# 12/2/08

- Announce:
  - Take online quizzes
  - Project Scheduling
- Relativity Review
- Ch. 11
- Daytime observation

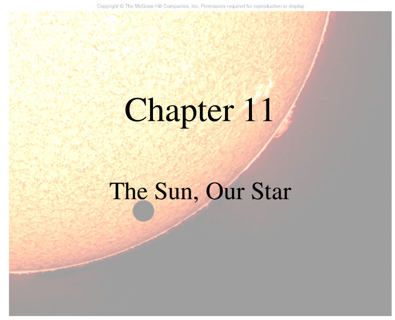
- **http://math.ucr.edu/home/baez/physics/Relativity/SR/experiments.html**
- Domain of Applicability
- Test Theories of SR
- Optical Extinction
- Early experiments (Pre-1905)
- Roentgen, Eichenwald, Wilson, Rayleigh, Arago, Fizeau, Hoek, Bradley, Airy.
- Tests of Einstein's Two Postulates
- Round-Trip Tests of Light Speed Isotropy
- Michelson and Morley
- Kennedy and Thorndike
- Modern Laser/Maser Tests
- Other
- One-Way Tests of Light Speed Isotropy
- Cialdea, Krisher, Champeny, Turner & Hill.
- Tests of Light Speed from Moving Sources
- Cosmological Sources: DeSitter, Brecher
- Terrestrial Sources: Alvaeger, Sadeh, ...
- Measurements of the Speed of Light, and Other Limits on it
- NBS Measurements, 1983 Redefinition of the Meter
- Limits on Variations with Frequency
- Limits on Photon Mass
- Tests of the Principle of Relativity and Lorentz Invariance
- Trouton Noble
- Other
- Tests of the Isotropy of Space
- Hughes-Drever, Prestage, Lamoreaux, Chupp, Phillips, Brillet and Hall.
- Tests of Time Dilation and Transverse Doppler Effect
- Ives and Stilwell
- Particle Lifetimes
- Doppler Shift Measurements
- Tests of the Twin Paradox
- Hafele and Keating, Vessot et al., Alley, Bailey et al.
- The Clock Hypothesis

Lots of experimental tests…

# Twin Paradox

- Hafele and Keating, Nature 227 (1970), pg 270 (proposal). Science Vol. 177 pg 166–170 (1972) (experiment).
- They flew atomic clocks on commercial airliners around the world in both directions, and compared the time elapsed on the airborne clocks with the time elapsed on an earthbound clock (USNO). Their eastbound clock lost 59 ns on the USNO clock; their westbound clock gained 273 ns; these agree with GR predictions to well within their experimental resolution and uncertainties (which total about 25 ns). By using four cesium-beam atomic clocks they greatly reduced their systematic errors due to clock drift.





# Chapter 11

The Sun, Our Star



# The Sun

- The Sun is a star, a luminous ball of gas more than 100 times bigger than the Earth
- Although seemingly quiescent from a naked eye view, telescopic observations reveal a bevy of violent activity – fountains of incandescent gas and twisting magnetic fields
- The Sun's core is equally violent with a furnace of thermonuclear fire converting hydrogen into helium to the tune of an energy production equivalent to the detonation of 100 nuclear bombs
- The force of gravity keeps the Sun in check – for now

# 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)

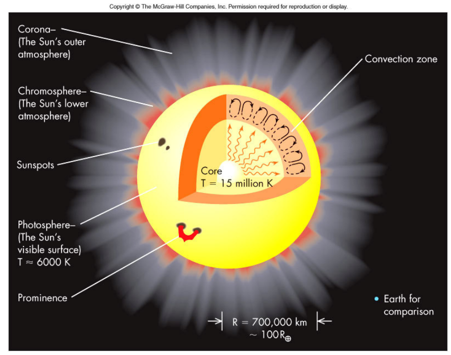
## Properties of the Sun

- 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

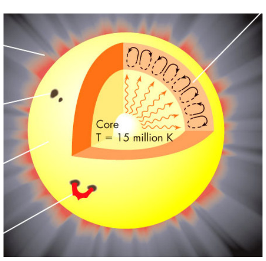
## Properties of the Sun

- 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 ($4 \times 10^{26}$ 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

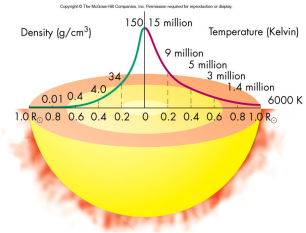



## The Solar Interior




- 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

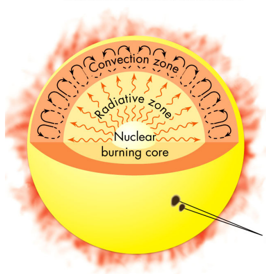



- Theoretical calculations show that the Sun's surface temperature and density both increase as the core is approached
  - The density is similar to that found at sea level on Earth at the Sun's surface and 100× that of water at the core

## 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***

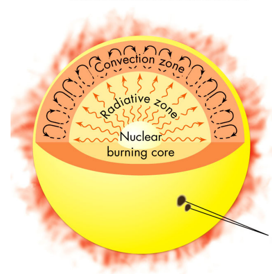





## The Radiative Zone

- 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!

