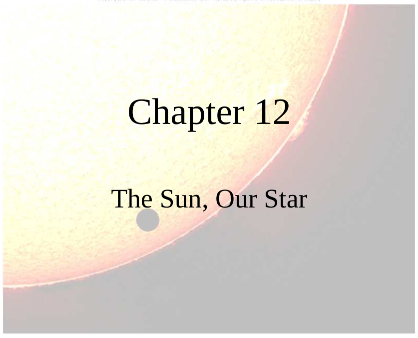


Chapter 12

The Sun, Our Star

The Sun

- With a radius 100× and a mass of 300,000× that of Earth, the Sun must expend a large amount of energy to withstand its own gravitational desire to collapse
- To understand this process requires detailed observations as well as sophisticated calculations involving computer models and the laws of physics

Properties of the Sun

- The Sun's distance from Earth (about 150 million km or 1 AU) was once measured by triangulation, but is now done by radar
- Once the distance is known, its diameter (about 1.4 million km) can be found from its angular size (about 1/2 degree)

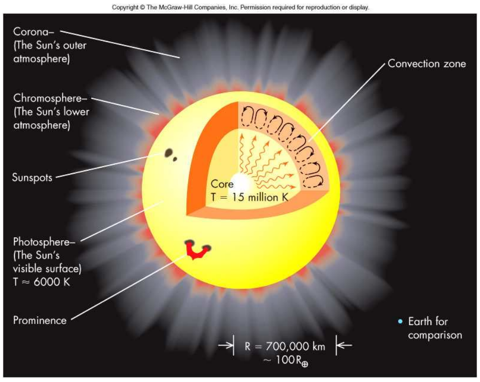
Properties of the Sun

- From the Sun's distance and the Earth's orbital period, Kepler's modified third law gives the Sun's mass
- Mass and radius, the surface gravity of the Sun is found to be 30× that of Earth
- Next, the surface temperature (5780 K) is found from the Sun's color and the use of Wien's law for a blackbody

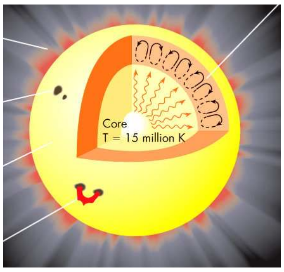
Properties of the Sun

- Theoretical considerations then establish the Sun as gaseous throughout with a core temperature of 15 million K
- From the amount of solar energy that reaches the Earth (4×10^{26} watts), this energy must be replenished by fusion processes in its core
- The Sun has plenty of hydrogen for fusion: its surface spectra shows hydrogen is 71% and 27% helium

The Structure of the Sun

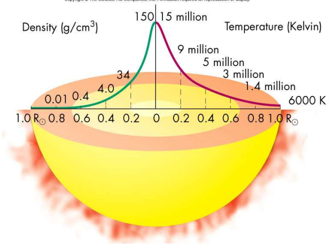


The Solar Interior



- The low density upper layers of the Sun, where any photons created there can freely escape into space is called the ***photosphere***
- The photosphere is yellow "surface" we see with our eyes
- Layers below the photosphere are opaque, photons created there are readily absorbed by atoms located there

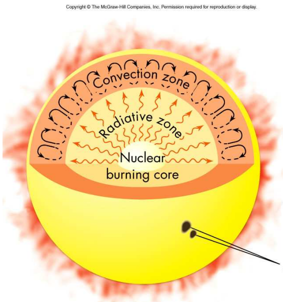
The Solar Interior



- Theoretical calculations show that the Sun's surface temperature and density both increase as the core is approached
  - The density is similar to that found at sea level on Earth at the Sun's surface and 100× that of water at the core

