The Sun

Basic Properties

Radius: $R_{Sun} = 6.96\times10^{5}\ \text{km} \approx 109\, R_{\oplus}$

$\Rightarrow \langle r \rangle_{Sun} = 1.41\,\text{g cm}^{-3}$

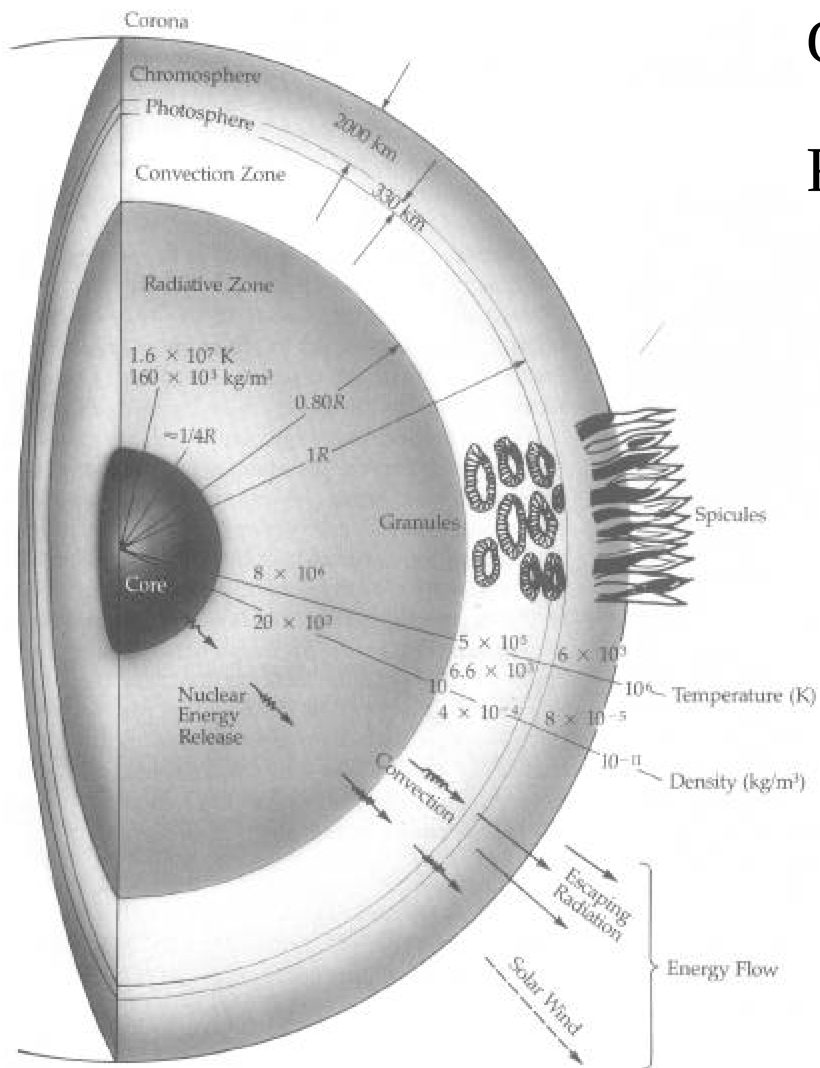
Mass: $M_{Sun} = 1.99\times10^{30}\ \text{kg} \approx 3.33\times10^{5}\ M_{\oplus}$

Luminosity: $L_{Sun} = 3.86\times10^{26}\ \text{W}$

Effective Temperature: $L_{Sun} = 4pR_{Sun}^{2}s\,T_e^{4} \Rightarrow T_e \cong 5770\,\text{K}$

The Sun is gaseous, hence rotates differentially. Shortest period at equator (about 25 days).

Structure of the Sun



	radius	T (K)	ρ (kg/m³)
Core:	$r \leq 0.25 R_{Sun}$	1.6×10^7	1.6×10^5
Radiative zone:	$0.25 R_{Sun} \leq r \leq 0.7 R_{Sun}$	8×10^6	2×10^4
Convective zone:	$0.7 R_{Sun} \leq r \leq R_{Sun}$	5×10^5	7×10^3
Photosphere:	$\Delta r \approx 300\,\text{km}$	6×10^3	4×10^{-4}
Chromosphere:	$\Delta r \approx 2000\,\text{km}$	$\leq 10^4$	8×10^{-5}
Corona:	$\Delta r \approx 0.01 R_{Sun} - 0.1 R_{Sun}$	$\geq 10^6$	10^{-11}

Upper corona merges into the Solar Wind.