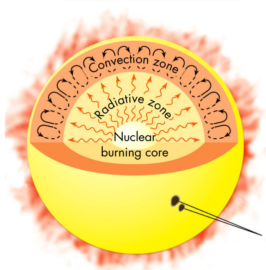





## The Convection Zone

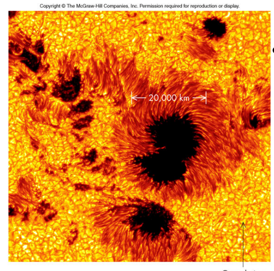
- Above the radiative zone energy is more efficiently transported by the rising and sinking of gas – this is the ***convection zone***






## Granulation



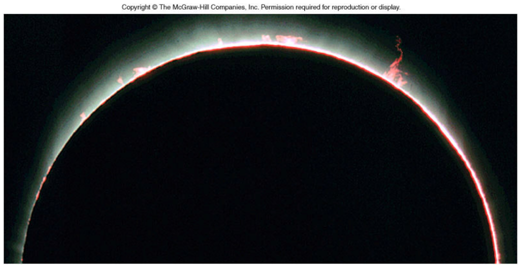



Granulation

- 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

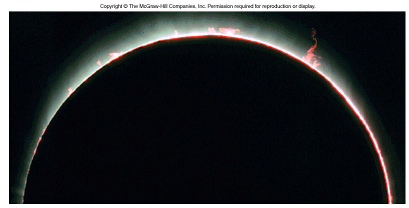
## The Chromosphere

- 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 H$\alpha$
  – The chromosphere contains millions of thin columns called ***spicules,*** each a jet of hot gas



## The Corona



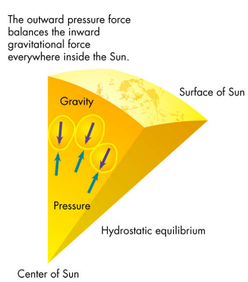


- Temperature in the corona eventually reaches about 1 million K (not much energy though due to low density)
- The corona, visible in a total solar eclipse, can be seen to reach altitudes of several solar radii
- The corona is not uniform but has streamers and *coronal holes* dictated by the Sun's magnetic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

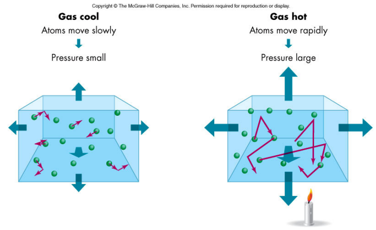





Without balance the Sun would rapidly change!

## 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

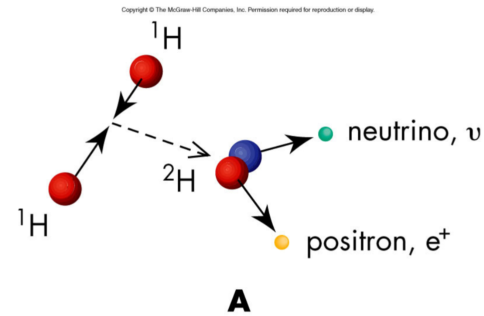
## Powering the Sun

- 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

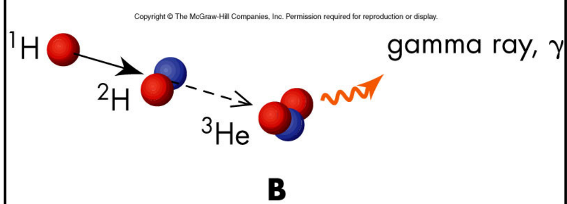
## Powering the Sun

- A detailed process for mass conversion in the Sun called ***nuclear fusion*** was found:
  - Sun's <u>core</u> 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***

