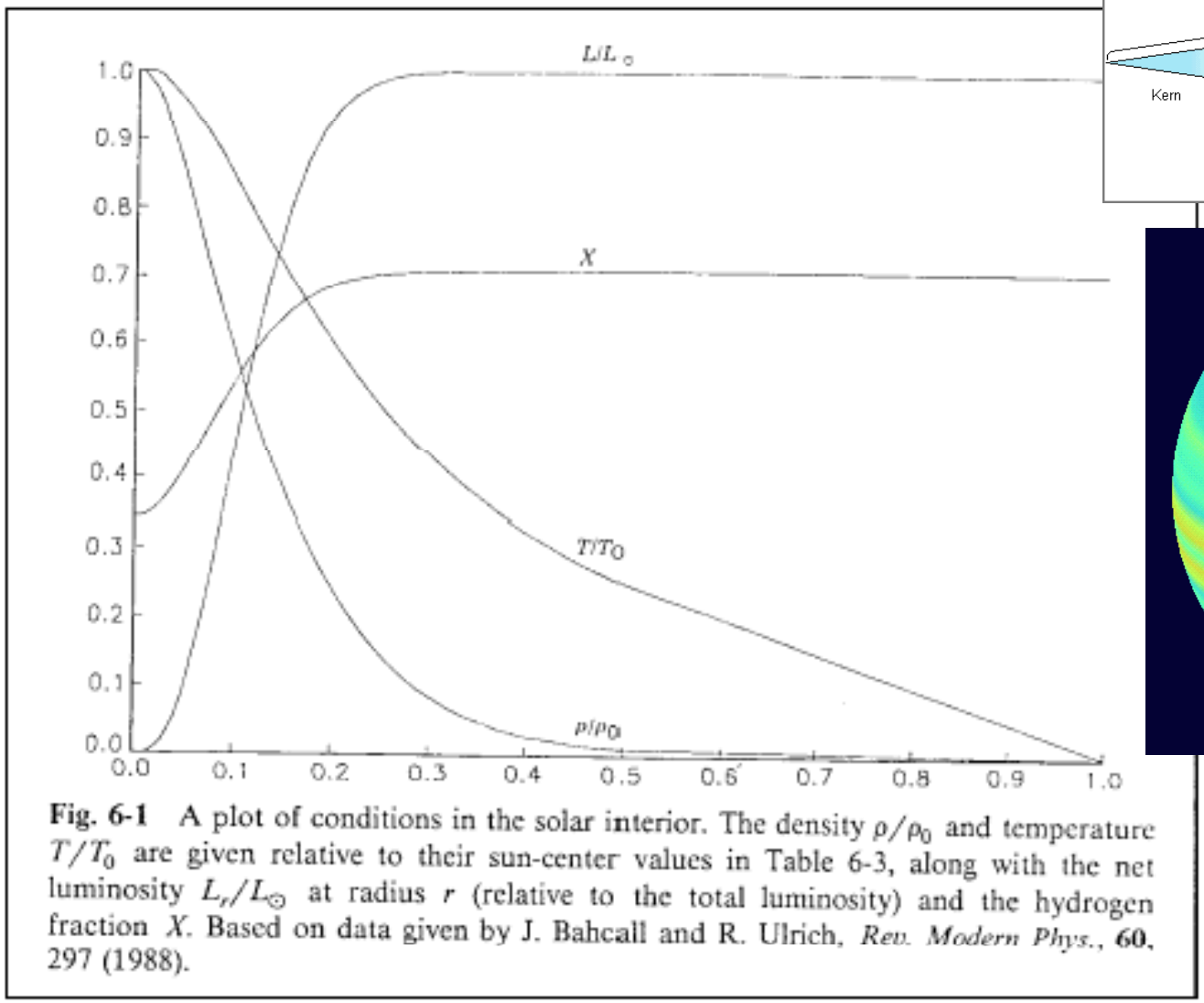


Fig. 6-1 A plot of conditions in the solar interior. The density ρ/ρ_0 and temperature T/T_0 are given relative to their sun-center values in Table 6-3, along with the net luminosity $L_r/L_\odot$ at radius r (relative to the total luminosity) and the hydrogen fraction X. Based on data given by J. Bahcall and R. Ulrich, *Rev. Modern Phys.*, **60**, 297 (1988).

interior

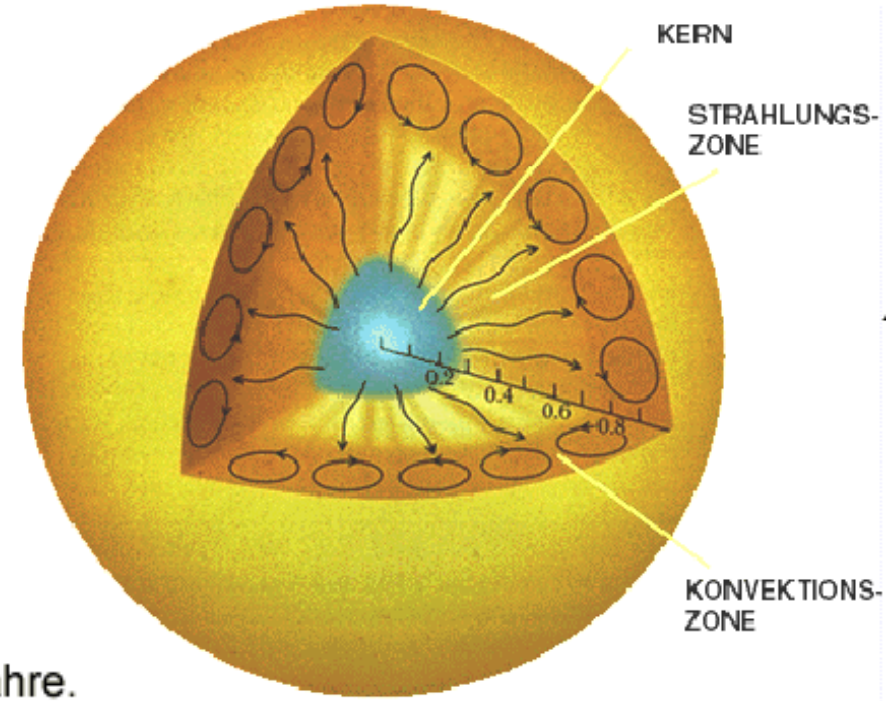
radiation zone

Bereich: $0.25 - 0.75 \cdot R_0$

Temperatur: $8 \cdot 10^6 - 1.6 \cdot 10^6$ K

Dichte: $2 \cdot 10^4 - 1 \cdot 10^2$ kg/m^3

emission ~ absorption



$$t_{rad} \approx \frac{R^2 \cdot \chi \cdot \rho}{c} \approx \frac{4.9}{3} \cdot 10^{11} \text{ s} = 5.1 \cdot 10^4 \text{ Jahre.}$$