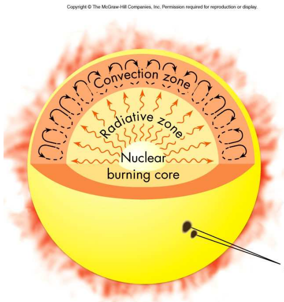
The Radiative Zone

- Since the core is hotter than the surface, heat will flow outward from the Sun's center
- Near the Sun's center, energy is moved outward by photon radiation – a region surrounding the core known as the ***radiative zone***



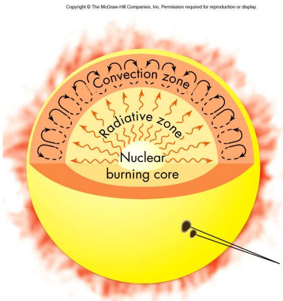
The Radiative Zone

- Photons created in the Sun's interior do not travel very far before being reabsorbed – energy created in the Sun's center will take about 16 million years to eventually diffuse to the surface!

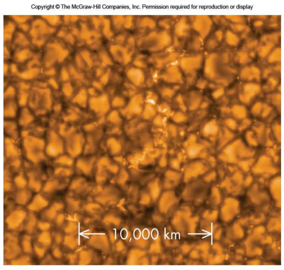


The Convection Zone

- Above the radiative zone energy is more efficiently transported by the rising and sinking of gas – this is the ***convection zone***



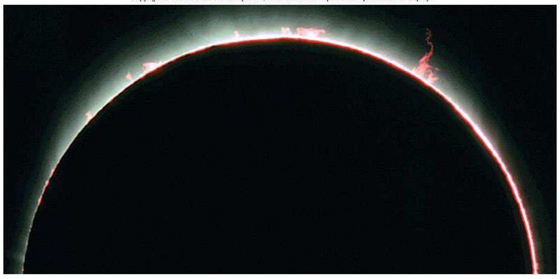
Granulation



Hinode JAXA/NASA/PPARC

- Convection manifests itself in the photosphere as ***granulation,*** numerous bright regions surrounded by narrow dark zones

The Sun's Atmosphere



- The extremely low-density gases that lie above the photosphere make up the Sun's atmosphere

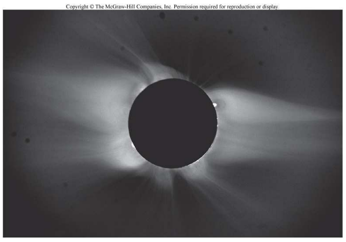
The Sun's Atmosphere

- The density of the atmosphere decreases steadily with altitude and eventually merges with the near-vacuum of space
- Immediately above the photosphere, the temperature of the atmosphere decrease but at higher altitudes, the temperature grows hotter, reaching temperatures of several million Kelvin
- The reason for the increase in temperature is unknown, but speculation is that Sun's magnetic field plays an important role

The Chromosphere

- The lower part of the atmosphere is referred to as the ***chromosphere***
  - The chromosphere appears as a thin red zone around the dark disk of a totally eclipsed Sun
  - The red is caused by the strong red emission line of hydrogen Hα
  - The chromosphere contains millions of thin columns called ***spicules,*** each a jet of hot gas

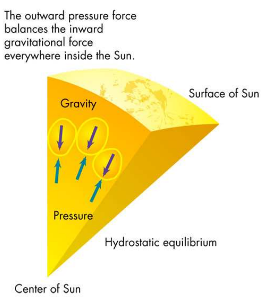
The Corona



- Temperature in the corona eventually reaches about 1 million K (not much energy though due to low density)
- The corona, visible in a total solar eclipse, can be seen to reach altitudes of several solar radii
- The corona is not uniform but has streamers and *coronal holes* dictated by the Sun's magnetic field

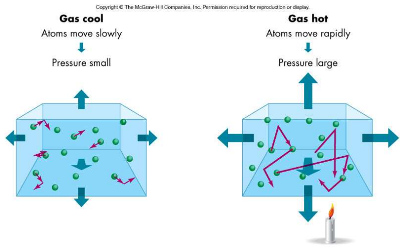
How the Sun Works

- Structure of the Sun depends on a balance between its internal forces – specifically, a hydrostatic equilibrium between a force that prevents the Sun from collapsing and a force that holds it together
- The inward (holding) force is the Sun's own gravity, while the outward (non-collapsing) force arises from the Sun's internal gas pressure



Without balance the Sun would rapidly change!