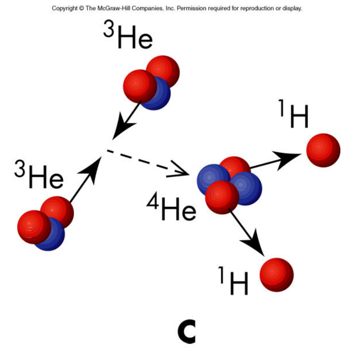
## The Proton-Proton Chain: Step 1




## The Proton-Proton Chain: Step 2

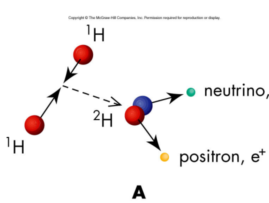



## The Proton-Proton Chain: Step 3

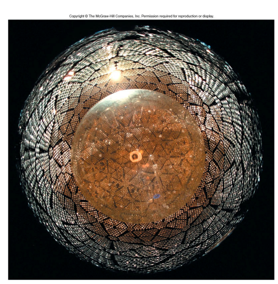



## Solar Neutrinos

- 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

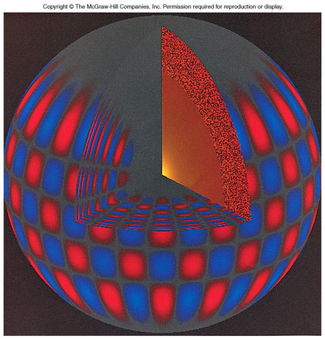
- Detected neutrinos are about three times less than predicted – possible reasons:
  - Model of solar interior could be wrong
  - Neutrinos have properties that are not well understood
- Current view to explain measured solar neutrinos: neutrinos come in three varieties (instead of previous one), each 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

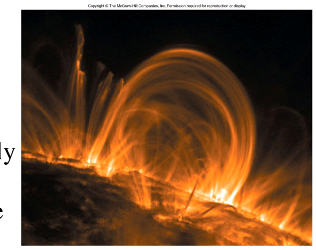




## Solar Magnetic Activity

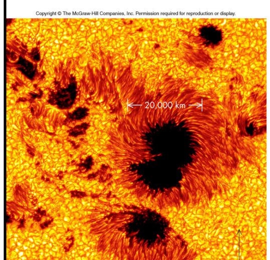
- Surface waves are but one type of disturbance in the Sun's outer layers
- A wide class of dramatic and lovely phenomena occur on the Sun and are caused by its magnetic field





## Sunspots

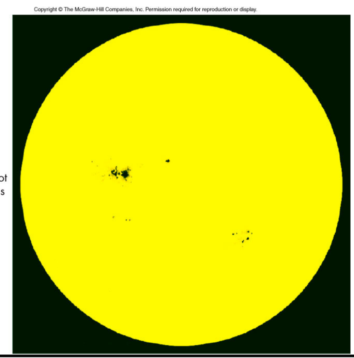





- Dark-appearing regions ranging in size from a few hundred to a few thousand kilometers across
- Last a few days to over a month
- Darker because they are cooler than their surroundings (4500 K vs 6000 K)
- Cooler due to stronger magnetic fields within them

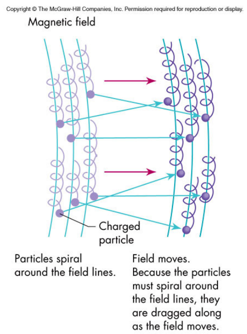
## Sunspots



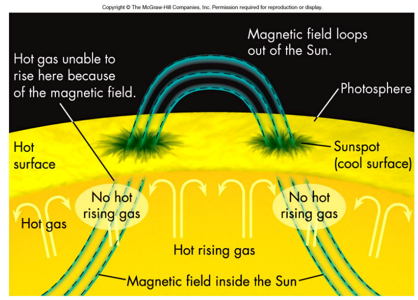


## Origin of Sunspots

- 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

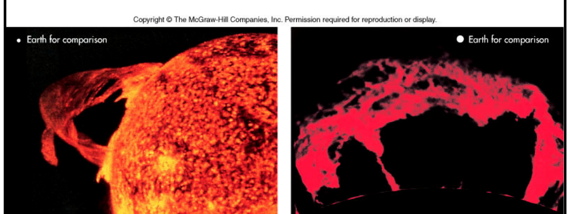



## Origin of Sunspots



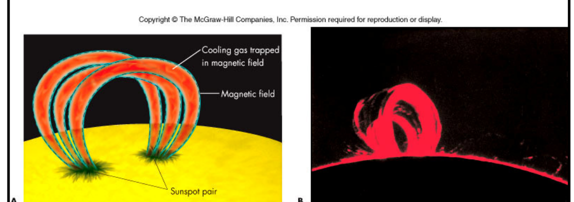

- Starved of heat from below, the surface cools where the magnetic fields breach the surface creating a dark sunspot

