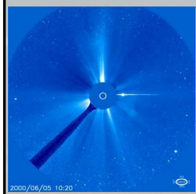
Introduction into the Physics of the Solar Corona and the Heliosphere
Lectures for the IMPRS, 28 Oct to 1 Nov 2002 at MPAe
by Eckart Marsch (M) and Rainer Schwenn (S)

Mon	9:30	S1	Introduction. Solar Output. Interior. Solar Radiation
	10:30	S2	Solar Corona: Observations (SUMER, LASCO etc). Facts
	11:30	M1	Solar Radiation and Magnetic fields
Tue	9:30	M2	Coronal Heating
	10:30	S3	Solar Wind: Facts
	11:30	M3	Coronal Expansion. Models
Wed	9:30	M4	Solar Wind Microphysics 1
	10:30	M5	Solar Wind Microphysics 2
	11:30	S4	Heliosphere in 3D
Thu	9:30	M6	Solar Wind Evolution
	10:30	M7	Turbulence and Waves
	11:30	S5	CMEs, Flares, Shock Waves
Fri	9:30	S6	Solar CycleVariations
	10:30	S7	Outer Heliosphere. Cosmic Rays
	11:30	M8	Solar Energetic Particles and Cosmic Rays

Physics of the heliosphere: an introduction



Lectures at the International Max-Planck-Research School Oktober 2002
by Rainer Schwenn, MPAe Lindau

1. **The Sun, our star: a survey.**
- A little introduction
- Basic data
- A thorough look into the Sun's interior
- The solar output: an overview
- Radiation from the Sun

The Sun as the source of life

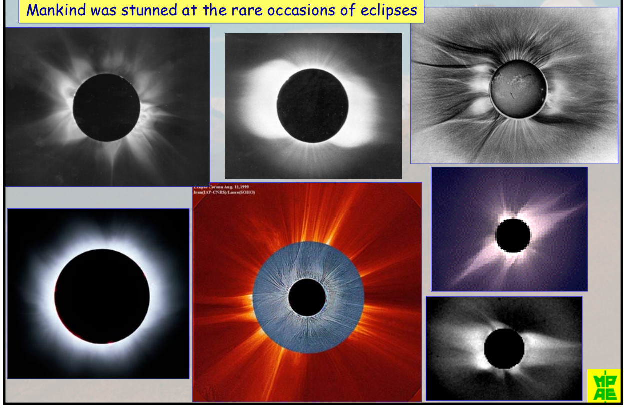
Mankind realized the Sun to be the source of all life on Earth: The Sun is God

Aton, the Sun, was declared God by king Echnathon in ancient Egypt

Sungod Huitzilopochtli in the center of the Aztec calender

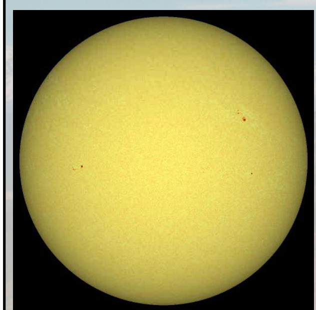
The miracle of eclipses

Mankind was stunned at the rare occasions of eclipses



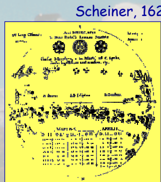
The turn from a divine into a scientific object

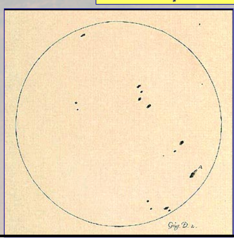
First scientific „remote sensing" of the Sun