Interior

Nuclear reactions in core via p-p chain:

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + n \qquad (1.44\,\mathrm{MeV})$$

$$^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + g \qquad (5.49\,\mathrm{MeV})$$

$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H} \qquad (12.9\,\mathrm{MeV})$$

Provides sufficient energy to explain observed luminosity. Photons diffuse through opaque Sun - emerge from surface after $> 10^5$ yr.

Only direct probes of solar interior are:

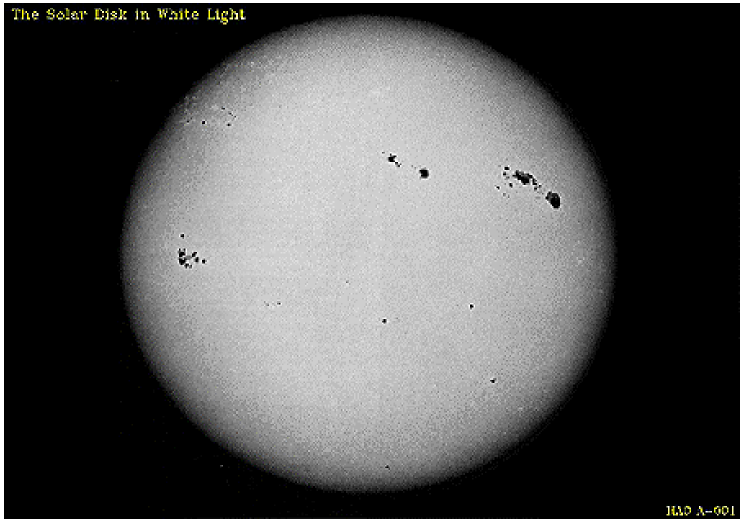
(1) Solar neutrino flux, since ν freely escape from core. However, only 1/3 -1/2 of expected number observed - solar neutrino problem;

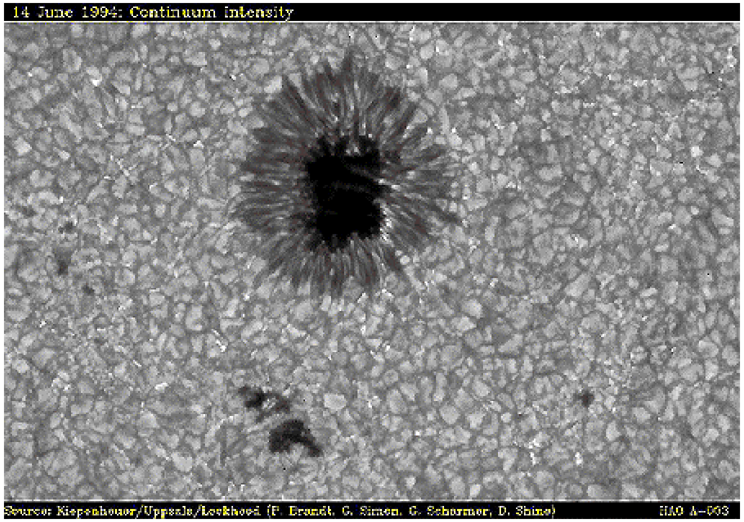
(2) Helioseismology - acoustic waves at surface reveal interior structure, like seismology on Earth.

Surface and Atmosphere

Surface features are a “perturbation” on solar model. Do not affect interior energy generation or evolution, but can have terrestrial consequences.

Photosphere - the effective “surface” of the Sun.





Sun in visible light.

Close-up view of granulation.

Note sunspots and granules, and limb darkening of sphere.

Photosphere

Granules - bright spots surrounded by dark lanes, i.e., hot upwelling fluid and cooler downflowing fluid. Caused by convection. Scale ~ 1000 km.

Sunspots - Dark patches. Cooler (~3800 K) than rest of photosphere. Strong magnetic fields (~0.1 T vs. average 10^{-4} T). Convective energy transport inhibited by magnetic field.

Can understand the effective surface (photosphere) and limb darkening of the Sun in terms of optical depth τ.