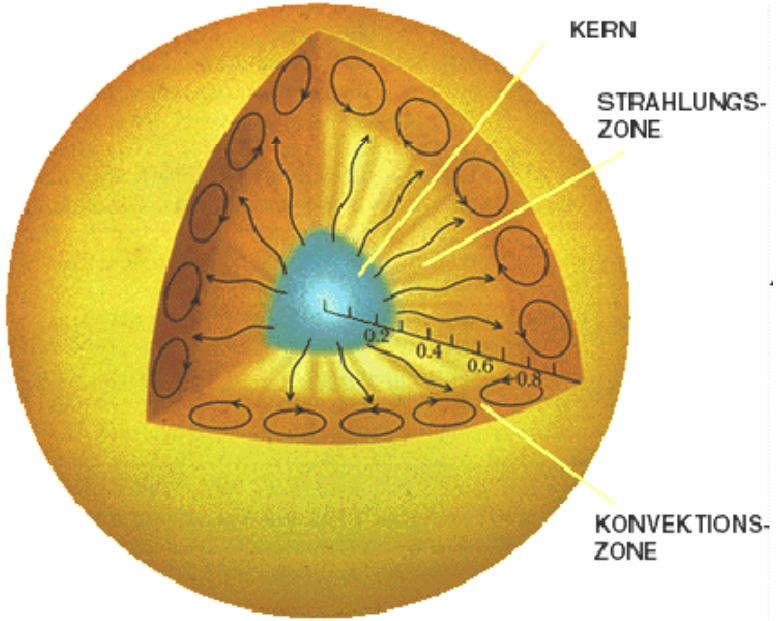
interior

convection zone

Bereich: $0.75 - 1 \cdot R_0$

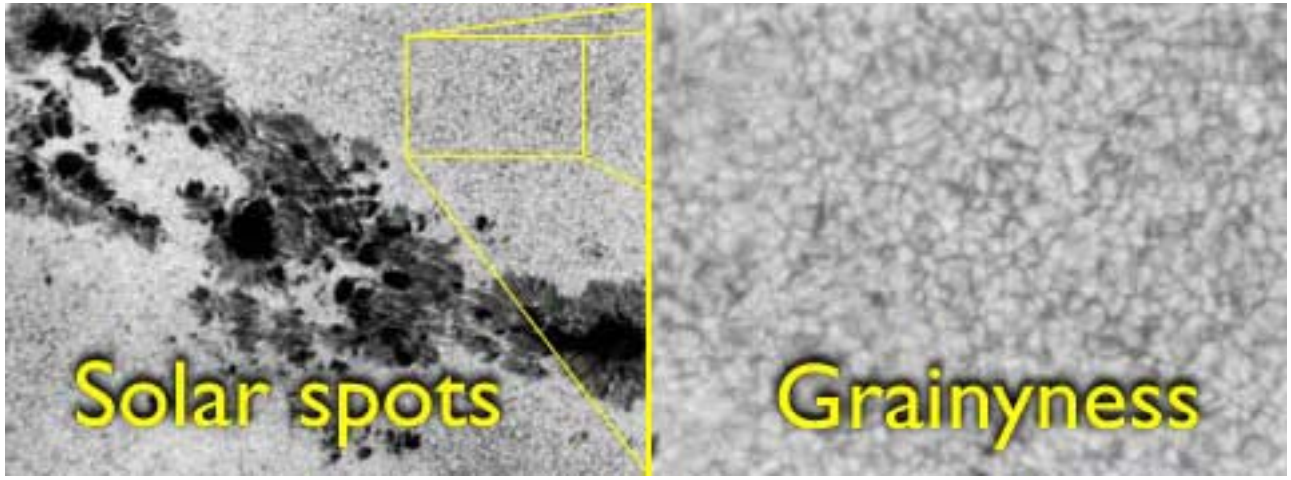
Temperatur: $1.6 \cdot 10^6 - 6000$ K

Dichte: $1 \cdot 10^2 - 3 \cdot 10^{-4}$ kg/m^3

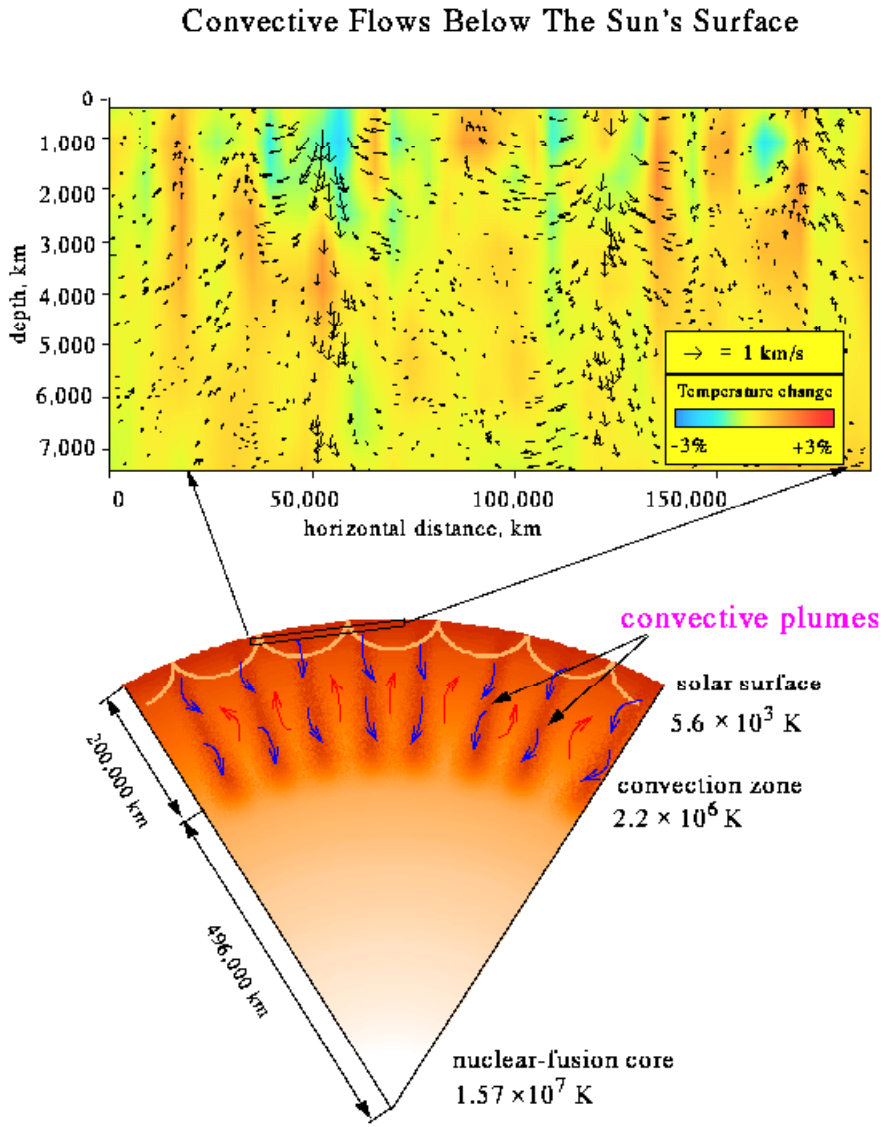


emission < absorption

granulation due to convection
within the deeper photosphere

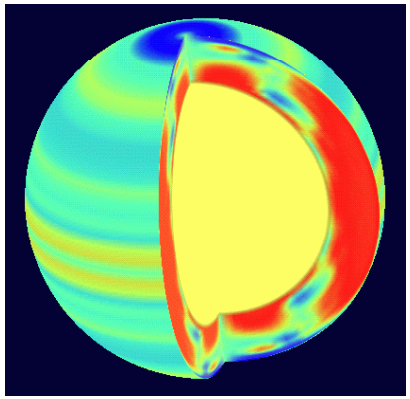


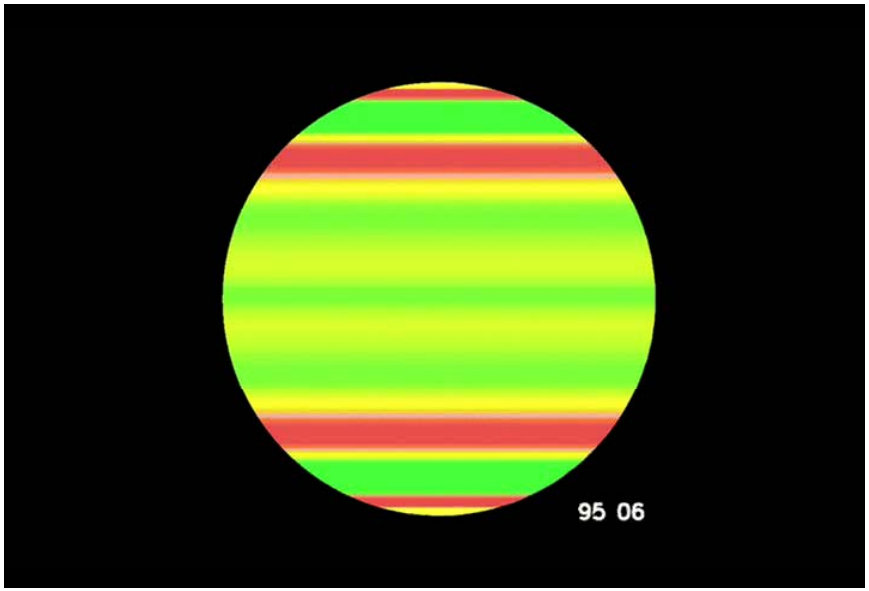
interior convection zone



toroidal and poloidal magnetic fields

• fields of velocity due to differential rotation and convective flow cause and amplify magnetic fields by induction of the conductive plasma