## Prominences




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

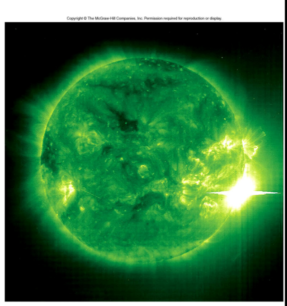
## Prominences




- 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

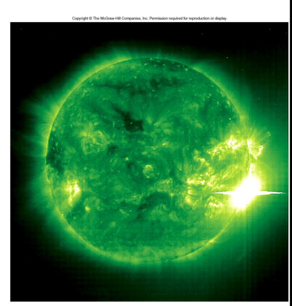
## Solar Flares

- 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



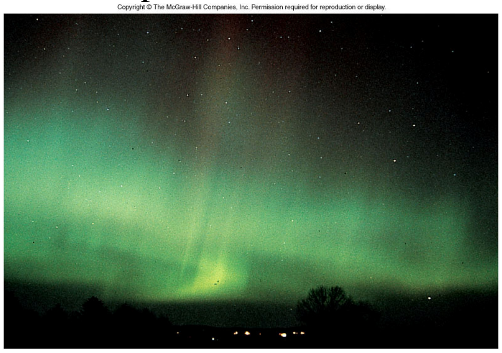
## Solar Flares

- 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



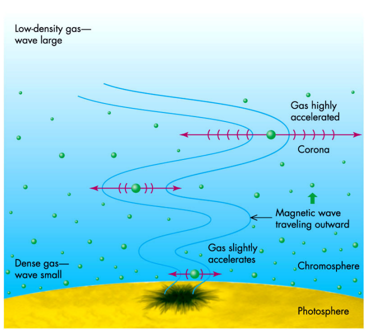


## Heating of the Chromosphere and Corona

- 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

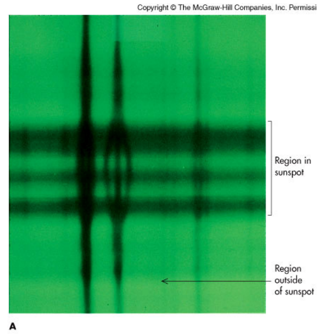
## Heating of the Chromosphere and Corona






## The Zeeman Effect





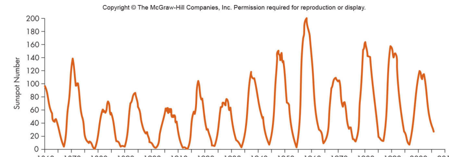

- Magnetic fields and their strength can be detected by the ***Zeeman effect***
- Magnetic fields can split the spectral lines of an atom into two, three, or more components by changing the energy levels of the atom's electrons

## 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

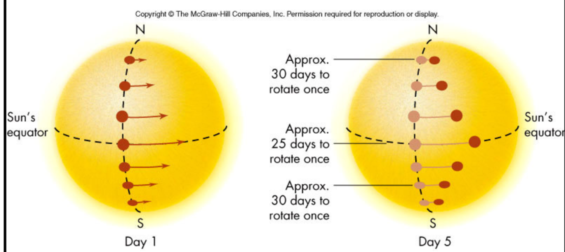
## The Solar Cycle





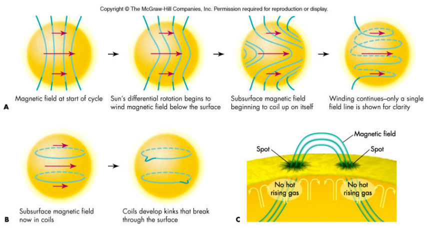

- Sunspot, flare, and prominence activity change yearly in a pattern called the ***solar cycle***
- Over the last 140 years or so, sunspots peak in number about every 11 years
- Climate patterns on Earth may also follow the solar cycle

## Differential Rotation



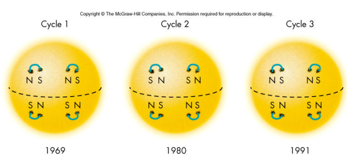

- The Sun undergoes differential rotation, 25 days at the equator and 30 at the poles

## Cause of the Solar Cycle



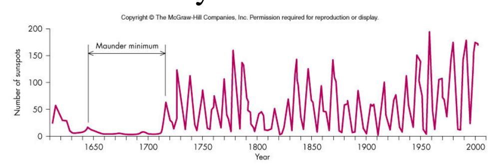

- This rotation causes the Sun's magnetic field to "wind up" increasing solar activity (magnetic field "kinks" that break through the surface) as it goes
- The cycle ends when the field twists too "tightly" and collapses – the process then repeats

## 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