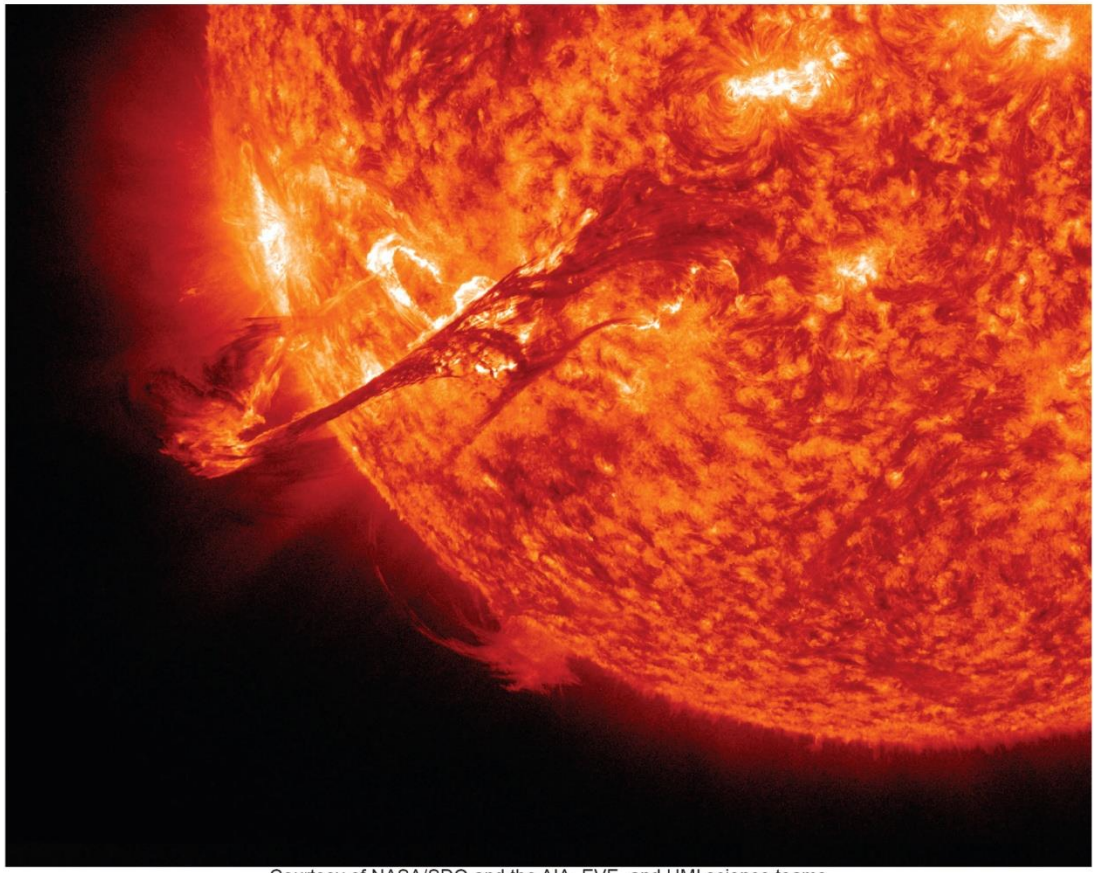
Chapter 12

The Sun, Our Star



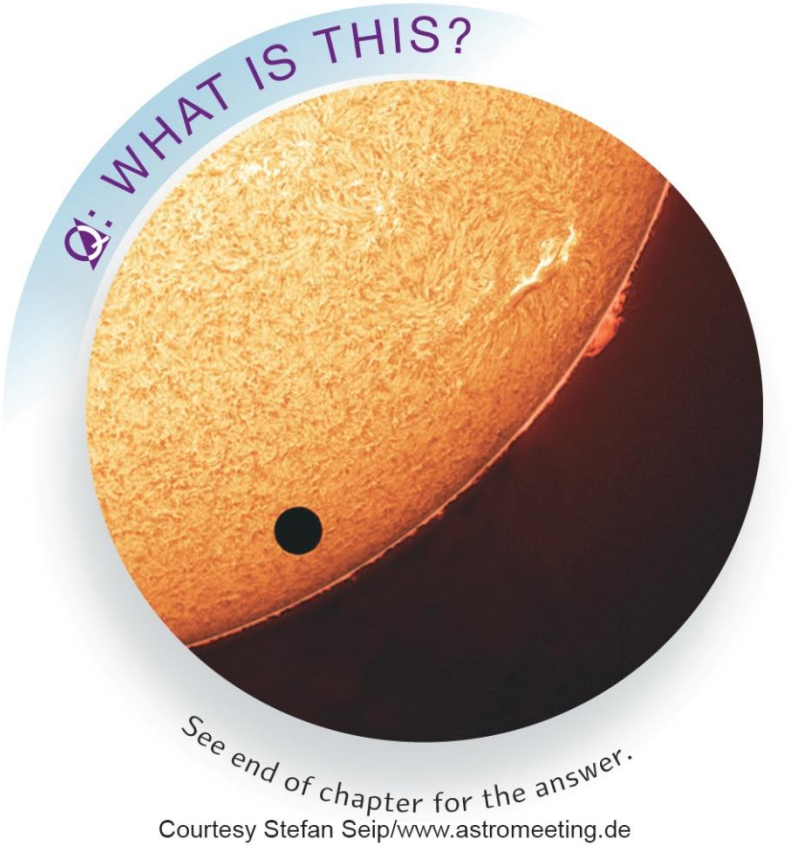
Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams

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