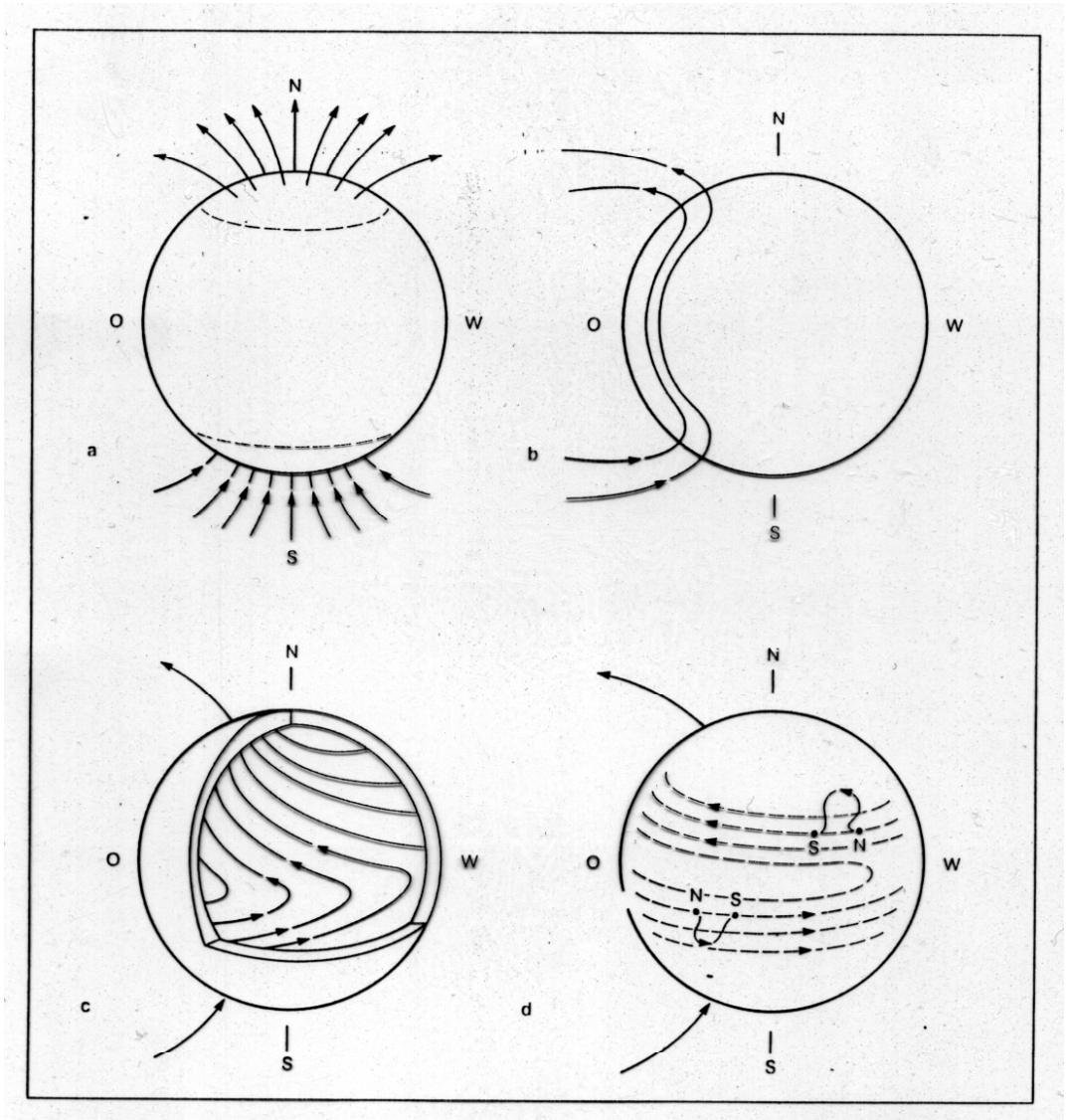




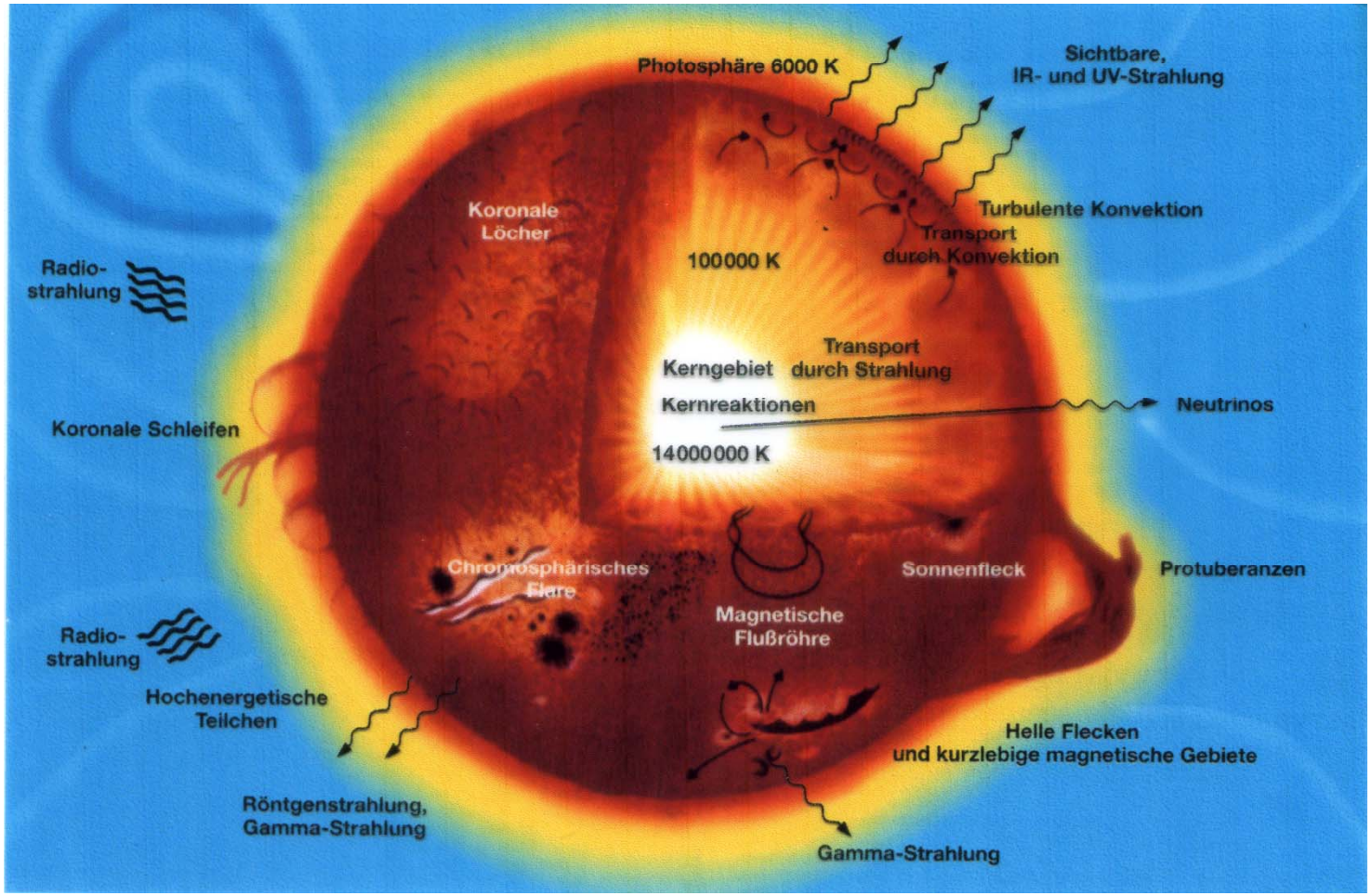
• rotation rates at the bottom of the convection zone change periodically

interior solar dynamo

- global magnetic field : weak
- local magnetic fields : strong



interior sun



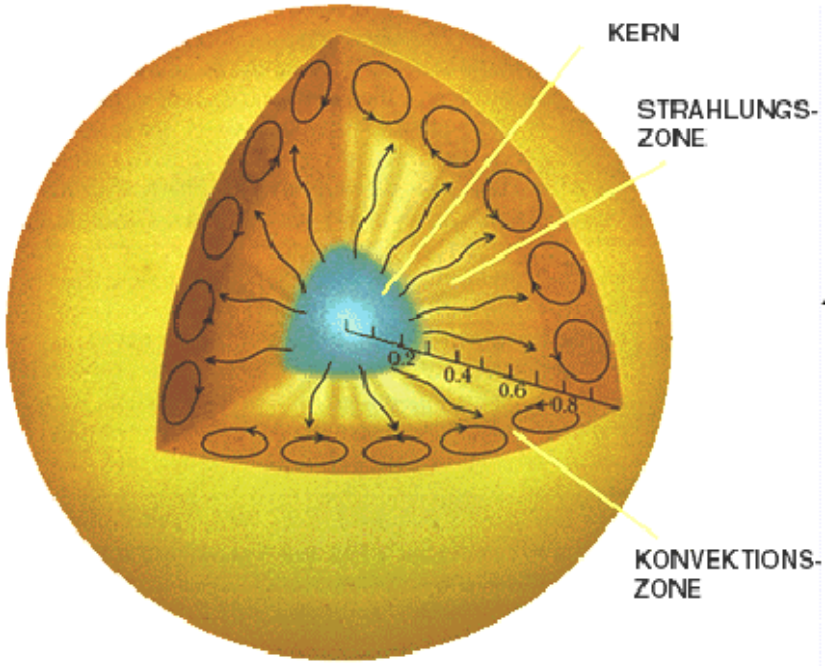
interior

fusion core

Bereich: $0 - 0.25 \cdot R_0$

Temperatur: $\approx 1.5 \cdot 10^7$ K

Dichte: $\approx 1.6 \cdot 10^5$ kg/m³



Kernfusion

- Verschmelzung von leichten Atomkernen mit Energiegewinn verbunden
  - schwierig durch Coulomb-Abstoßung
- Kernfusion ist Energiequelle der Sonne
  - nicht durch chemische Prozesse möglich
- fusionierende Kerne erhalten durch hohe Temperatur so viel kinetische Energie, daß sie die Coulomb-Abstoßung überwinden.

$$1\text{keV} \leftrightarrow 1.16 \cdot 10^7 \text{K}$$

- Wasserstoffbrennen
  - Verschmelzung von 4 Protonen zu ^{4}He

$$p + p \rightarrow d + e^+ + n$$

$$p + d \rightarrow {}^3\text{He} + \gamma$$

$${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$$

  - Energiegewinn: 6,5MeV/Nukleon

Fusion in der Sonne

- Input zur Fusionsrate
  - Energieverteilung der Protonen
    - Maxwell-Boltzmann-Verteilung
  - Wirkungsquerschnitte der Reaktionen
    - Coulombbarriere (Tunneleffekt)
    - schwache WW
    - starke WW zwischen Nukleonen
    - ...
- Rate:

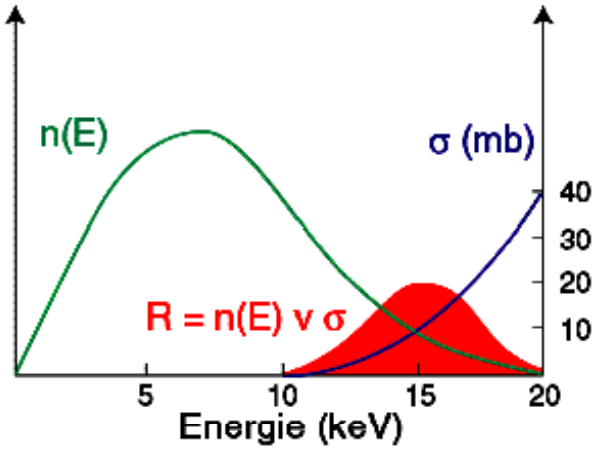
$$r = n_1 \cdot n_2 \cdot \sigma(E) \cdot v$$

- Tatsächliche Raten in der Sonne:

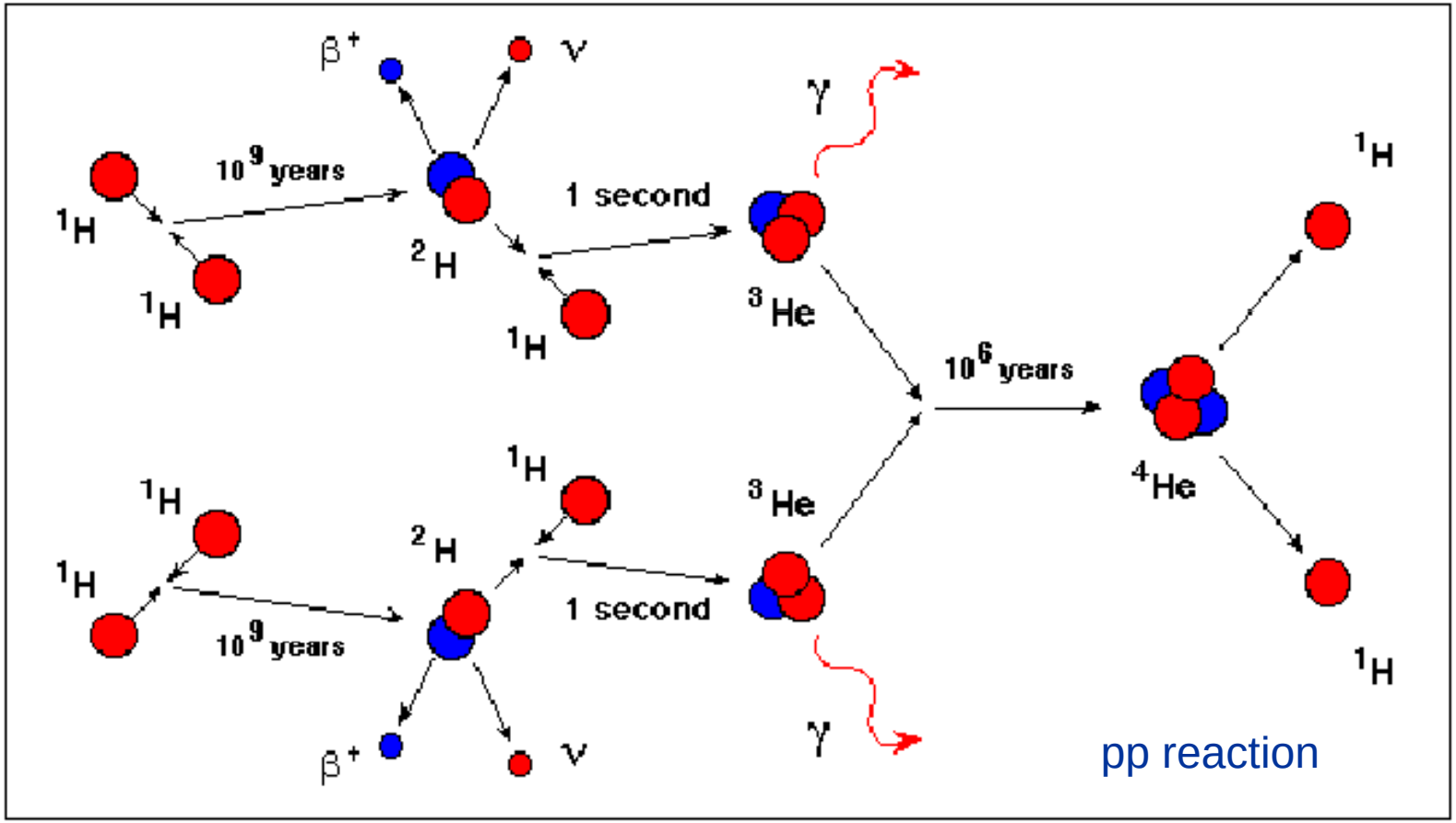
$$\tau(pp) \approx 10^{10}\text{a}$$

$$\rho(p) \approx 10^{20}\text{m}^{-3}$$

$$\Rightarrow 10^{9}\ \text{Reaktionen}/(\text{s}\cdot\text{cm}^3)$$



interior fusion



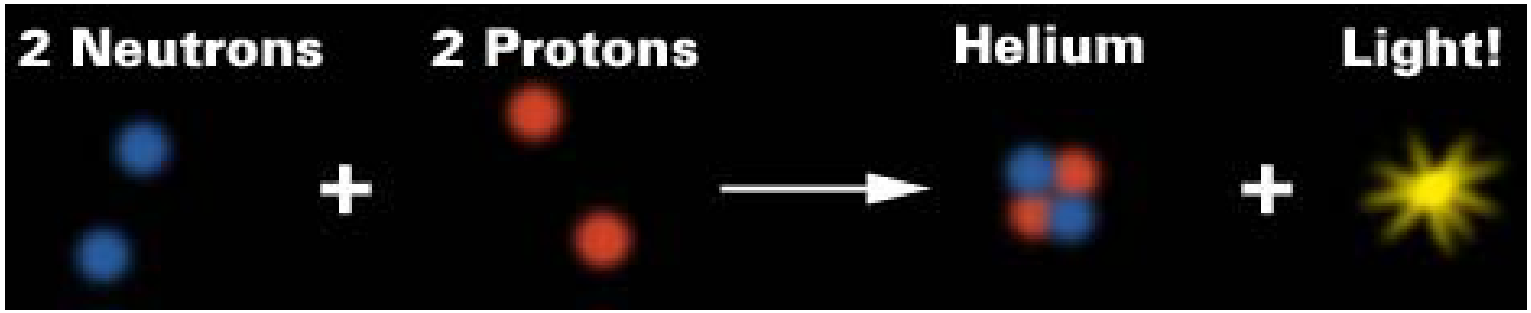
$^{1}H + {}^{1}H \rightarrow {}^{2}D + e^{+} + \nu + 1.44\ MeV \quad (14 \cdot 10^{9}a)$