Optical Depth

Radiation is absorbed within the Sun due to <u>opacity</u> κ_λ. Note that the mean free path of a photon is $l_{mfp}=1/\rho\kappa_\lambda$.

Consider flux of photons trying to reach us from depth *x* within star:

$$\frac{dF_l}{dx} = -\frac{F_l}{l_{mfp}} \Rightarrow dF_l = -k_l r F_l dx.$$

For ρ, κ_λ constant, get $F_l(x) = F_l(0)\exp(-k_l r x)$.

Define optical depth τ to be the distance normalized to l_{mfp}

$$dt = dx/l_{mfp} = k_l r dx \Rightarrow F_l(t) = F_l(0)\exp(-t).$$

Rule of thumb:

$\tau > 1$ => most radiation does not reach us.

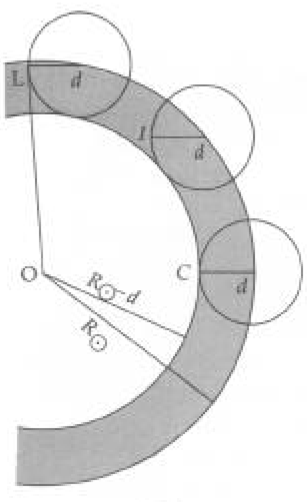
$\tau < 1$ => radiation flies outward and reaches us.

Optical Depth

$\tau = 1$: where photons make transition from "random walk" to "flying", i.e., the photosphere.

Opacity beneath the photosphere due to H^- ion. Absorption of photon via dissociation reaction $H^- + g \rightarrow H + e^-$.

Limb darkening: $\tau = 1$ samples hotter regions (more emission) towards center, and cooler regions (less emission) towards edge. This due to T increasing with depth.

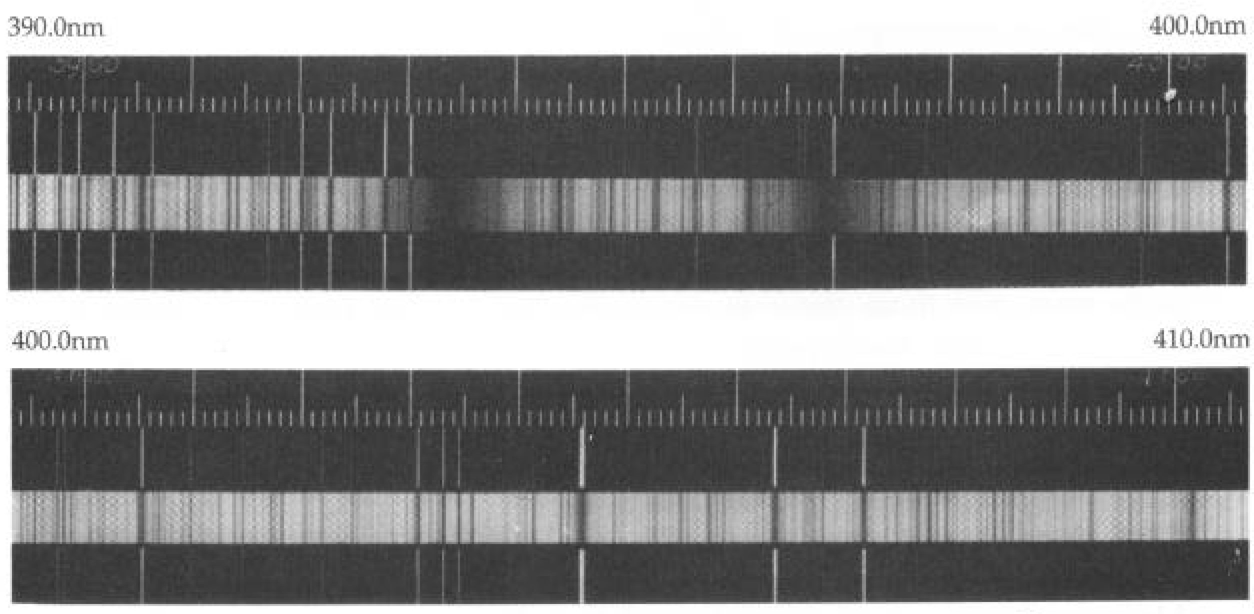


Geometry of limb darkening for a uniform density sphere.

Absorption Lines

Presence of atoms capable of making a particular transition increase the opacity at a particular wavelength λ.

