Chapter 08
The Sun

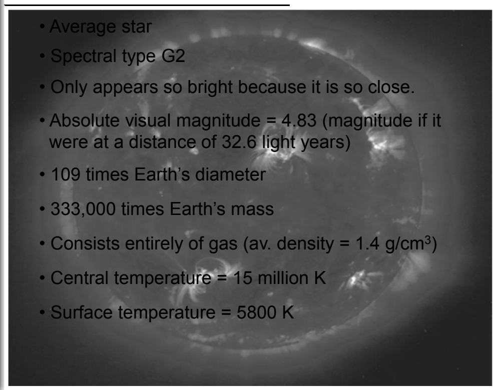
Guidepost

The Sun is the source of light an warmth in our solar system, so it is a natural object to human curiosity. It is also the star most easily visible from Earth, and therefore the most studied.

In this chapter you will discover how analysis of the solar spectrum paints a detailed picture of the sun's atmosphere and how basic physics solved the mystery of what goes on in the sun's core. The important questions to keep in mind are:

- What can you learn about the Sun by observing it's surface and atmosphere?
- What are sunspots?
- Why does the sun go through cycles of activity?
- What is the source of the sun's energy?

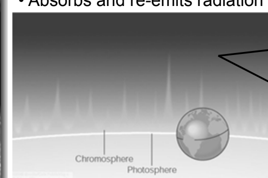
General Properties

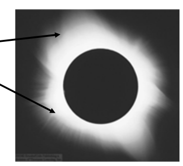


- Average star
- Spectral type G2
- Only appears so bright because it is so close.
- Absolute visual magnitude = 4.83 (magnitude if it were at a distance of 32.6 light years)
- 109 times Earth's diameter
- 333,000 times Earth's mass
- Consists entirely of gas (av. density = 1.4 g/cm^3)
- Central temperature = 15 million K
- Surface temperature = 5800 K

The Photosphere

- Apparent surface layer of the sun
- Depth ≈ 500 km
- Temperature ≈ 5800 ^{o}K
- Highly opaque (H^- ions)
- Absorbs and re-emits radiation produced in the solar interior





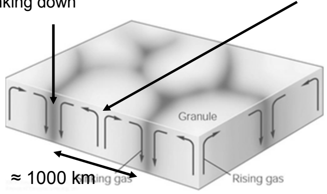
The solar corona

Energy Transport in the Photosphere

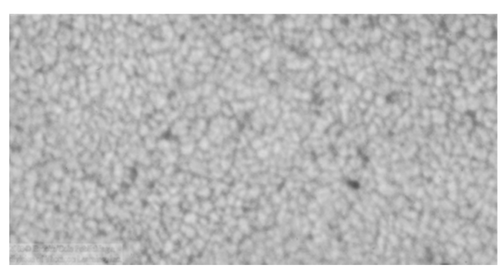
Energy generated in the sun's center must be transported outward.

In the **photosphere**, this happens through

Convection:

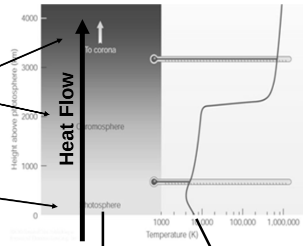


Granulation



… is the visible consequence of convection

The Solar Atmosphere



Only visible during solar eclipses

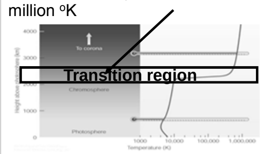
Apparent surface of the sun

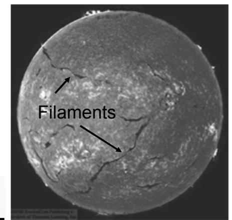
Solar interior

Temp. incr. inward

The Chromosphere

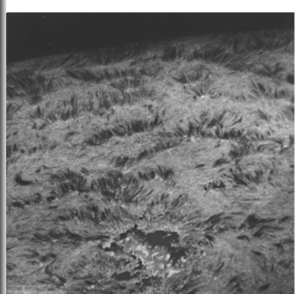
- Region of sun's atmosphere just above the photosphere.
- Visible, UV, and X-ray lines from highly ionized gases
- Temperature increases gradually from ≈ 4500 ^oK to ≈ 10,000 ^oK, then jumps to ≈ 1 million ^oK





