What is the Sun’s structure?

**Radius:**
6.9 x 10^8 m  
(109 times Earth)

**Mass:**
2 x 10^30 kg  
(300,000 Earths)

**Luminosity:**
3.8 x 10^26 watts

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General Properties

- Average star
- Spectral type G2
- Only appears so bright because it is so close.
- 109 times Earth’s diameter
- 333,000 times Earth’s mass
- Consists entirely of gas (av. density = 1.4 g/cm^3)
- Central temperature = 15 million K
- Surface temperature = 5800 K

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Radiation Zone

Energy transported upward by photons

Energy transported upward by rising hot gas

10^4 – 10^5 K  
~10^6 K

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Solar wind:

A flow of charged particles from the surface of the Sun
Atmosphere

- **Photosphere**: the visible surface
  - Has granules that form and vanish in minutes
  - Typically larger than Texas+Oklahoma
  - Hot gas rising, cooling and falling back
  - Temperature from blackbody spectrum 5800 K

- **Chromosphere**: Region of sun’s atmosphere just above the photosphere.
  - Visible, UV, and X-ray lines from highly ionized gases
  - Temperature increases gradually from ≈ 4500 K to ≈ 10,000 K, then jumps to ≈ 1 million K

- **Corona**: surrounds chromosphere
  - Very hot and tenuous layer extending many million km
  - Heated by the action of solar magnetic fields accelerating charged particles
  - Emits X-rays because of high temperature

Energy Transport in the Photosphere

Energy generated in the sun’s center must be transported outward.

In the photosphere, this happens through

**Convection**:

- Cool gas sinking down
- Bubbles of hot gas rising up
- Bubbles last for ≈ 10 – 20 min.

Granulation

... is the visible consequence of convection

Limb Darkening

- But, T rises through chromosphere, so why doesn’t limb appear brighter?
- Opacity and optical depth are low in chromosphere

\[
\frac{dF_\lambda}{dr_\lambda} = -\kappa_\lambda \rho F_\lambda \ dx
\]

\[
\tau_\lambda = \kappa_\lambda F_\lambda \ dx
\]

\[
F_\lambda(\tau) = F_\lambda(0) \ exp(-\tau)
\]

Opacity and Optical Depth
The Solar Atmosphere

- Only visible during solar eclipses
- Apparent surface of the sun

Atmosphere: Continued

- Chromosphere: surrounds photosphere

The Chromosphere

Spicules: Filaments of cooler gas from the photosphere, rising up into the chromosphere.

Each one lasting about 5 – 15 min.
Coronal Holes

X-ray images of the sun reveal coronal holes. These arise at the foot points of open field lines and are the origin of the solar wind.

The Layers of the Solar Atmosphere

Visible Sunspot Regions Ultraviolet Chromosphere

Coronal activity, seen in visible light

What is solar activity?

Solar activity is like “weather”

- Sunspots
- Solar Flares
- Solar Prominences
- All related to magnetic fields
**Sunspots**

- Are cooler than other parts of the Sun's surface (4000 K)
- Are regions with strong magnetic fields

Sunspots are cooler regions of the photosphere (T \approx 4240 K). Only appear dark against the bright sun. Would still be brighter than the full moon when placed on the night sky! Caused by differential rotation of the sun.

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**The Solar Cycle**

11-year cycle

- Reversal of magnetic polarity
- After 11 years, North/South order of leading/trailing sunspots is reversed

Total solar cycle = 22 years

The Maunder butterfly diagram

Sunspot cycle starts out with spots at higher latitudes on the sun. Evolve to lower latitudes (towards the equator) throughout the cycle.
Number of sunspots rises and falls in 11-year cycle

Sunspot cycle has something to do with winding and twisting of Sun’s magnetic field

Solar Prominences

Prominences

Looped prominences: gas ejected from the sun’s photosphere, flowing along magnetic loops
Eruptive Prominences (Ultraviolet images)

Extreme events (solar flares) can significantly influence Earth’s magnetic field structure and cause northern lights (aurora borealis).

Charged particles spiral along magnetic field lines

Loops of bright gas often connect sunspot pairs

Loops trace magnetic field lines

Magnetic fields trap gas...
Magnetic activity causes solar flares that send bursts of X-rays and charged particles into space.

Corona appears bright in X-ray photos in places where magnetic fields trap hot gas.

How does solar activity affect humans?

Coronal mass ejections send bursts of energetic charged particles out through the solar system.

Charged particles streaming from Sun can disrupt electrical power grid and can disable communications satellites.
Energetic particles high in Earth's atmosphere cause auroras (Northern Lights)