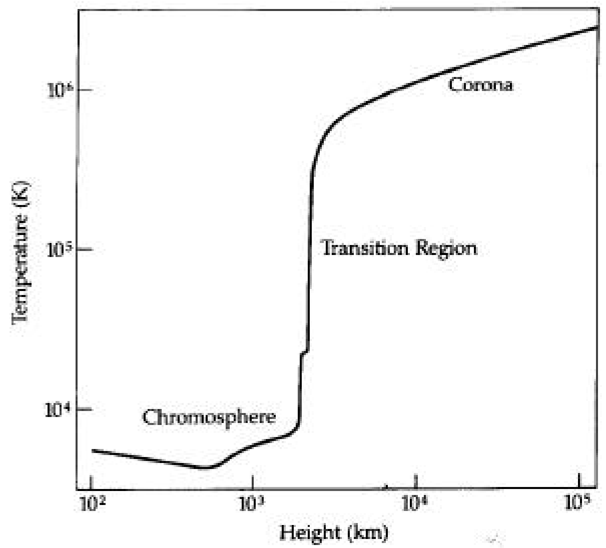
Optical depth τ increases => observations sample higher, cooler part of photosphere at that λ. Get apparently less emission at that λ than from surroundings => absorption line.



Solar spectrum

Chromosphere and Corona

Temperature rises in the chromosphere, and especially the corona.

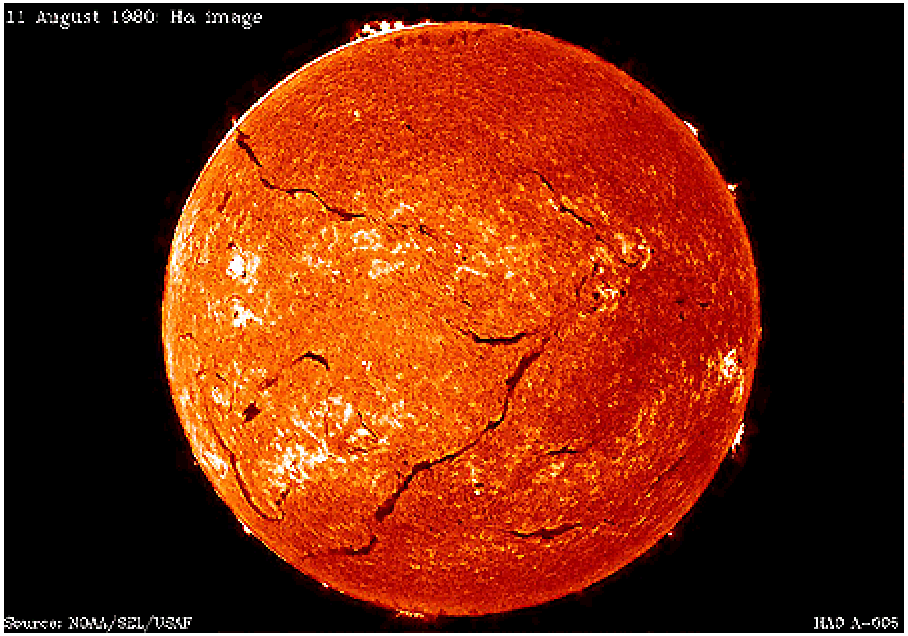


Temperature rise with height is contrary to expectations of thermal equilibrium. Source unknown. But required energy is relatively small. Thermal energy density *U = 3/2 n k T* =>

$$\frac{U_{corona}}{U_{photosphere}} = \frac{n(corona)}{n(photosphere)} \frac{T(corona)}{T(photosphere)} \approx \frac{10^{-11}}{10^{-4}} \frac{10^{6}}{6000} = 1.7 \times 10^{-5}.$$