MDI on SOHO, 2001

Scheiner, 1625

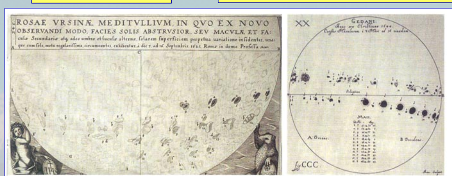


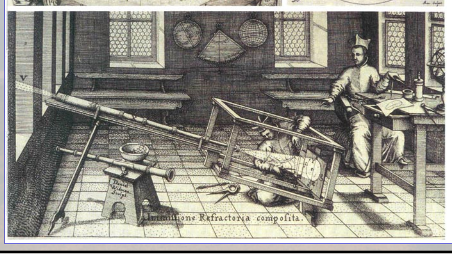


Galilei, from 1610

Sunspots

First scientific „remote sensing" of the Sun

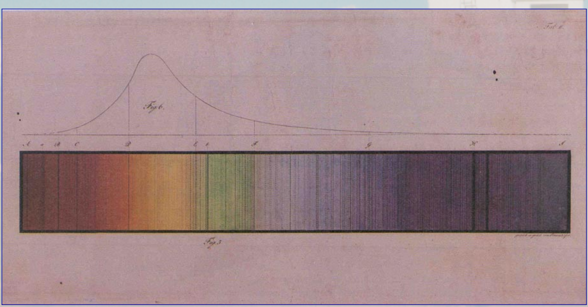




Christoph Scheiner (1575–1650), der auf einer zeitgenössischen Darstellung gerade ein Sonnenbild projiziert, und Johannes Hevelius (1611–1687) lieferten die ersten genauen Abbildungen der Sonnenoberfläche. Scheiners Sonnenzeichnung (links) vereint Beobachtungen, die zwischen dem 3. und 16. September 1625 gemacht wurden, während Hevelius für seine Zeichnung die Sonnenflecken zwischen dem 3. und 16. Mai 1644 registrierte. Beide bestimmten aus der Wanderung der Flecken die Lage der Rotationsachse der Sonne und die Zeit für eine Umdrehung

Progress in remote sensing: spectroscopy

The Sun's yellowish color is due to the fact that most energy is radiated in the yellow part of the visible spectrum, like from a „black body" at a temperature of 5800 K.



Fraunhofer's original spectrum showing solar absorption lines

The Sun, our star

Name	Sun	
Parent galaxy	Milky Way	
Type	fixed star	
Spectral class	G2	
Magnitude	+ 4.8	
Distance to Earth	149,598,000 km	i.e., 1 AU
Radius R_s	696,000 km	i.e., 109 R_E
Total mass M_s	1.989 x 10^{30} kg	i.e., 333.000 M_E
Density (average)	1.409 g cm^{-3}	
Surface temperature	5800 K	
Rotation duration	27.25 days (synodic), at equator, 25.38 days (sideric), at equator.	
Age	4.60 billion years	
Number of planets	9, plus many tiny ones	
Next neighbor star	Alpha-Centauri, at 4.37 lightyears	
Next neighbor galaxy	Magellan's Clouds, at 165,000 lightyears	
Earth's distance variation	+/- 1.69 % (+ in July, - in January)	
Apparent diameter	31' 59.3" = 1913.3 "	i.e. 0.5 degree
Apparent radius	959.65"	i.e. 1000 arcsec
1 arcsec on sun, from Earth	725 km	
Energy output	3.82 x 10^{33} Watt	
Energy input into Earth	1,370 Watt/m^{-2}	
total	173 Mio Gigawatt	

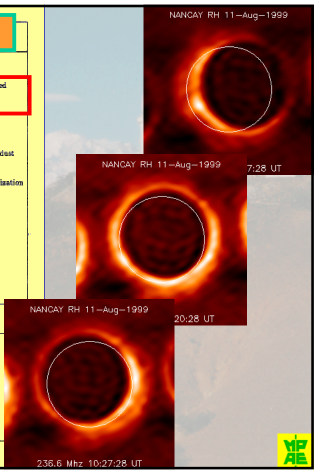
Solar output: an overview

Spectral range	Source	Characteristics
Radio mm IR	"quiet" corona and chromosphere	electromagnetic radiation from moving charged particles (thermal radiation).
white light	photosphere chromosphere K-corona F-corona	continuum, thermal radiation. line emission and absorption. spectral lines from various ions. continuum, photospheric light reflected from dust particles.
UV	chromosphere transition region corona	spectral lines from various ions at various ionization stages.
EUV	corona	see UV.
X-rays	upper corona "hot" corona, flares etc.	spectral lines as for UV, Bremsstrahlung. Bremsstrahlung.
γ-rays	strong flares	Bremsstrahlung + line emission from nuclear processes.

2. Particles

Type	Source	Characteristics
solar wind	corona	H^+ up to 2 keV, electrons up to 1 keV
"low energy" particles	transients; shocks	H,He,C,N,O up to ~ 100 keV
"energetic" particles	flares	energies up to ~ 100 MeV.