$^{2}D + {}^{1}H \rightarrow {}^{3}He + \gamma + 5.49\ MeV \quad (6s)$

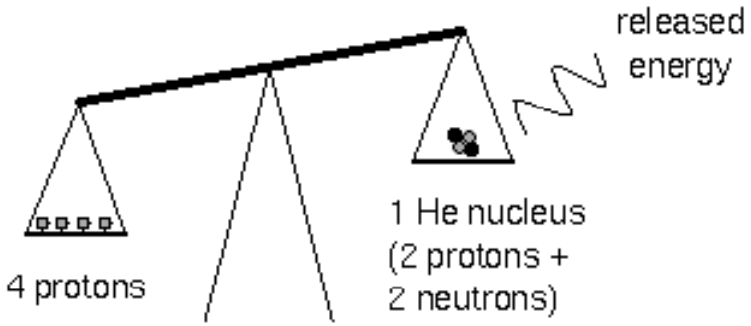
$2\ {}^{3}He \rightarrow {}^{4}He + 2\ {}^{1}H + 12.85\ MeV \quad (10^{6}a)$

interior fusion

particle balance :



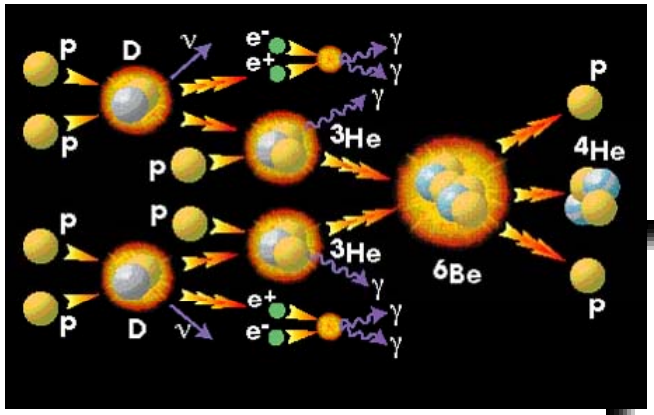
energy balance :

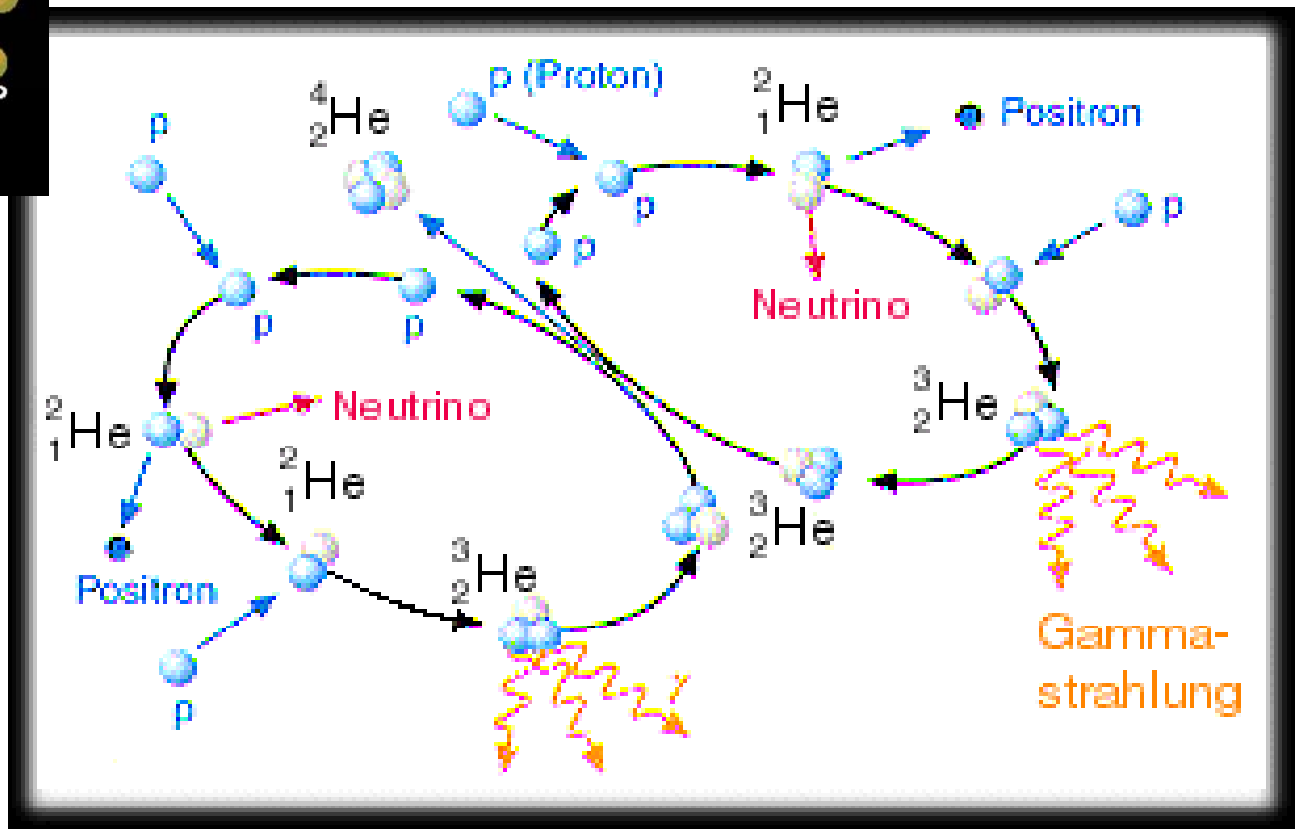


$\Delta E = 4.2 \cdot 10^{-12} J = 26.2 MeV$

Some mass is converted into energy ($E=mc^2$)

interior fusion





interior fusion

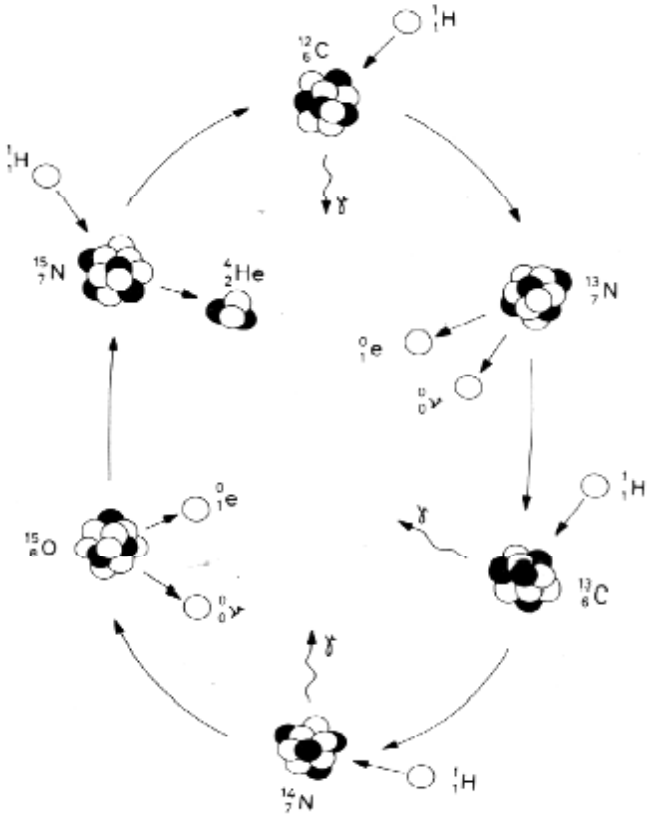
$4\,^1H \rightarrow {}^4He + 2e^+ + 2\nu$	Q = +26.731	
$^1H + {}^1H + e^- \rightarrow {}^2D + \nu$ (p-e-p)	1.442	(1.442)
or		
$^1H + {}^1H \rightarrow {}^2D + e^+ + \nu$ (p-p)	1.442	($\leq$ 0.420)
$^2D + {}^1H \rightarrow {}^3He + \gamma$	5.493	
$^3He + {}^3He \rightarrow {}^4He + 2\,^1H$	12.859	
or		
$^3He + {}^1H \rightarrow {}^4He + e^+ + \nu$ (hep)	19.795	
or		
$^3He + {}^4He \rightarrow {}^7Be + \gamma$	1.587	(9.625)
then		
$^7Be + e^- \rightarrow {}^7Li + \nu$	0.862	{0.862 MeV; 89.7% / 0.384 MeV; 10.3%}
and		
$^7Li + {}^1H \rightarrow 2\,^4He$	17.347	
or		
$^7Be + {}^1H \rightarrow {}^8B + \gamma$	0.135	
and		
$^8B \rightarrow {}^8Be^* + e^+ + \nu$	15.079	($\leq$ 14.02)
and		
$^8Be^* \rightarrow 2\,^4He$	2.995	