Chromospheric structures visible in Hα emission (filtergram)

The Chromosphere (2)

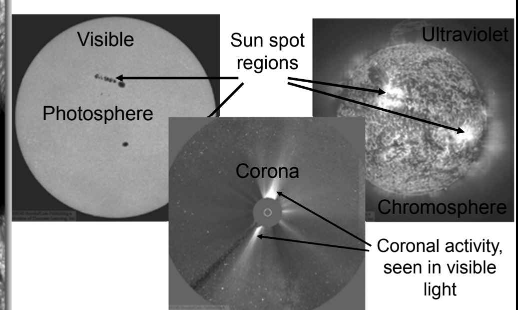


Spicules: Filaments of cooler gas from the photosphere, rising up into the chromosphere.

Visible in Hα emission.

Each one lasting about 5 – 15 min.

The Layers of the Solar Atmosphere

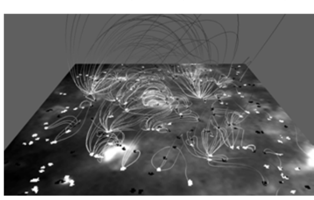


Sun spot regions

Coronal activity, seen in visible light

The Magnetic Carpet of the Corona

- Corona contains very low-density, very hot (1 million ^oK) gas
- Coronal gas is heated through motions of magnetic fields anchored in the photosphere below ("magnetic carpet")



Computer model of the magnetic carpet

Extreme UV image w/ black and white areas marking zones of opposite polarity.

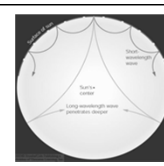
Helioseismology – Below the Photosphere

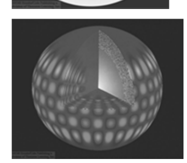
The solar interior is opaque (i.e. it absorbs light) out to the photosphere.

⇒ Only way to investigate solar interior is through **helioseismology**

= analysis of vibration patterns visible on the solar surface:

Approx. 10 million wave patterns!





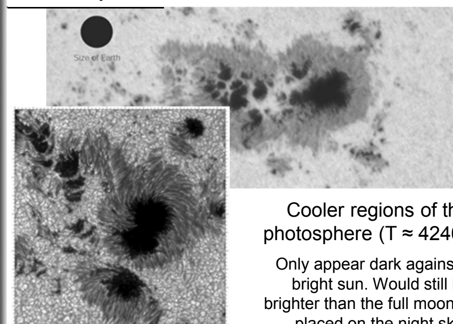
Very Important Warning:

Never look directly at the sun through a telescope or binoculars!!!

This can cause permanent eye damage – even blindness.

Use a projection technique or a special sun viewing filter.

Sun Spots

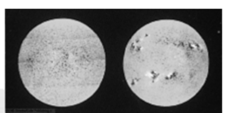


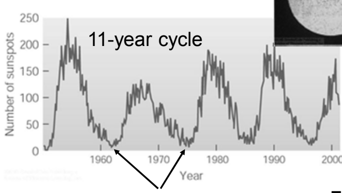
Cooler regions of the photosphere (T ≈ 4240 K).

Only appear dark against the bright sun. Would still be brighter than the full moon when placed on the night sky!

The Solar Cycle

After 11 years, North/South order of leading/trailing sun spots is reversed



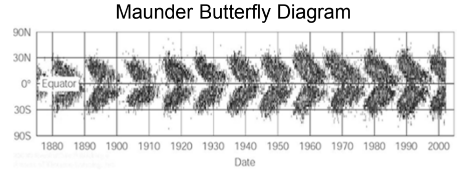


Reversal of magnetic polarity

=> Total solar cycle = 22 years

The Solar Cycle (2)

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.

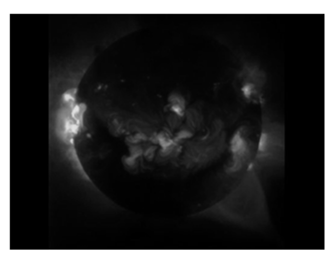
The Solar Constant

A small change in solar output could have a large effect on Earth's climate.

The Solar Constant is ~1370 J/m^2 – s, but recent studies show that a long term decrease in output by 0.018%/yr.

The Little Ice Age (1500-1850) may have been caused by a reduction of solar irradiation caused by sunspot activity.