Table 2: Forms of solar output



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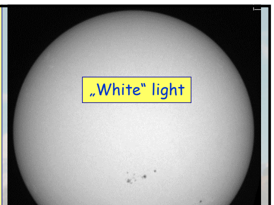

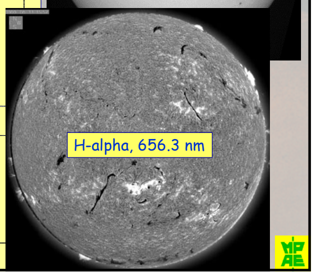

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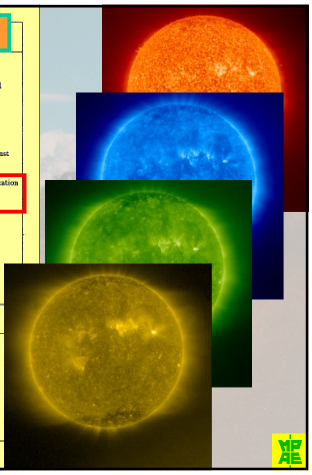

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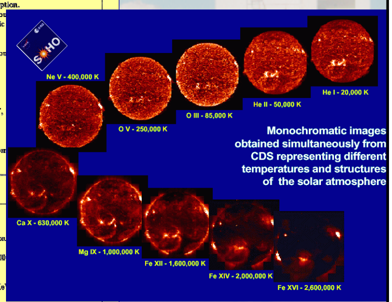

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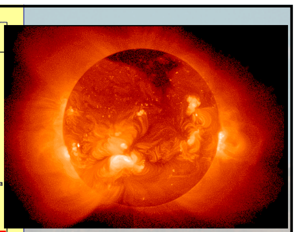

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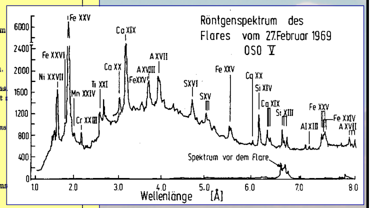

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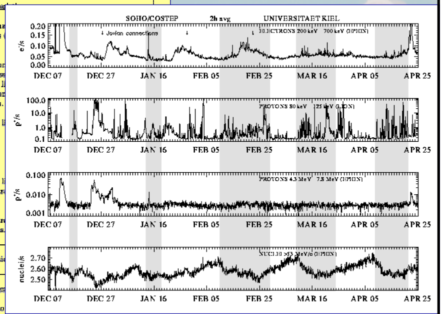

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Solar output: an overview

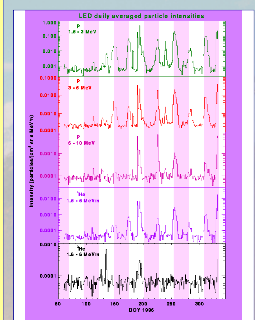


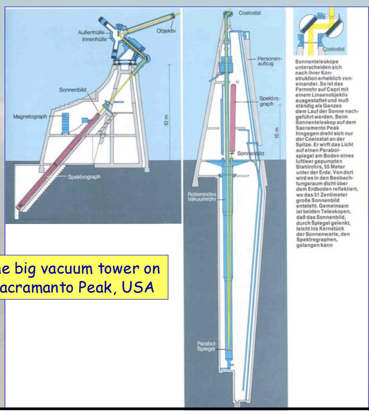
Table 2: Forms of solar output

The sources of knowledge

Solar observatories all over the Earth

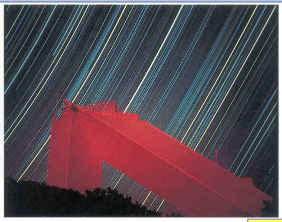
Bernhard Lyot put up his new coronagraph in the 1930s right here and saw, for the first time, the solar corona outside an eclipse

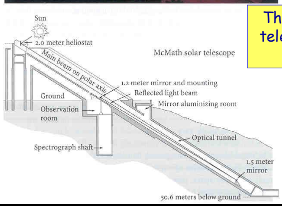
Solar observatories all over the Earth



The big vacuum tower on Sacramanto Peak, USA

Solar observatories all over the Earth





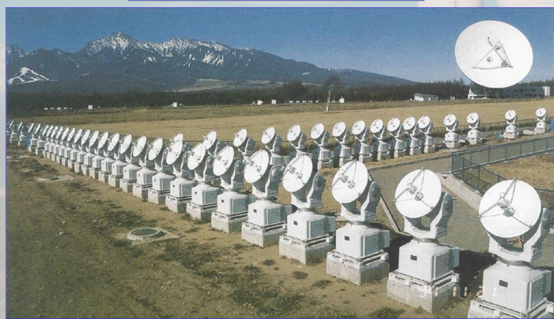
The worlds largest solar telescope on Kitt Peak, in Tucson, Arizona