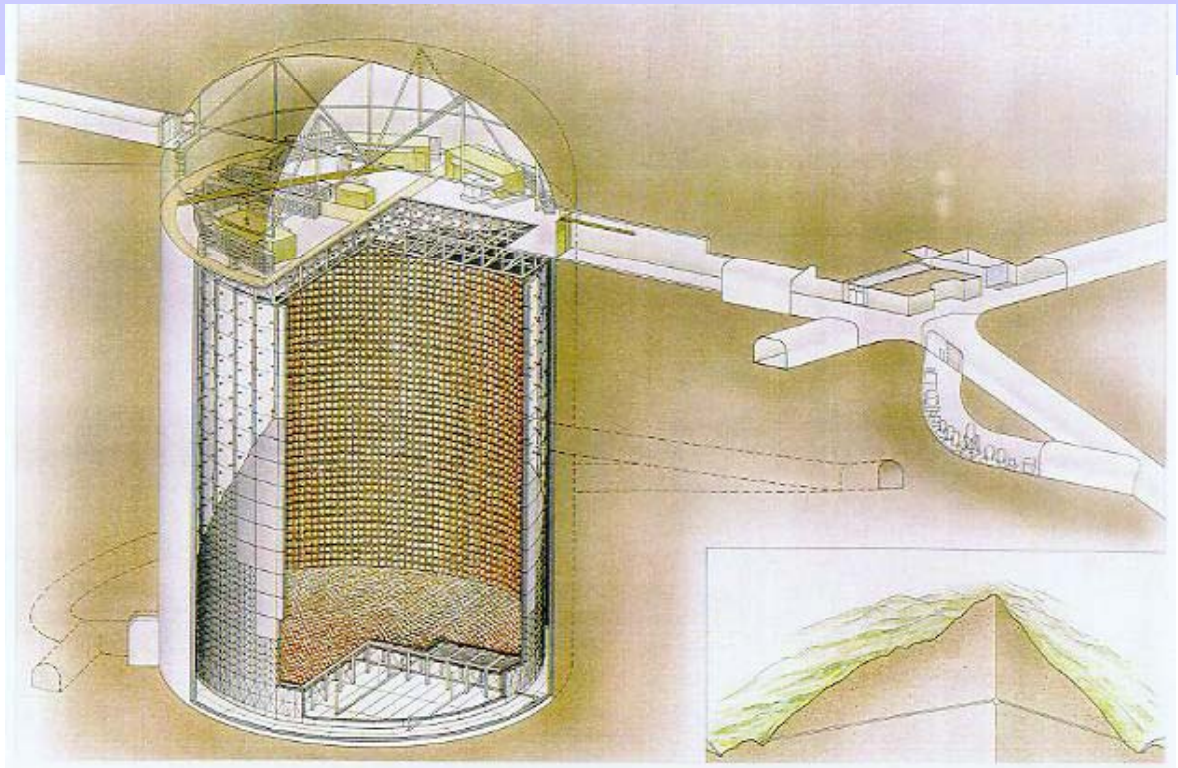
interior fusion

1. a) $^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \gamma$ Q=1,95 MeV b) $^{13}_{7}N \rightarrow ^{13}_{6}C + ^{0}_{1}\beta^{+} + ^{0}_{0}\nu$ Q=1,19 MeV
2. $^{13}_{6}C + ^{1}_{1}H \rightarrow ^{14}_{7}N + \gamma$ Q=7,55 MeV
3. a) $^{14}_{1}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma$ Q=7,35 MeV b) $^{15}_{8}O \rightarrow ^{15}_{7}N + ^{0}_{1}\beta^{+} + ^{0}_{0}\nu$ Q=1,68 MeV
4. $^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He$ Q=4,96 MeV

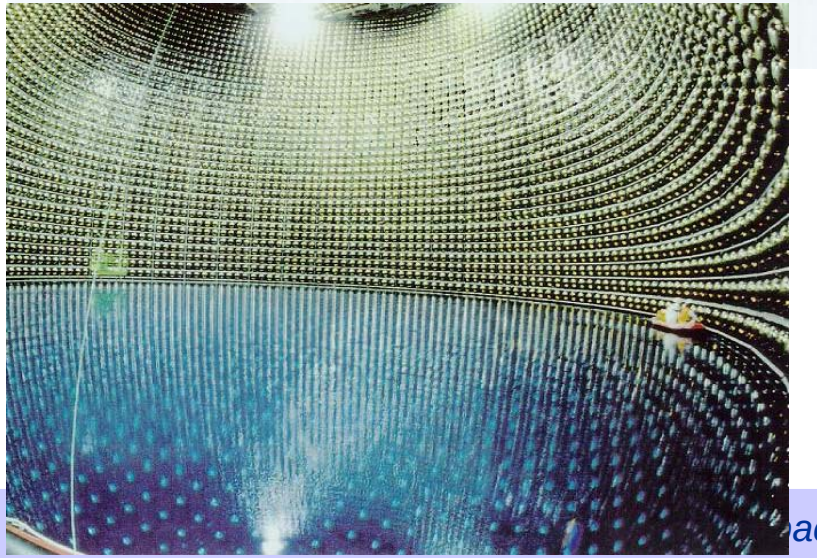
➔ Q_{ges}=24.68 MeV

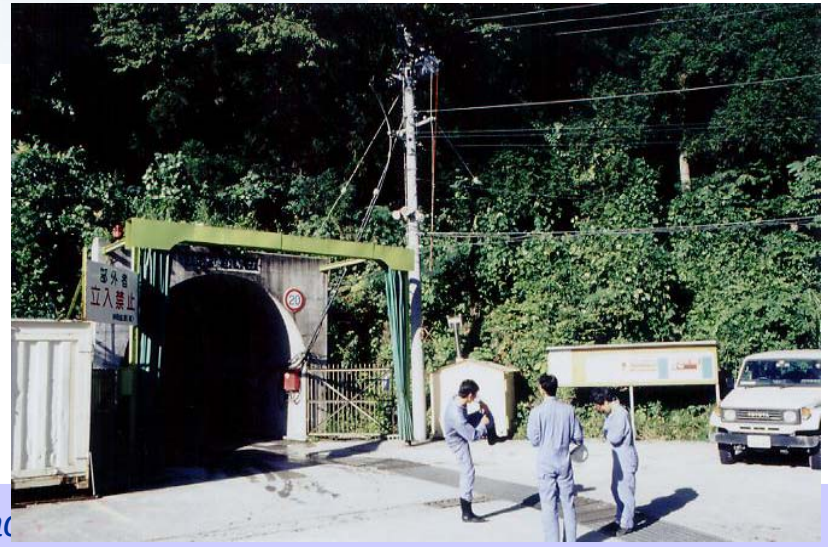
CNO cycle





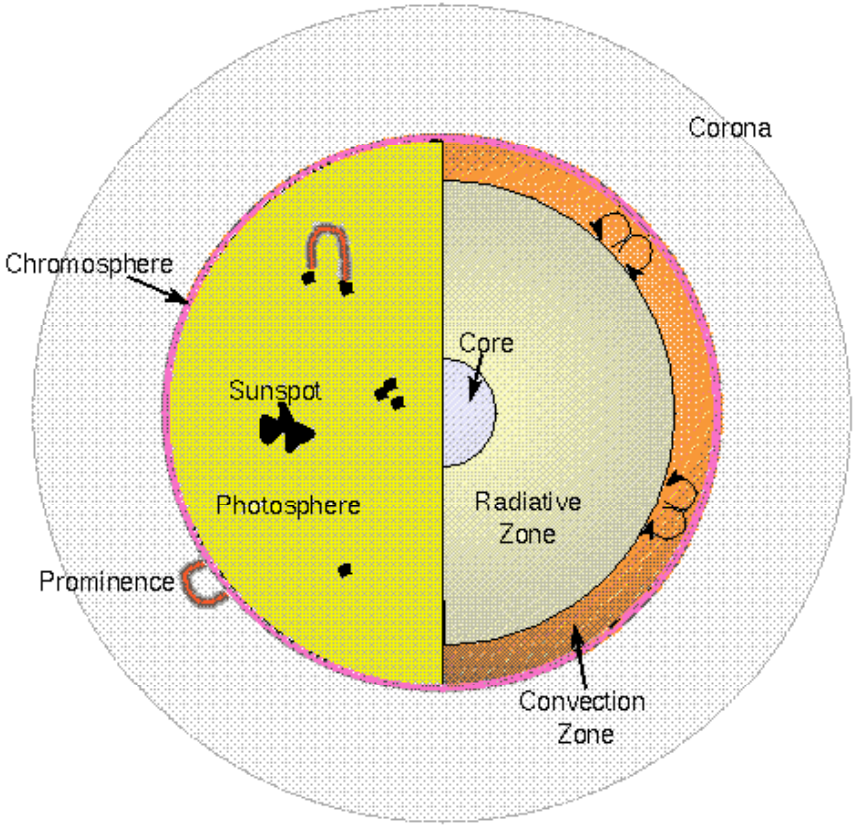
Super-Kamiokande

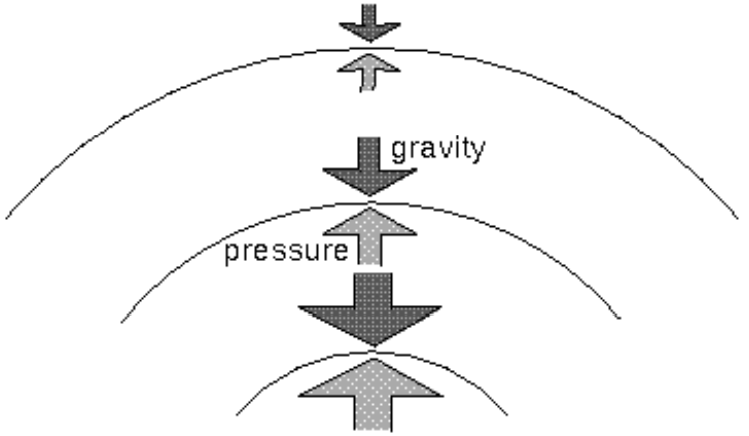




interior

Sun





Deeper layers have more gravity compression, so they have greater outward pressure to compensate.