Pressure in the Sun



- ***Pressure*** in a gas comes from atomic collisions
- The amount of pressure is in direct proportion to the speed of the atoms and their density and is expressed in the ***perfect*** or ***ideal gas law***

Powering the Sun

- Given that the Sun loses energy as sunshine, an internal energy source must be present to maintain hydrostatic equilibrium
  - If the Sun were made of pure coal, the Sun would last only a few thousand years
  - If the Sun were not in equilibrium, but creating light energy from gravitational energy (the Sun is collapsing), the Sun could last 10 million years
  - These and many other chemical-based sources of energy are not adequate to account for the Sun's several billion year age

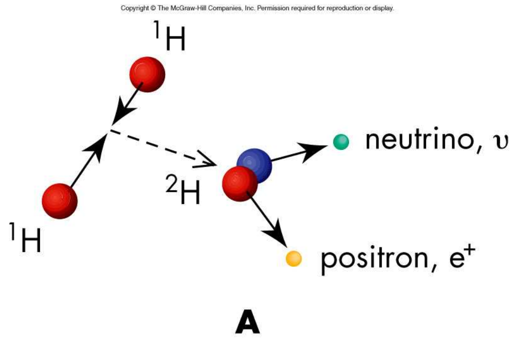
Powering the Sun

- Mass-energy is the key
  - In 1905, Einstein showed that energy and mass were equivalent through his famous $E = mc^2$ equation
  - 1 gram of mass is equivalent to the energy of a small nuclear weapon
  - The trick is finding a process to convert mass into other forms of energy

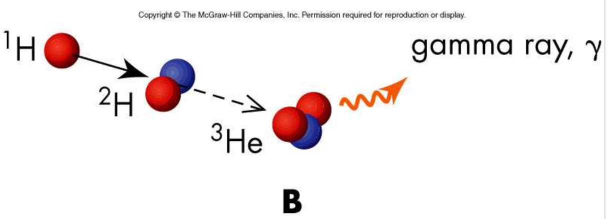
Powering the Sun

- A detailed process for mass conversion in the Sun called ***nuclear fusion*** was found:
  - Sun's core temperature is high enough to force positively charged protons close enough together to bind them together via the ***nuclear*** or ***strong force***
  - The net effect is that four protons are converted into a helium nucleus (plus other particles and energy) in a three-step process called the ***proton-proton chain***

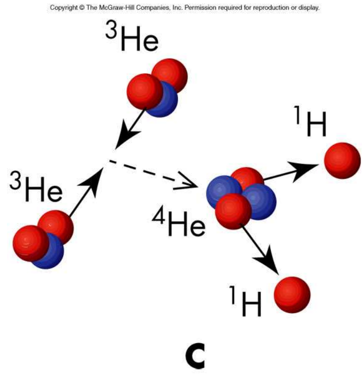
The Proton-Proton Chain: Step 1



The Proton-Proton Chain: Step 2

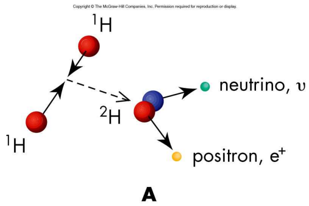


The Proton-Proton Chain: Step 3

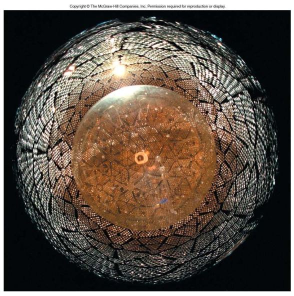


Solar Neutrinos

- The nuclear fusion process in the Sun's core creates neutrinos
- ***Neutrinos*** lack electric charge, have a very small mass, escape the Sun's interior relatively unaffected, and shower the Earth (about 1 trillion pass through a human per second)