Solar observatories all over the Earth

Several famous solar telescopes in Teneriffa (and La Palma)

Solar observatories all over the Earth

The Nobeyama (Japan) radioheliograph

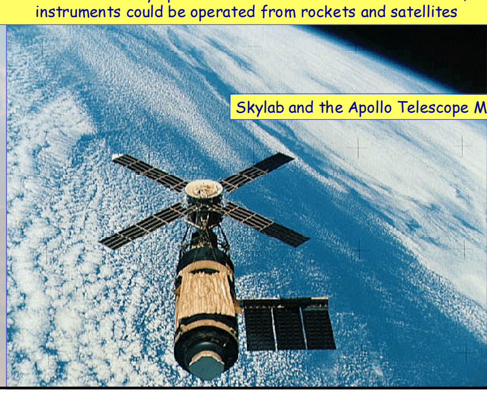


Large antenna arrys are needed for imaging the Sun in radiofrequencies

The German Argentinean Solar Observatory near San Juan, Argentina, with the MICA coronagraph (MPAe) and the HASTA telescope (MPE)

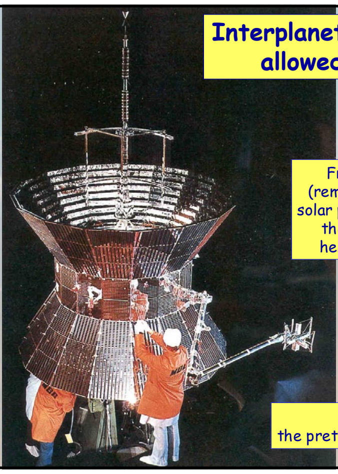
Remote sensing of the Sun from space

The solar UV and X-ray spectrum was revealed from the 1940s on, when instruments could be operated from rockets and satellites



Skylab and the Apollo Telescope Mount

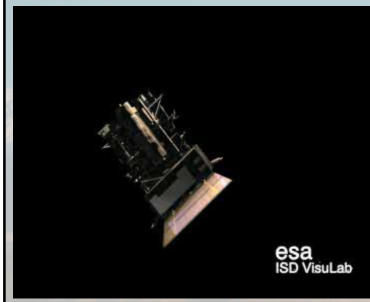
Interplanetary space probes allowed new insights



From 1973 on, with Skylab (remote sensing) and the Helios solar probes (in situ observations), the modern era of solar and heliospheric research began.

Helios,
the prettiest spaceprobe ever!

The best solar observatory ever



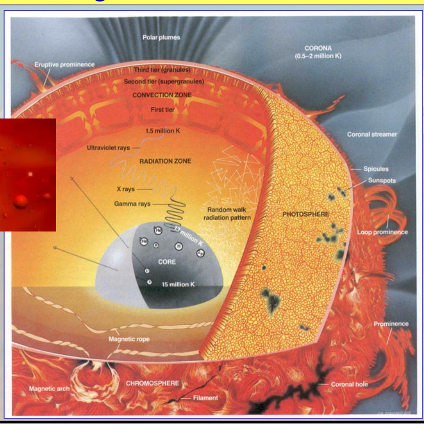
SOHO

Main scientific questions:

- Solar interior: what are the structure and dynamics?
- Corona: why does it exist and how is it heated?
- Solar wind: where ist it acelerated and how?

- The Solar and Heliospheric Observatory (SOHO) is a bilateral space project between ESA and NASA.
- It has been observing the Sun continuously since early 1996.
- Most data are on the Internet almost in real time!
- SOHO has allowed major discoveries in several disciplines

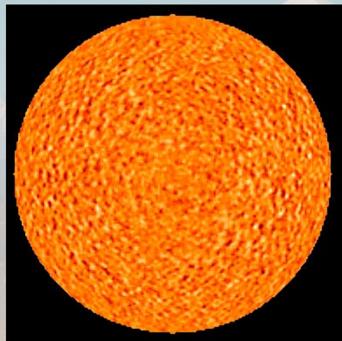
A thorough look into a star's interior!

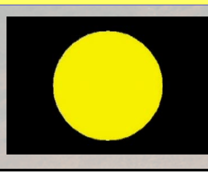


A thorough look into a star's interior!