Energy is generated in the **core** where the temperature reaches 16 million K and the density is 160 g/cm^3 and then transported outward by radiation. In the **convection zone** rising and falling gas is used to tranfer the energy to the **photosphere** (''surface'' of the Sun). **Sunspots** are cooler, dimmer regions with strong magnetic fields. Some sunspots have **prominences** forming over them. The **chromosphere** is a thin pink layer above the photosphere that is hotter than the photosphere. The temperature increases outward into the **corona**, the very hot (1–2 million K) but tenuous atmosphere of the sun. Fast moving ions in the corona escape the Sun to form the **solar wind.**

interior Sun

- fusion rate $R = \frac{L_O}{Q(4p)} = \frac{2.4 \cdot 10^{39} MeV/s}{26 MeV} = 1 \cdot 10^{38} s^{-1}$

- converted hydrogen

$$M^* = M(4p) \cdot R = 6.4 \cdot 10^{-24} g \cdot 1 \cdot 10^{38} s^{-1} = 6.4 \cdot 10^{14} g/s$$

- duration for fusion at L_O

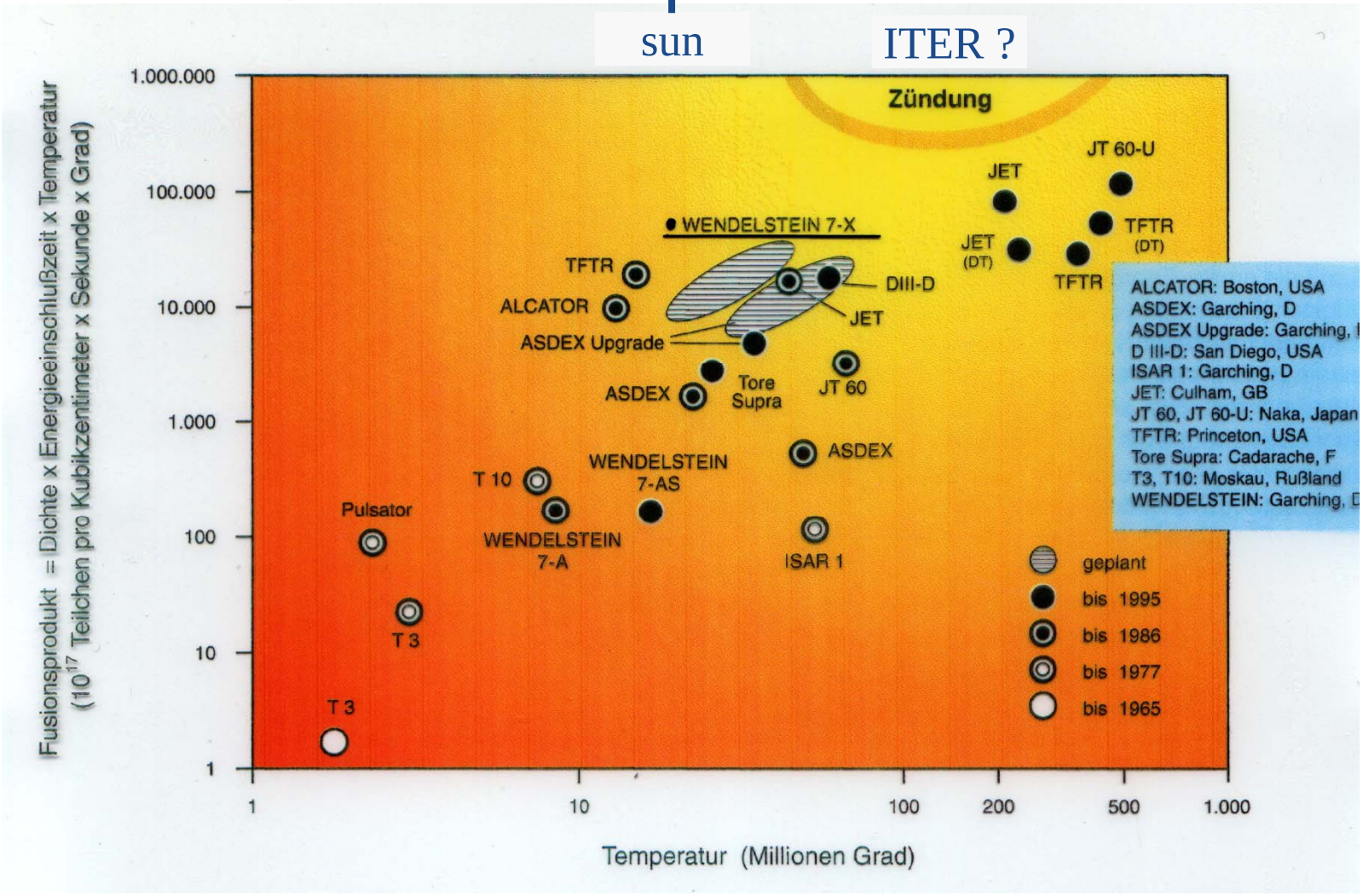
$$t_O = \frac{M_O}{M^*} = \frac{2 \cdot 10^{33} g}{6.4 \cdot 10^{14} g/s} = 3 \cdot 10^{18} s$$

- ***Sun = self-controlled fusion reactor***

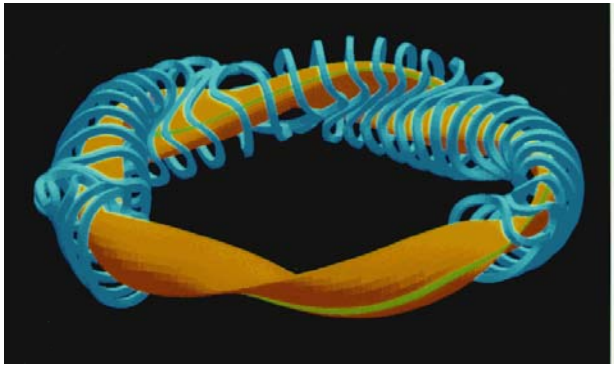
interior fusion

fusion plasmas

sun ITER ?



interior fusion



evolution of the Sun

evolution stars

stars :
compact plasma spheres in space

⟷ like Sun **!!!**

- stars at different states of evolution :
  ZAMS, main sequence, giant stadium, white dwarf

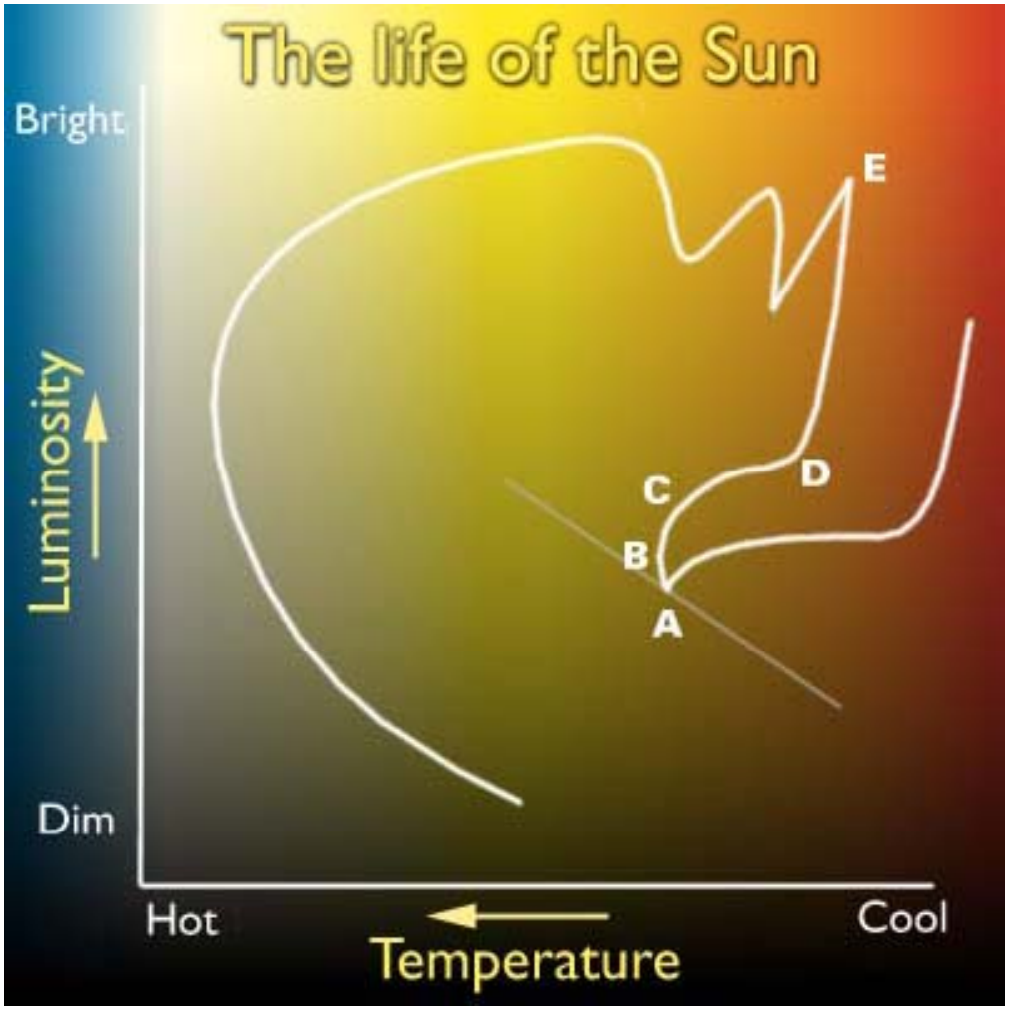
different states of plasma
⟷ (density, temperature, energy conversion)