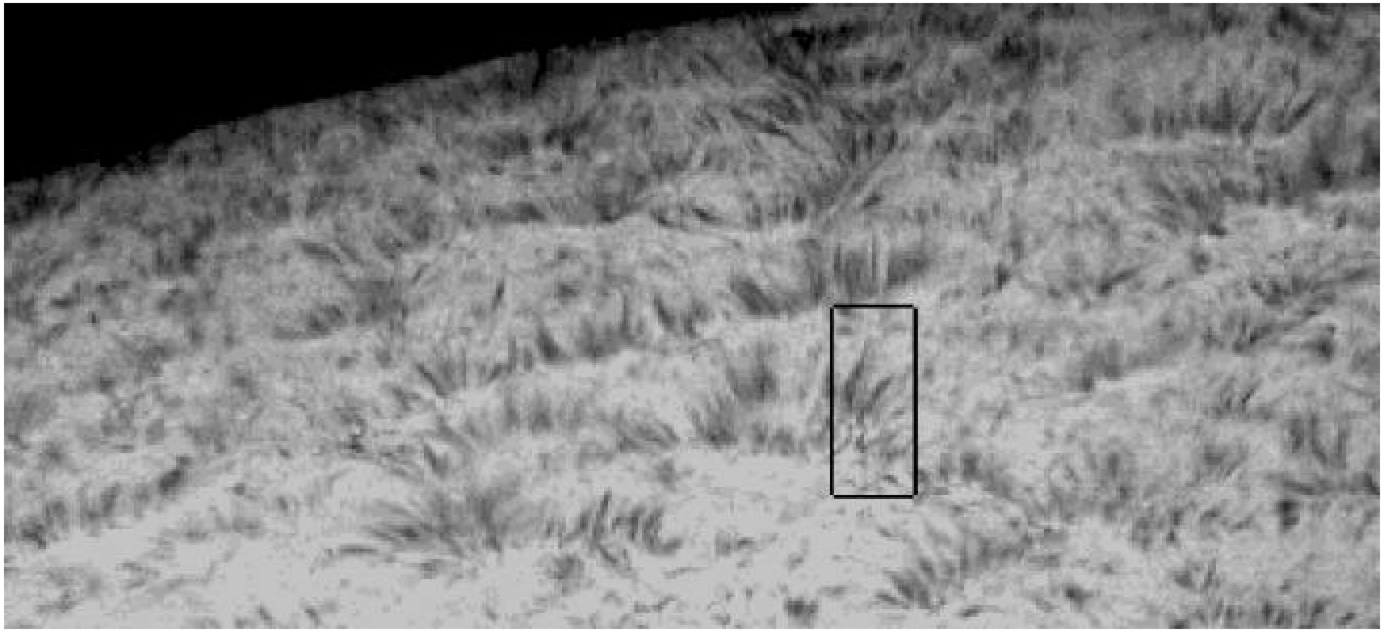
Chromosphere

Balmer lines formed here - need higher T to get n=2 states populated. Hα and Ca II H and K lines prominent. Helium (He) first identified here.



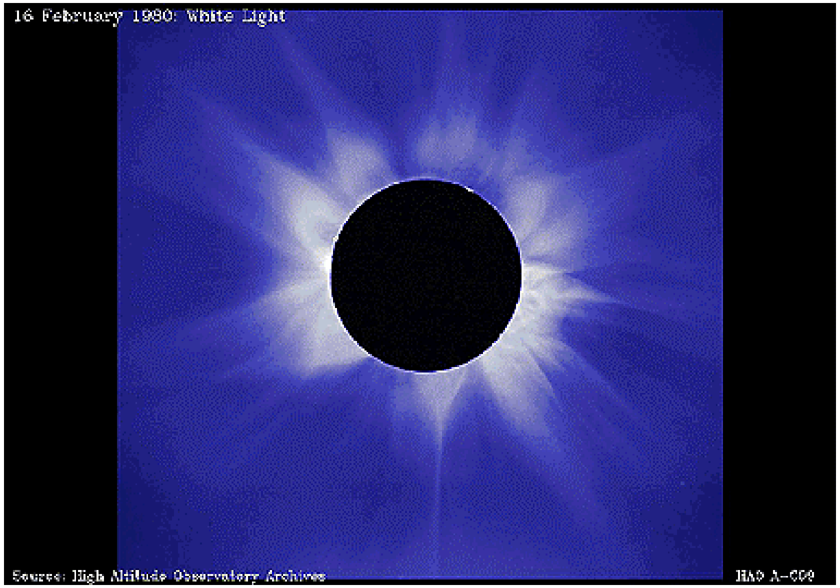
Sun in Hα line. Note the bright regions (plages) and filaments (prominences) consisting of relatively cooler material suspended at large heights.