Helioseismology

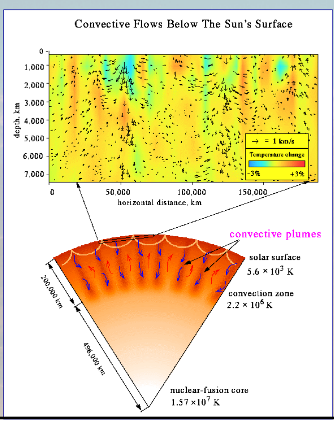
- The entire Sun vibrates from a complex pattern of acoustic waves.
- The sound waves are influenced by conditions inside the Sun.
- By observing these oscillations on the surface we can learn about the structure of the solar interior





From MDI on SOHO: 40000 times electronically sped up

A thorough look into a star's interior!



MDI on SOHO reveals flow patterns below the Sun's surface

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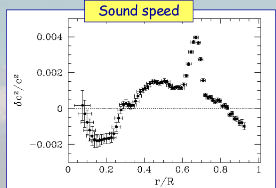
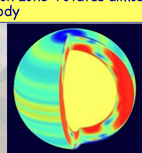
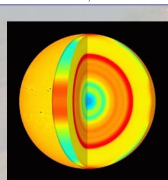


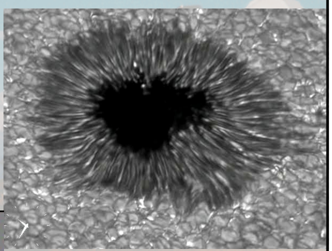
- Convection zone: differential rotation
- Radiation zone: rotates almost as a rigid body

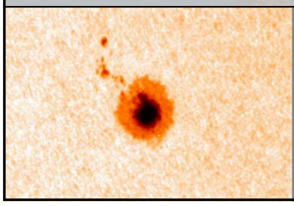




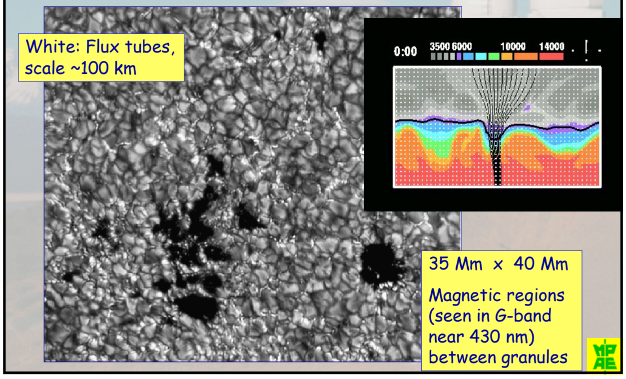
Sunspots and what is underneath!

- Sunpots are dark areas (umbra, penumbra) on the solar disk.
- They are due to strong magnetic fields which inhibit energy transport from solar interior.
- Their frequency varies with the 11-year solar activity cycle