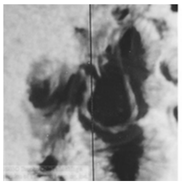
Face of the Sun

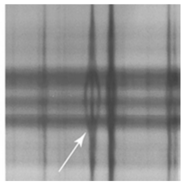


Solar activity, seen in soft X-rays

Magnetic Fields in Sunspots

Magnetic fields on the photosphere can be measured through the Zeeman effect – splitting of spectral lines due to intense magnetic fields.

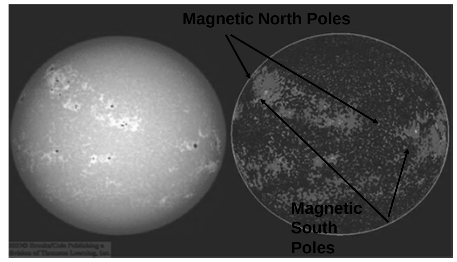




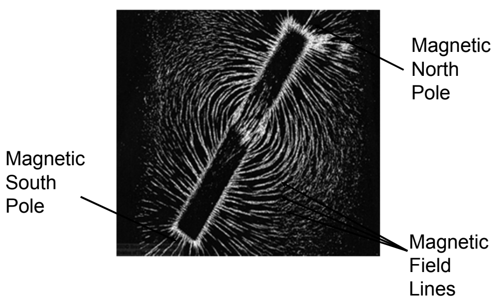
→ Sunspots are related to magnetic activity on the photosphere

Sunspots (2)

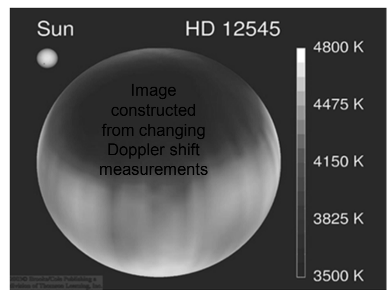
Magnetic field in sunspots is about 1000 times stronger than average.



Magnetic Field Lines



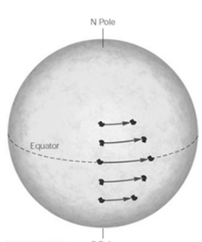
Sunspots on Other Stars?

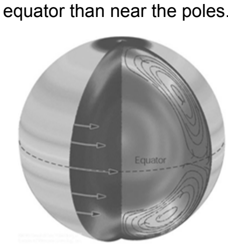


Other stars might also have sunspot activity:

The Sun's Magnetic Dynamo

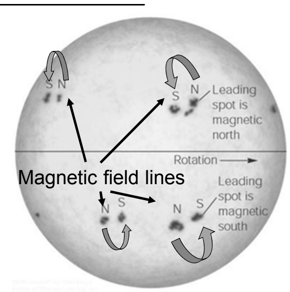
The sun rotates faster at the equator than near the poles.





This differential rotation might be responsible for magnetic activity of the sun.

Magnetic Loops



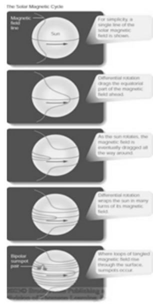
The Sun's Magnetic Cycle

After 11 years, the magnetic field pattern becomes so complex that the field structure is re-arranged.

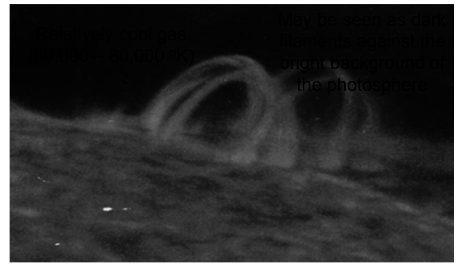
→ New magnetic field structure is similar to the original one, but reversed!