Solar Neutrinos



- A neutrino's low reactivity with other forms of matter requires special detection arrangements
  - Detectors buried deep in the ground to prevent spurious signals as those produced by ***cosmic rays*** (high energy particles, like protons and electrons, with their source beyond the Solar System)
  - Large tanks of water and special light detectors

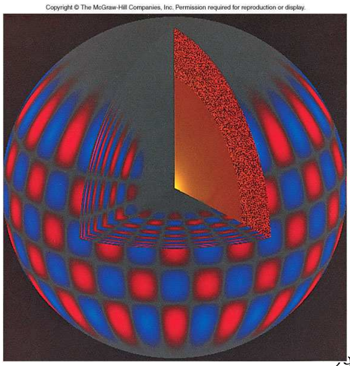
Solar Neutrinos

- Detected neutrinos are about three times less than predicted – possible reasons:
  - Model of solar interior could be wrong
  - Neutrinos have properties that are not well understood
- Current view to explain measured solar neutrinos: neutrinos come in three varieties (instead of previous one), each with a different mass, and Earth detectors cannot detect all varieties
- Important ramifications: A solar astronomy observation of neutrinos may lead to a major revision of our understanding of the basic structure of matter

Solar Seismology

- Solar seismology is the study of the Sun's interior by analyzing wave motions on the Sun's surface and atmosphere
- The wave motion can be detected by the Doppler shift of the moving material
- The detected wave motion gives temperature and density profiles deep in the Sun's interior
- These profiles agree very well with current models

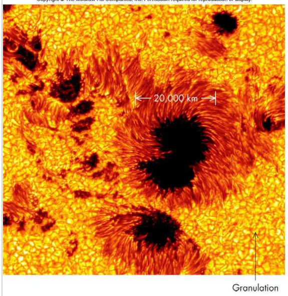
Solar Seismology



Solar Magnetic Activity

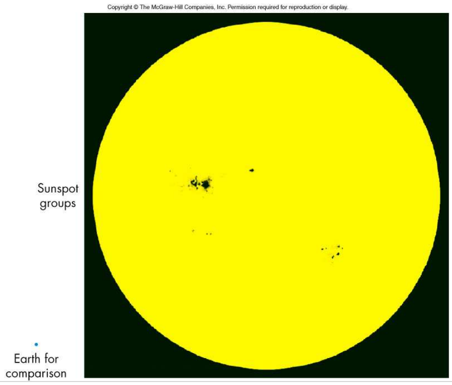
- Surface waves are but one type of disturbance in the Sun's outer layers
- A wide class of dramatic and lovely phenomena occur on the Sun and are caused by its magnetic field

Sunspots



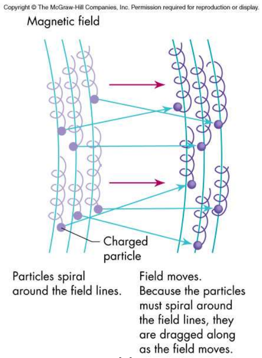
- Dark-appearing regions ranging in size from a few hundred to a few thousand kilometers across
- Last a few days to over a month
- Darker because they are cooler than their surroundings (4500 K vs 6000 K)
- Cooler due to stronger magnetic fields within them

Sunspots

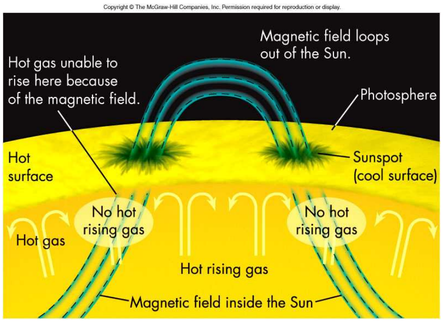


Origin of Sunspots

- Charged particles tend to spiral along magnetic field lines easier than they drift across them
- Consequently, magnetic fields at the Sun's surface slow the ascent of hot gases from below