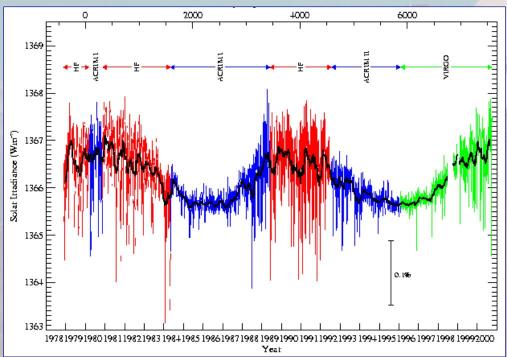




Small magnetic flux tubes and photospheric granulation



Solar irradiance: the Sun as a star



VIRGO on SOHO measures total solar irradiance

Some facts about radiation from the Sun

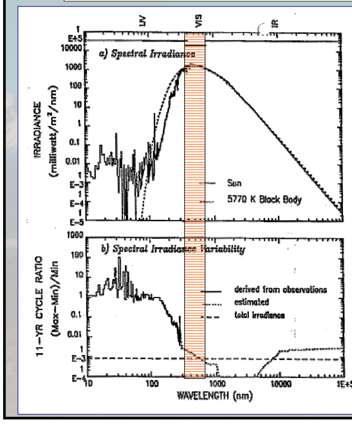


Figure 2. (*a*) The Sun's spectral irradiance typical of solar minimum conditions, compared with the spectrum of a blackbody radiator at 5770°K. The broad spectral bands identified along the top of this figure are the ultraviolet (UV), visible (VIS), and infrared (IR). Not shown, at wavelengths longward of the IR, is the microwave, or radio, portion of the solar spectrum. (*b*) The approximate amplitude of the Sun's spectral irradiance variation from the maximum to the minimum of the 11-year activity cycle is also shown. The variations at $\lambda < 300$ nm (solid line) were derived from satellite observations during solar cycle 21. The variations at longer wavelengths (dotted line) were determined from knowledge of the solar cycle variation in the fraction of the Sun's disc covered with active regions and of their contrasts (shown in Figure 11 and discussed further in section 3.2). The dashed line indicates the variation during solar cycle 21 of the total (spectrally integrated) irradiance. Note that solar cycle variations at wavelengths from 1100 to 3500 nm are predicted to be out of phase with solar activity, with a maximum negative amplitude of −0.03% at 1400 nm.

The Sun's radiation at the Earth

What we get through our atmosphere

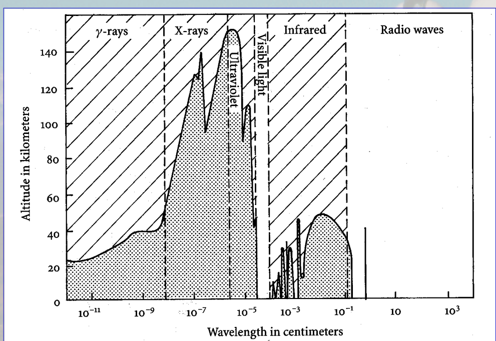
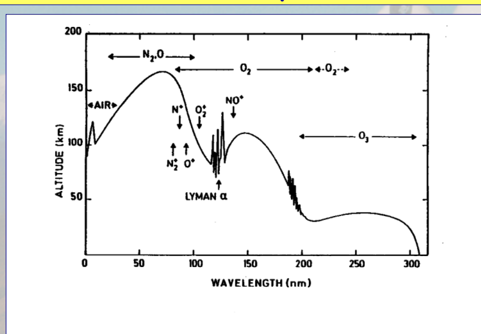


Figure 1. Depth of penetration of energetic short wavelength solar radiation as a function of wavelength. Altitudes correspond to an attenuation of 1/e for an overhead Sun. The main absorbers and ionization limits are indicated.

1/e penetration depth of UV light in the Earth's atmosphere



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Temperature changes in the Earth's atmosphere,
due to solar cycle variation of UV irradiation

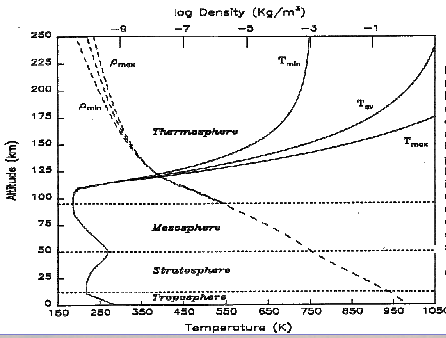
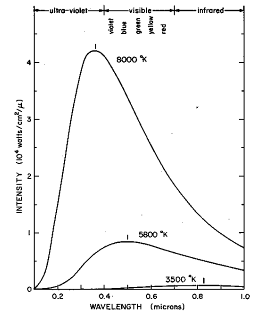


Figure 3. Temperature (T) and total mass density (ρ) of the Earth's atmosphere from the surface to 250 km. Boundaries of the atmospheric regions, called "spheres," are based upon inflections in the temperature profile which is determined largely by solar radiative heating. Temperature and density in the thermosphere vary significantly according to the level of solar activity because of changes in the UV radiation absorbed at these altitudes; profiles are shown for maximum, average, and minimum solar activity.

Planck's radiation law

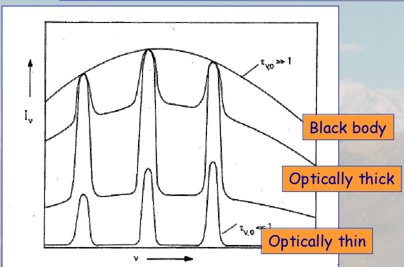


2.6 "Blackbody" curves showing how the intensity of radiation from perfectly efficient light emitters varies with wavelength, or color of the light. While real stars are not perfect emitters, the curves give an approximation of how the intensity of their radiation varies with color. An 8000° K star (such as Altair) is seen to emit most of its energy in the invisible ultraviolet, while a 3500° K star (such as Antares) emits most of its energy in the invisible infrared. A 5800° K star like the Sun emits most of its energy in the visible range. Note also that the intensity emitted per unit area of the star varies enormously with temperature (vertical scale at left).