→ New 11-year cycle starts with reversed magnetic-field orientation

→ This is called the Babcock Model



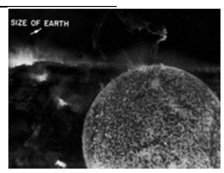
Prominences



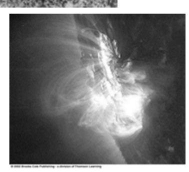
Looped **prominences**: gas ejected from the sun's photosphere, flowing along magnetic loops

Eruptive Prominences

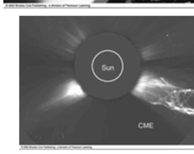
(Ultraviolet images)



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

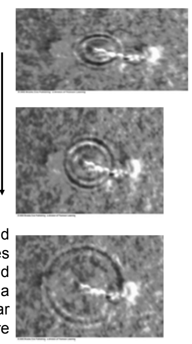


Space Weather



Coronal mass ejections

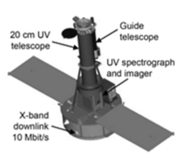
~ 5 minutes



Sound waves produced by a solar flare

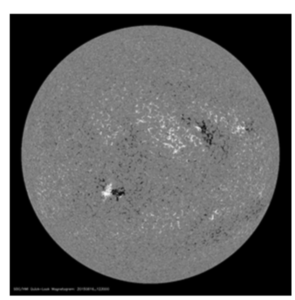
The Solar Dynamics Observatory

The SDO spacecraft returns images of the sun in multiple wavelengths.

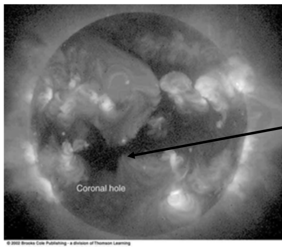


A new spacecraft, the Interface Region Imaging Spectrograph or IRIS will be launched on June 26th of this year.

Our Dynamic Sun



Coronal Holes



X-ray images of the sun reveal *coronal holes*.

These arise where the magnetic field does not loop back to the sun and are the origin of the solar wind.

Energy Production

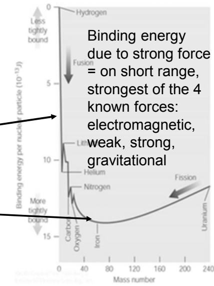
Energy generation in the sun (and all other stars):

nuclear fusion

= fusing together 2 or more lighter nuclei to produce heavier ones

Nuclear fusion can produce energy up to the production of <u>iron</u>;

For elements heavier than iron, energy is gained by nuclear fission.



Binding energy due to strong force = on short range, strongest of the 4 known forces: electromagnetic, weak, strong, gravitational

Energy Generation in the Sun: The Proton-Proton Chain

Basic reaction: 4 $^1H \rightarrow {}^4He$ + energy

4 protons have $0.048 \cdot 10^{-27}$ kg (= 0.7 %) more mass than ^4He.

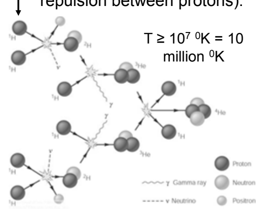
$\Rightarrow$ Energy gain = $\Delta m \cdot c^2$

= $0.43 \cdot 10^{-11}$ J

per reaction.

Need large proton speed ($\Leftrightarrow$ high temperature) to overcome *Coulomb barrier* (electromagnetic repulsion between protons).

$T \geq 10^7$ ^0K = 10 million ^0K



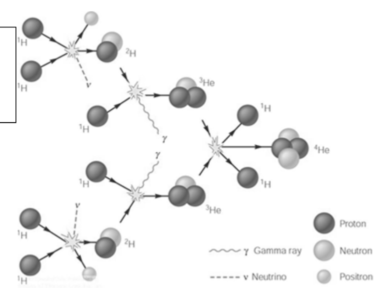
Energy Generation in the Sun: The Proton-Proton Chain

$\Rightarrow$ Energy gain = $\Delta m \cdot c^2$

= $0.43 \cdot 10^{-11}$ J

per reaction.

Sun needs 10^{38} reactions, transforming <u>5 million tons</u> of mass into energy every second, to resist its own gravity.



The Solar Neutrino Problem

The solar interior can not be observed directly because it is highly opaque to radiation.

But *neutrinos* can penetrate huge amounts of material without being absorbed.

Early solar neutrino experiments detected a much lower flux of neutrinos than expected ($\rightarrow$ the "solar neutrino problem").

Davis solar neutrino experiment, a giant chlorine tank

The Solar Neutrino Problem

The solar interior can not be observed directly because it is highly opaque to radiation.

Recent results have proven that neutrinos change ("oscillate") between different types ("flavors"), thus solving the solar neutrino problem.

Davis solar neutrino experiment, a giant chlorine tank