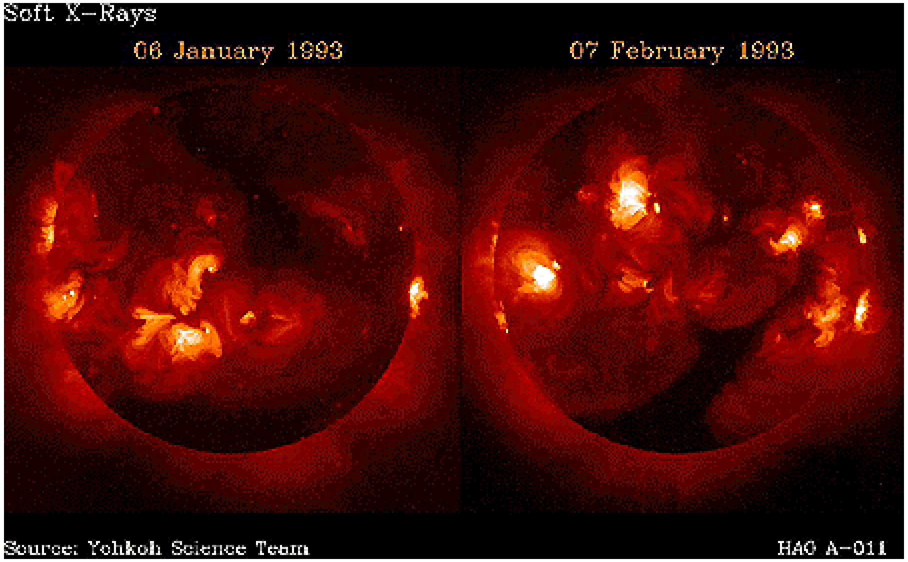
Chromosphere



A closer view also reveals spicules, glowing jets of gas which are distributed in a network pattern in regions of enhanced magnetic field.

Corona





Total solar eclipse, 1980

The Sun in X-rays, Jan/Feb. 1993

$T \geq 10^6$ K. Seen mainly in x-rays, with prominent emission lines of Fe X (637.4 nm) and Fe XIV (530.3 nm).

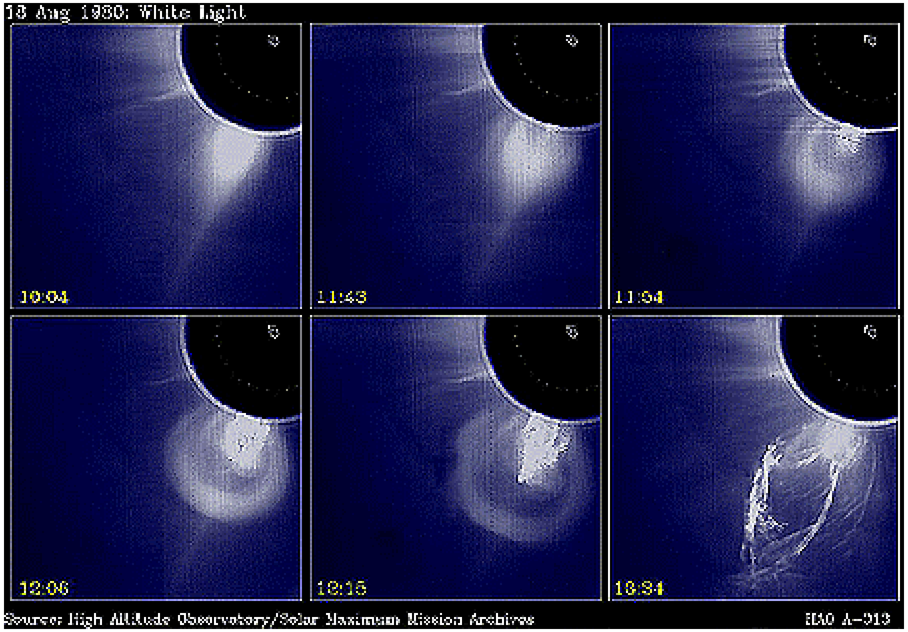
Consists of loops of magnetic field and ionized gas. Heating of corona from base of loops? Also, find coronal holes along which solar wind escapes. Charged particles reach Earth with speed ~ 500 km/s.

Corona

Energetic phenomena:

(1) Flare - A transient outburst of large quantities of energy in the form of radiation (x-ray, visual, radio) and charged particles. Related to magnetic structures in atmosphere. Can have terrestrial consequences (30 min to 24 h arrival time).

