# The Sun

"Sol" = latin word for "Sun"

- contains > 99% of the mass of the Solar System
- a "typical" star: ball of gas generating energy from ***fusion*** of hydrogen into helium.
- supports its weight by internal pressure: "hydrostatic equilibrium"
- Sun has typical composition (abundances of elements). By mass:
  - **73.4% hydrogen**
  - **25.0% helium**
  - 1.6% everything else ("metals")

## Three Observable Layers of the Sun

### 1. The Photosphere

- apparent "surface"
- deepest into the Sun we can see
- T ~ 5800 K

### 2. The Chromosphere

thin, low density emission-line region
hotter than the photosphere.
acoustic waves deposit mechanical (kinetic) energy into the chromosphere.
bright areas: ***plages*** regions where the magnetic field is bunched up just below the photosphere
dark areas: ***filaments*** cool gas that has been lifted above the photosphere.
Spicules:
due to charged particles following magnetic field lines.
upward moving (10 km $s^{-1}$) gas.

### 3. The Corona

- sits above the chromosphere
- **contains very hot, very low density gas.**
- **Temp ~ 2 x $10^6$ K**

$10^6$ times fainter than the photosphere (comparable in brightness to full Moon)
Because the corona is so hot, it emits mostly in X-rays (Wien's law).

Solar Wind

- outward stream of particles
- coronal particles are moving faster than escape speed.
- corona "boils off" the Sun.

# Sunspots

- Individual spots last a few hours to a few months
- Show the Sun is *not solid*
  - rotates differentially
  - takes 25 days to rotate at the equator;
  - equator rotates 30% faster than poles
- **Typical sunspot temperature: 4300 K**
- Large *magnetic fields* are associated with sunspots.
- *Sunspots are not dark!*

cooler than the photosphere. Since energy flux depends very strongly on temperature (Stefan-Boltzmann law), they *appear* dark in comparison.

- tend to occur in pairs
  - pairs have opposite magnetic polarity

What causes sunspots?

Strong magnetic fields can prevent convection. Since convection carries energy, if there is no convection, less energy is transported from below.

Less energy → lower temperature

Sunspots tend to occur in pairs

- pairs have opposite magnetic polarity
- northern hemisphere and southern hemisphere spots have reversed polarity.
- polarity pattern completely reverses every 11 years.

Large *magnetic fields* are associated with sunspots.

We know this because the spectrum of a sunspot shows lines that in are split in two.

Known as the "Zeeman Effect"

Some spectral lines are sensitive to "Zeeman splitting"

- Some electron energy levels are "degenerate" (i.e., they have multiple levels at the same energy).
- In the presence of a strong magnetic field, these energy levels are separated.

# Solar Interior

- Interior is hot and highly ionized
  - a *plasma* of free electrons and nuclei (completely ionized atoms)
- Temperature and ionization increases the deeper you go below the photosphere.
- Below the atmosphere lie 3 regions: ***convective zone, radiative zone, core***

Convective zone starts ~80% of the way out from the center (0.8 Rsun). Energy flow is dominated by convective motion of gas.

Radiative zone starts ~25% Rsun from the center. Energy flow is dominated by radiative transport (photons carry energy).

Core extends to 25% Rsun. Temperature ~15.5 million K. Core is where energy generation takes place. Energy is generated by thermonuclear fusion, mostly the fusion of hydrogen into helium.

### THERMONUCLEAR FUSION

At very high temperatures and pressure, protons will collide with such force that they *fuse* (combine) together. Temperature and density (pressure) must be high enough to overcome the repulsive Coulomb force between the positively charged protons.

Main reaction is the **"proton-proton" chain**:

- Two protons fuse to form deuterium: $^{2}H$
- Deuterium then fuses with another proton, forming a $^{3}He$ nucleus
- Two $^{3}He$ nuclei fuse forming $^{4}He$ and two protons are released.

Mass, charge, and momentum must be conserved. But in fact, mass is not conserved!
A $^{4}He$ nucleus has *slightly less mass* (0.7%) than the 4 protons that were used to make it!
*Mass has been converted into energy.*
The sum of mass + energy is conserved.

To conserve charge, *positrons* must be created.
*Positrons are anti-matter electrons:* they are just like electrons but with a positive charge. Positron will soon collide with electron and annihilate each other in a small burst of gamma-ray energy.

To conserve momentum, a particle called a *neutrino* ($\nu$) is created along the way. Neutrinos have no charge, very little mass and they almost never interact with ordinary matter. Research on solar neutrinos has helped us understand these elusive particles.

## Helioseismology

Photosphere oscillates in a very complex way. The Sun is ringing like a bell.

- *Helioseismology* uses these vibrations to generate a crude map of the inside of the Sun (like seismology on Earth).
- Helioseismology has confirmed the internal structure of the Sun.

## Solar Activity

Sun's luminosity is very steady (change < 0.1%), but not perfectly constant –dramatic short-term changes occur.

- Most activity is associated with magnetic fields.
- Sunspots are the most obvious manifestation.

Number of spots varies from year to year.

Number of sunspots varies on an 11-year cycle.
Sun's magnetic field reverses (N and S magnetic poles flip!) every 11 years. Thus the true solar magnetic cycle is 22 years long.

Origin of Filaments and Prominences

Convection produces kinks in magnetic field. The magnetic field can erupt through photosphere $\Rightarrow$ sunspots
Ionized gas trapped in magnetic field loop forms prominence
A *prominence* is relatively cool gas seen in emission above the limb of Sun.
When seen in against the hotter photosphere, they are in absorption and called *filaments.*
Filaments and prominences are physically the same thing.

## Solar Flares

***Solar flares***: violent eruptions caused by the release of magnetic energy

- Brightens in a few seconds.
- Typically last 5-10 min; sometimes for hours.
- Temp can reach $10^7$ K.

## Coronal Holes and Coronal Mass Ejection

Large, dark regions in X-rays are called "coronal holes".
Hot gases steadily escape from the Sun at the holes: solar wind.
Sometimes the Sun releases huge volumes of gas: "coronal mass ejections".

The solar wind, flares, prominences, and coronal mass ejections release particles that interact with the Earth's magnetic field. Collision of high-energy solar particles and the Earth's upper atmosphere produce *aurorae*. These can disrupt satellites, communications, and electric power transmission
**aurora** borealis = "northern lights"
**aurora** australis = "southern lights"