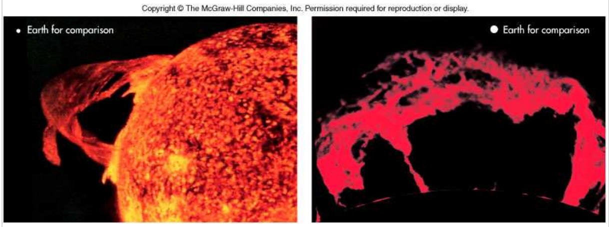


Origin of Sunspots



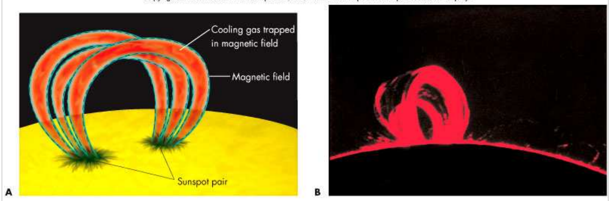
- Starved of heat from below, the surface cools where the magnetic fields breach the surface creating a dark sunspot

Prominences



- ***Prominences*** are huge glowing gas plumes that jut from the lower chromosphere into the corona

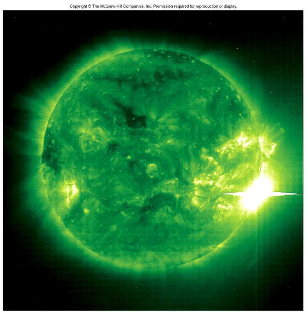
Prominences



- Cool prominence gas is confined by its high magnetic field and hot surrounding gas
- Gas streams through prominence in a variety of patterns
- Associated with sunspots

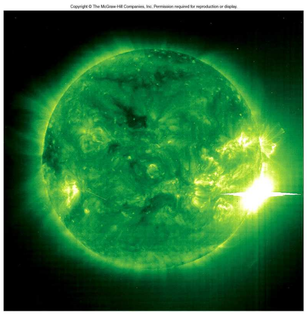
Solar Flares

- Sunspots give birth to ***solar flares,*** brief but bright eruptions of hot gas in the chromosphere
- Hot gas brightens over minutes or hours, but not enough to affect the Sun's total light output



Solar Flares

- Strong increase in radio and x-ray emissions
- Intense twisting and "breakage" of magnetic field lines is thought to be the source of flares
- Some flare eruptions can explosively shoot gas across the Solar System and result in spectacular auroral displays

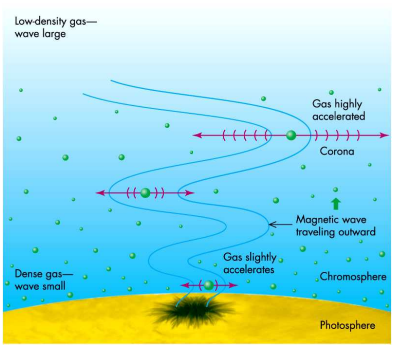


Impact of Solar Flares

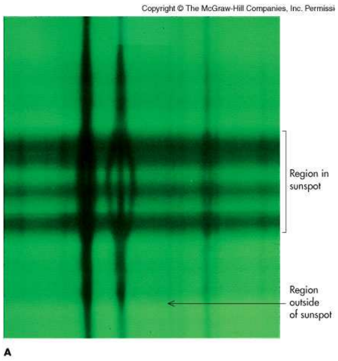
Heating of the Chromosphere and Corona

- While the Sun's magnetic field cools sunspots and prominences, it heats the chromosphere and corona
- Heating is caused by magnetic waves generated in the relatively dense photosphere
  - These waves move up into the thinning atmospheric gases, grow in magnitude, and "whip" the charged particles found there to higher speeds and hence higher temperatures
  - Origin of waves may be from rising bubbles in convection zone