nighty sky

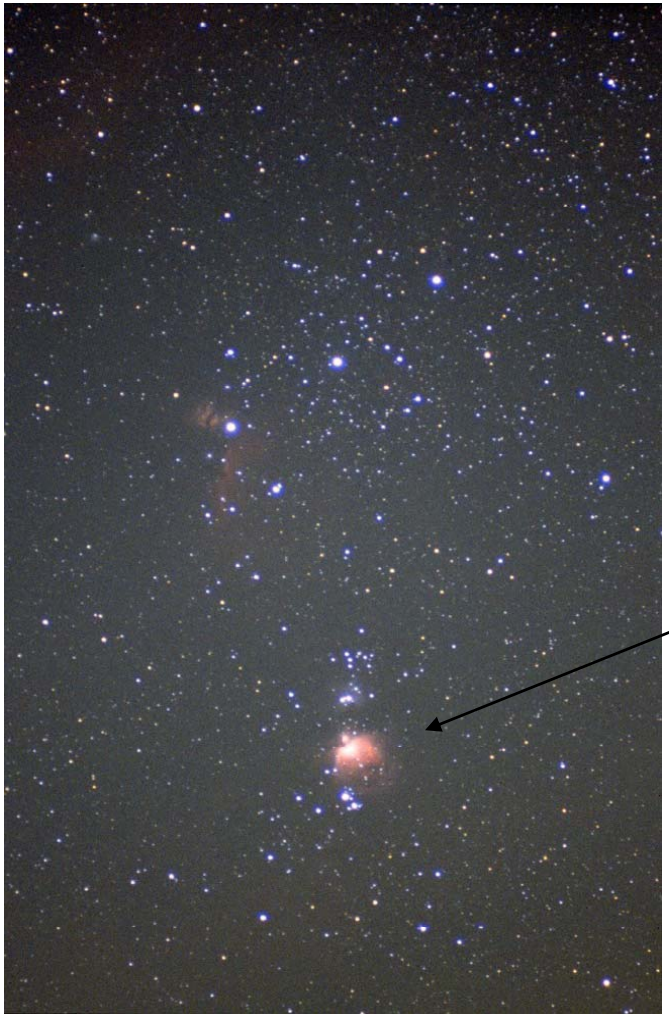
Prague
21.08.2009
23:00 MESZ

evolution

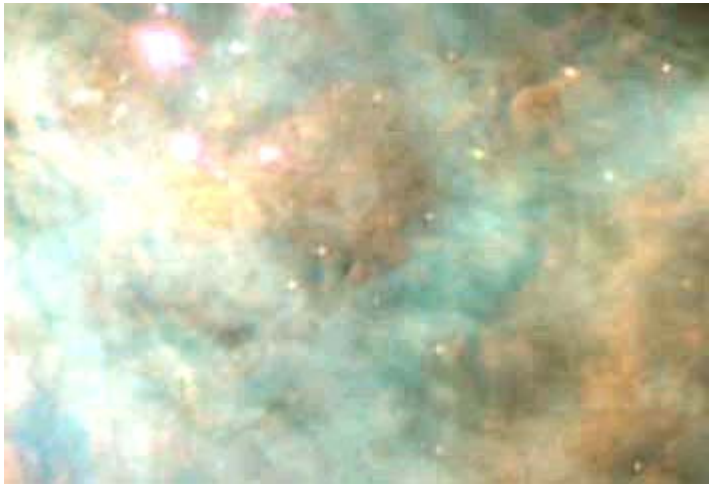
HRD for Sun



interstellar clouds

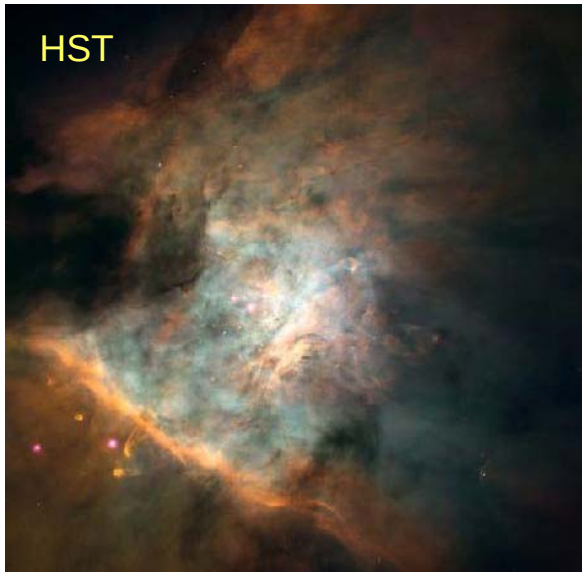


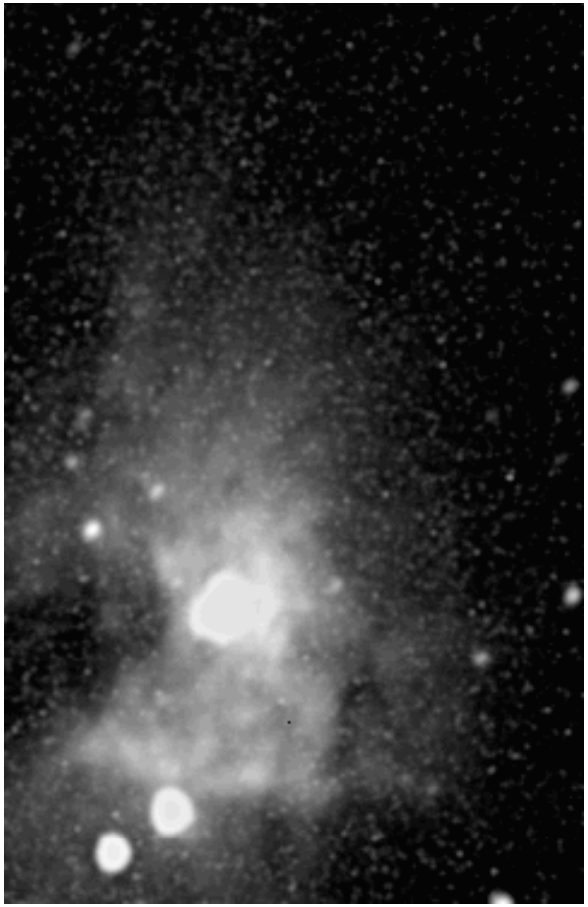
... are birth places for star,
e.g. Orion nebula M42



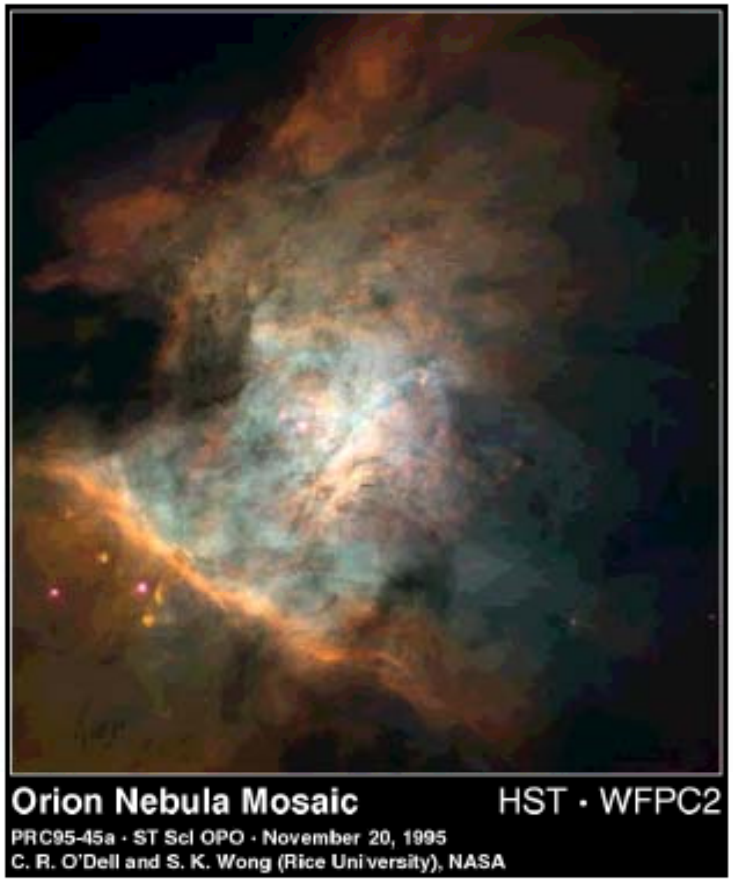
interstellar clouds

Orion nebula
M 42



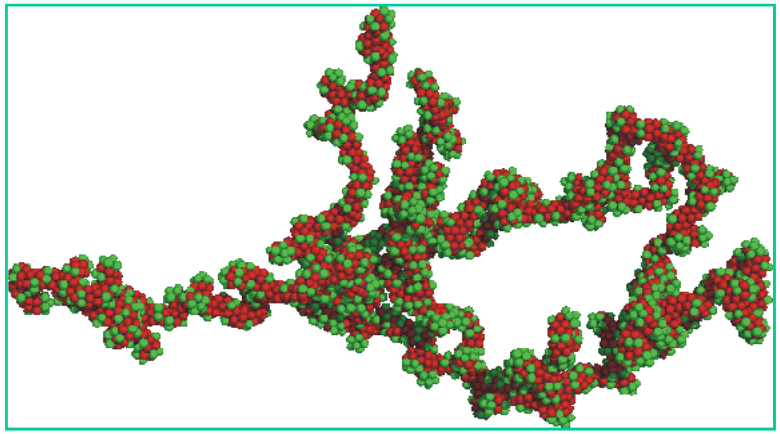


evolution interstellar clouds



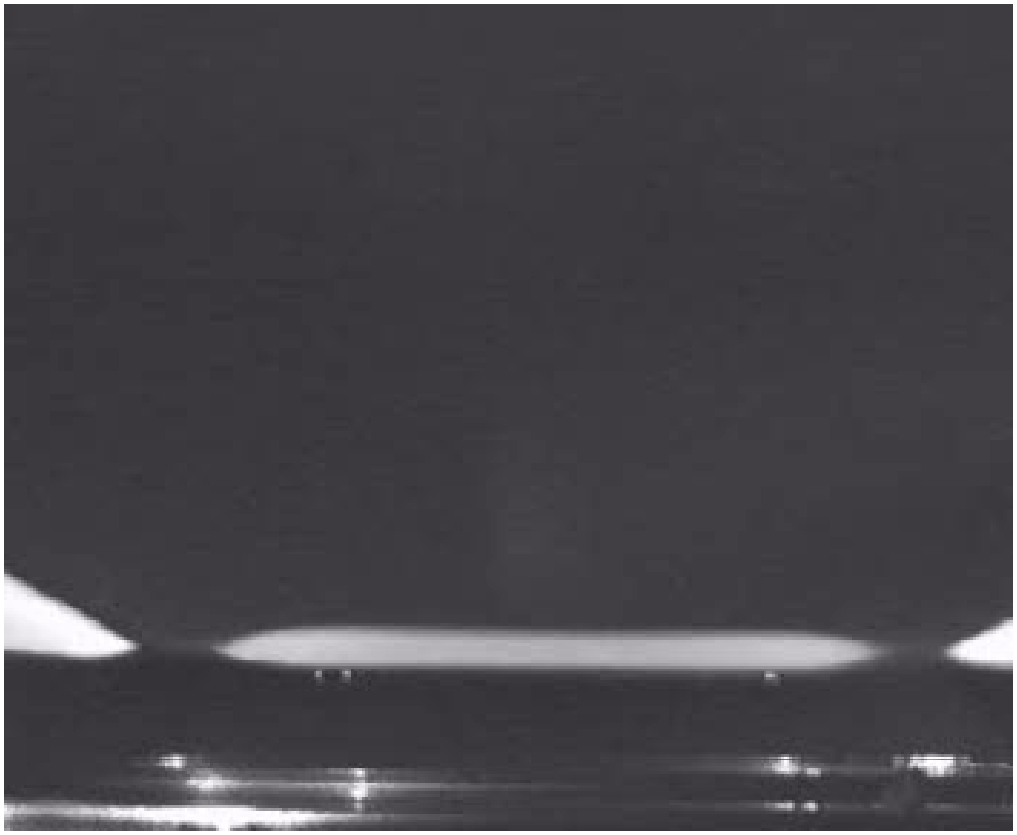
evolution

interstellar clouds



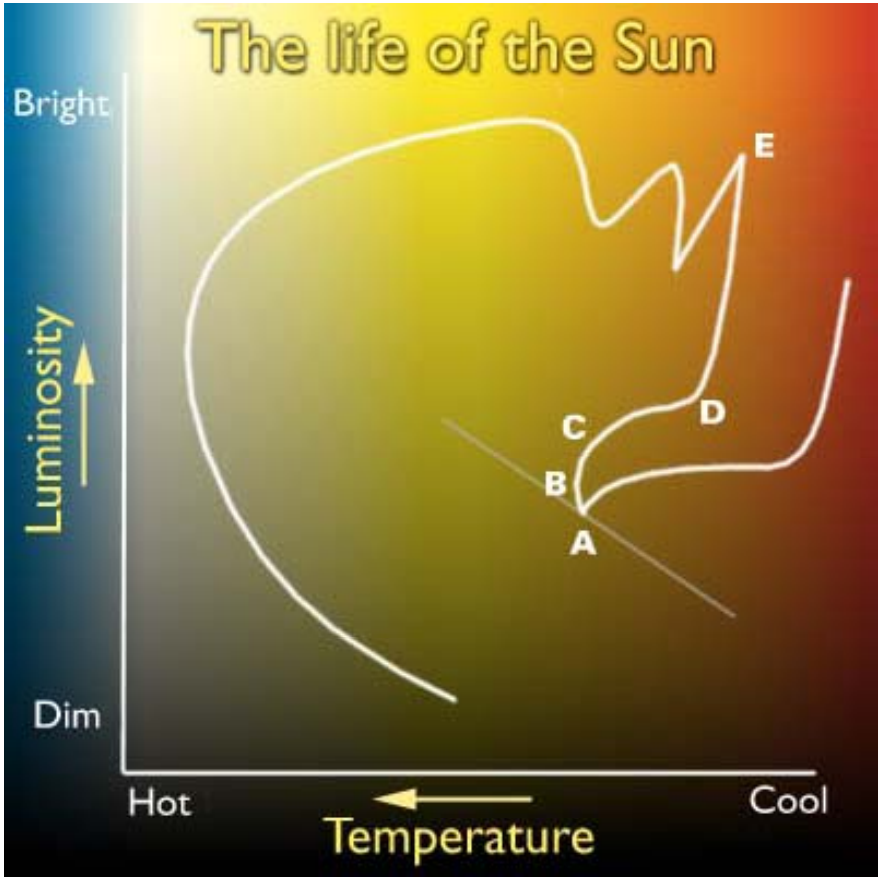
particle growth :
molecules, clusters, particles,
solids in pre-stellar clouds