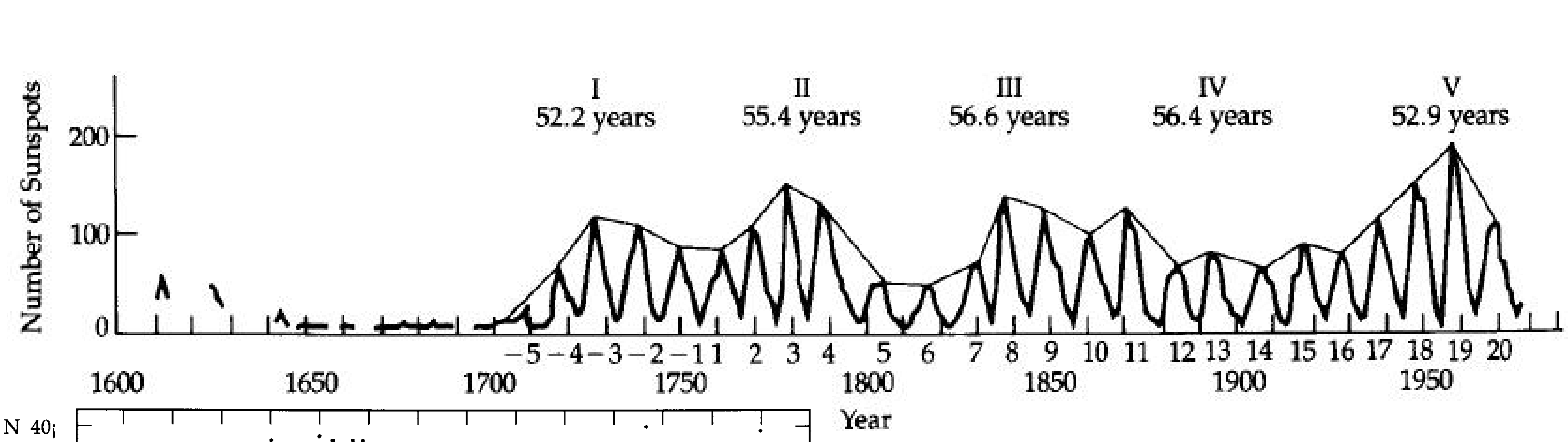
(2) Coronal Mass Ejection (CME) - Rapid release of huge amounts of coronal material (average ~10^{12} kg at ~400 km/s).

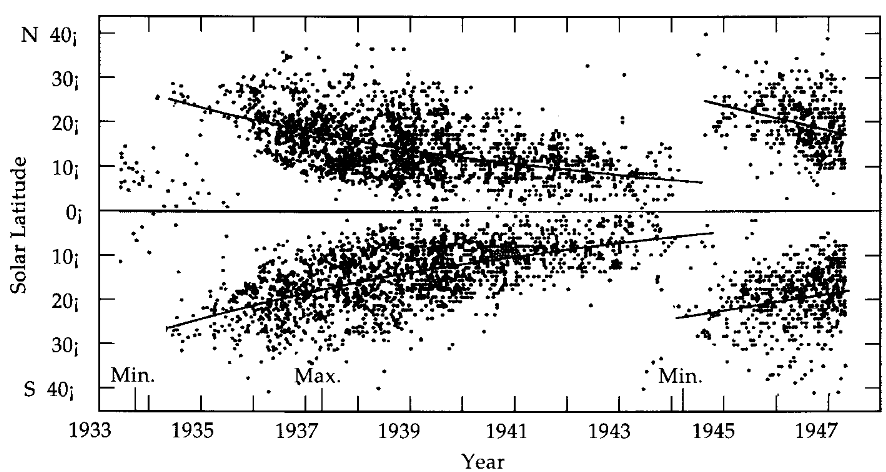


A CME followed by an erupting prominence.

The Solar Cycle

Periodic changes in solar activity. Current average period is 11 yr. Manifested in <u>active regions</u>, which contain sunspots, prominences, plages, and flares. Strength and number of active regions maximum at peak of cycle. Active Sun vs. Quiet Sun.





Note variations in number and latitude of sunspots. Maunder minimum occurred from 1645-1705; average Earth temperature dropped by 0.5 K.