Heating of the Chromosphere and Corona



The Zeeman Effect

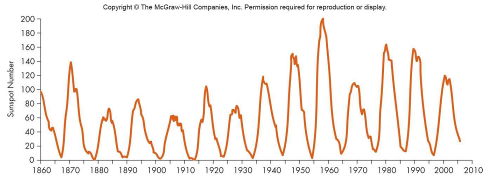


- Magnetic fields and their strength can be detected by the ***Zeeman effect***
- Magnetic fields can split the spectral lines of an atom into two, three, or more components by changing the energy levels of the atom's electrons

The Solar Wind

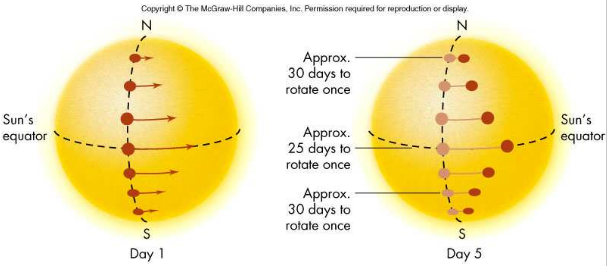
- The corona's high temperature gives its atoms enough energy to exceed the escape velocity of the Sun
- As these atoms stream into space, they form the ***solar wind,*** a tenuous gas of hydrogen and helium that sweeps across the entire Solar System
- The amount of material lost from the Sun via the Solar Wind is insignificant
- Typical values at the Earth's orbit: a few atoms per cm^3 and a speed of about 500 km/sec
- At some point, the solar wind mingles with interstellar space

The Solar Cycle



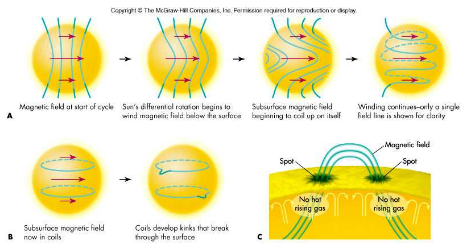
- Sunspot, flare, and prominence activity change yearly in a pattern called the ***solar cycle***
- Over the last 140 years or so, sunspots peak in number about every 11 years
- Climate patterns on Earth may also follow the solar cycle

Differential Rotation



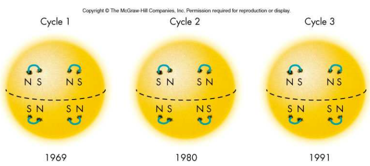
- The Sun undergoes differential rotation, 25 days at the equator and 30 at the poles

Cause of the Solar Cycle



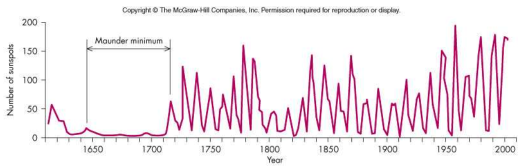
- This rotation causes the Sun's magnetic field to "wind up" increasing solar activity (magnetic field "kinks" that break through the surface) as it goes
- The cycle ends when the field twists too "tightly" and collapses – the process then repeats

Changes in the Solar Cycle



- The cycle may vary from 6 to 16 years
- Considering the polarity direction of the sunspots, the cycle is 22 years, because the Sun's field reverses at the end of each 11-year cycle
- Leading spots in one hemisphere have the same polarity, while in the other hemisphere, the opposite polarity leads

Solar Cycle and Climate



- Midwestern United States and Canada experience a 22-year drought cycle
- Few sunspots existed from 1645-1715, the ***Maunder Minimum,*** the same time of the "little ice age in Europe and North America
- Number of sunspots correlates with change in ocean temperatures