The spectrum radiated from a „black body" depends solely on its temperature T,

$K_\lambda = hc^2 / (\lambda^5 (e^{hc/\lambda kT} - 1))$

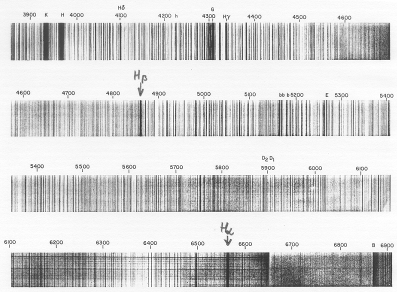
The concept of optical thickness



- Optically „thin" means: the intensity of emission lines is proportinal to the number of emitters along the line of sight.
- Optically „thick" means that not all emitted photons make it to the observer, because of absorption on the way.

Remember well: The blackbody radiation intensity is the maximum that a source with a given temperature can emit.

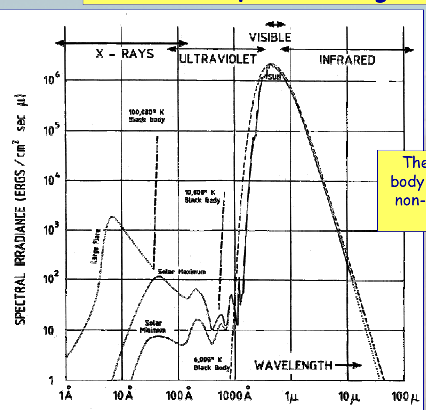
The solar spectrum: a gold mine!



2.8 Photographic image of the visible solar spectrum obtained with a large grating spectrograph. Wavelengths are given in Angstrom units at the top of the spectrum. The lines labeled B, C, D (shown here as D_1 and D_2), E, F, G, H, K are Fraunhofer's original description (see text). Also labeled are the hydrogen Balmer lines Hα (Fraunhofer's C line), Hβ, Hγ, and Hδ. (Courtesy Mt. Wilson Observatory, Carnegie Institution of Washington.)

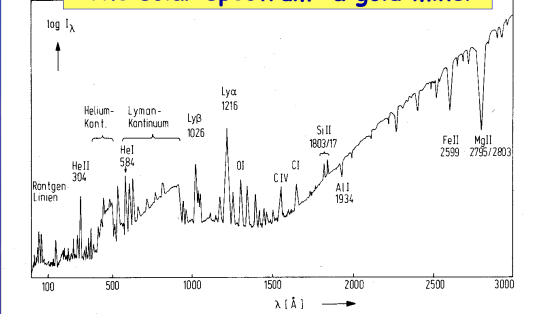
Almost all Fraunhofer lines are optically thin.
That allows to determine element abundances in the solar atmosphere

The solar spectrum: a gold mine!

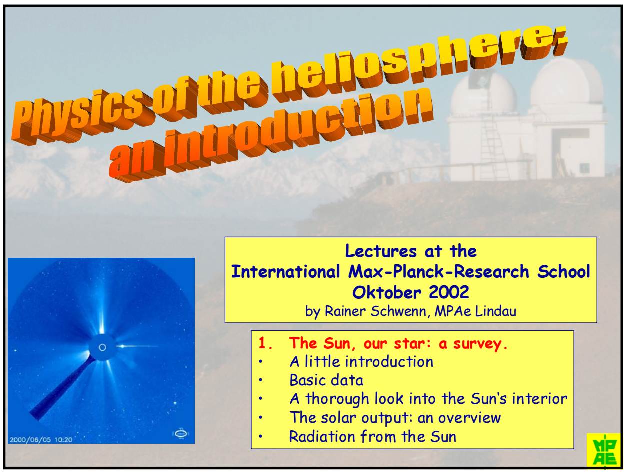


The Sun is not a black body, but close. Note the non-thermal radiation in the UV!

The solar spectrum: a gold mine!



Spectrum of the solar radiation in the visible and UV range. Note the transition from continuum radiation from photosphere (with Fraunhofer absorption lines) into the non-thermal emission line spectrum from the corona


Physics of the heliosphere:
an introduction
Lectures at the
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