dust in
interstellar plasma



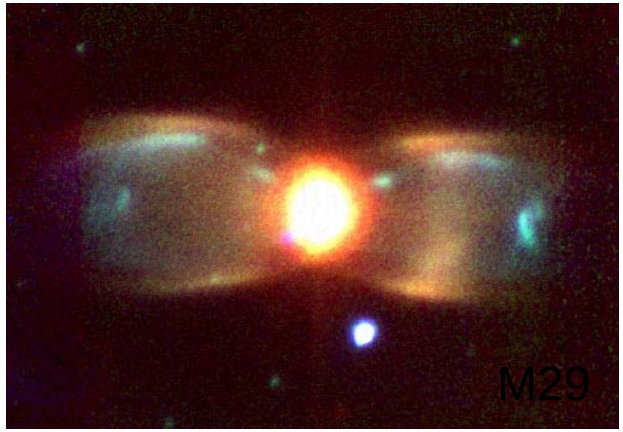
evolution

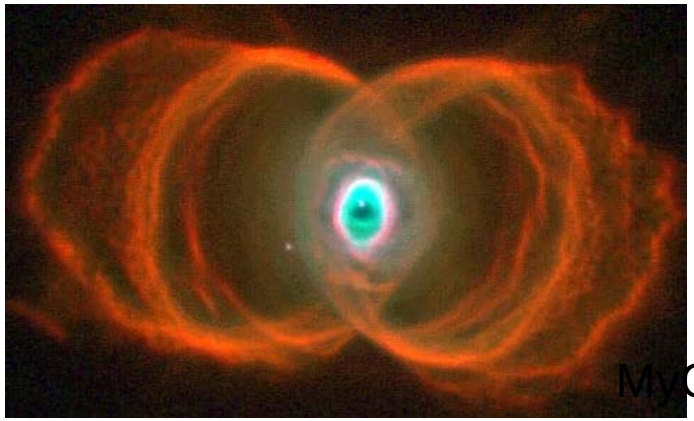
red giant

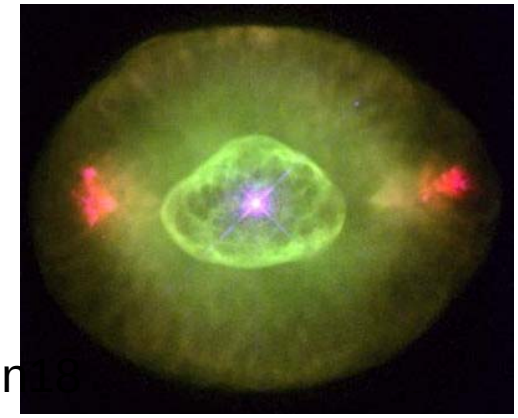


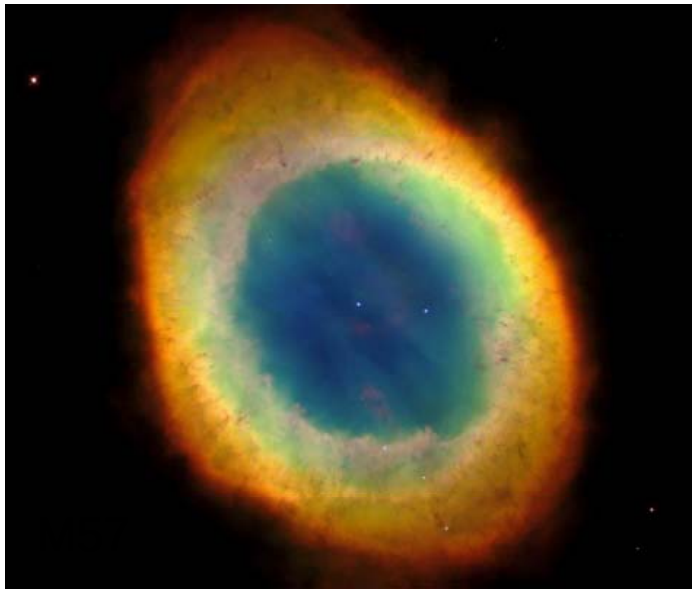
evolution interstellar clouds

planetary nebula

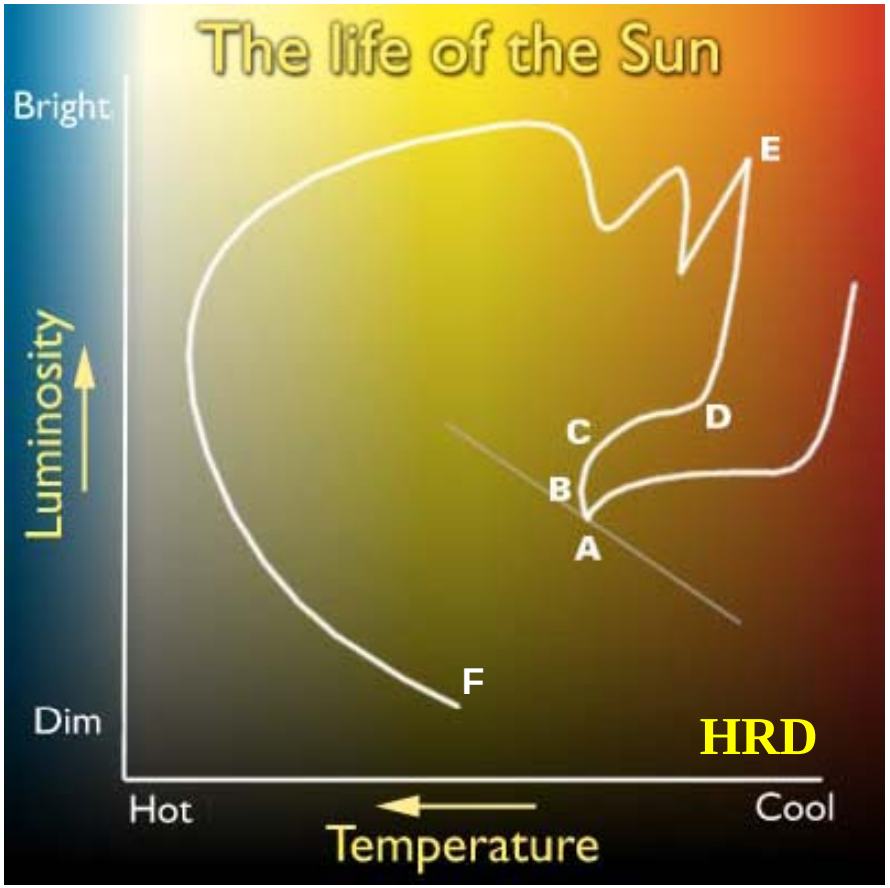
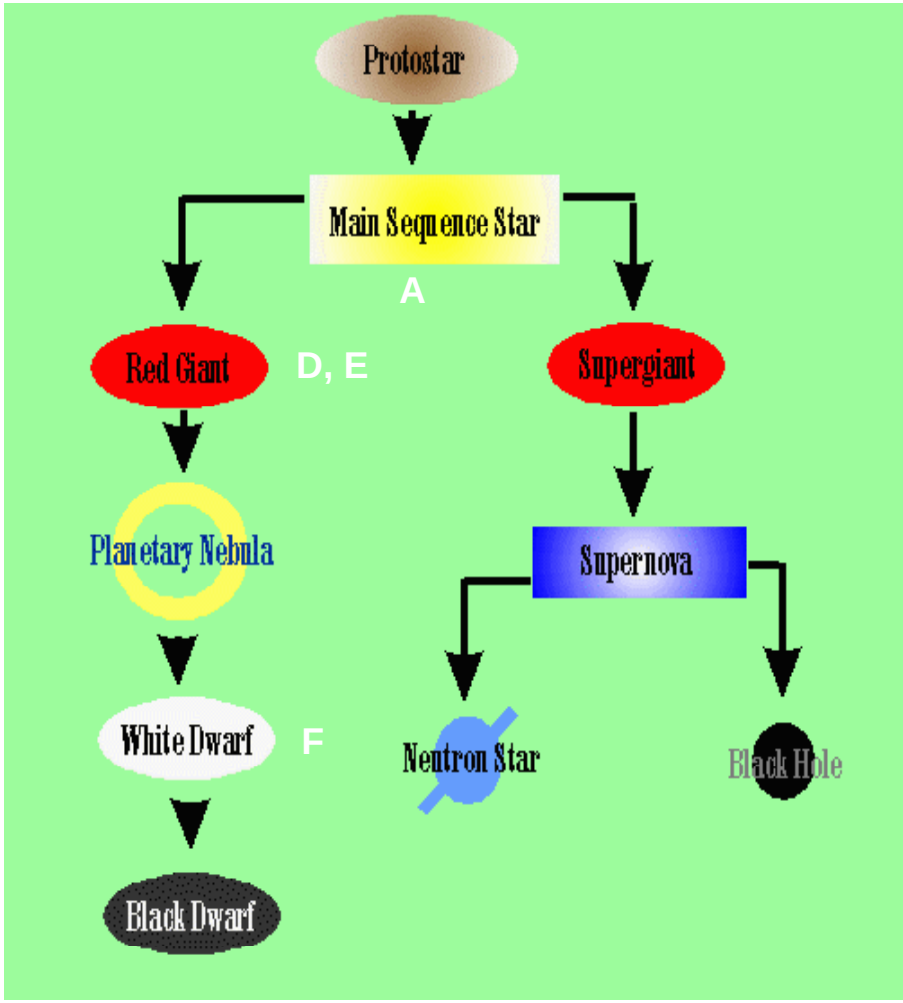








ring nebula

evolution

stars and Sun