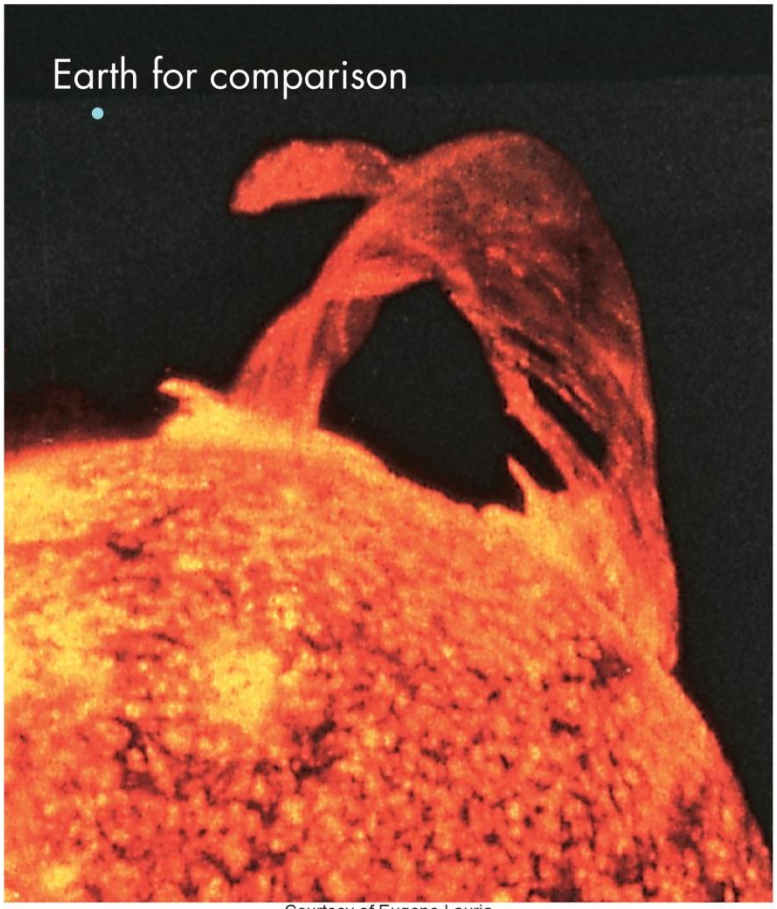
Radius and Mass

- 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 self-gravity



Courtesy Stefan Seip/www.astromeeting.de

Properties of the Sun



Courtesy of Eugene Lauria

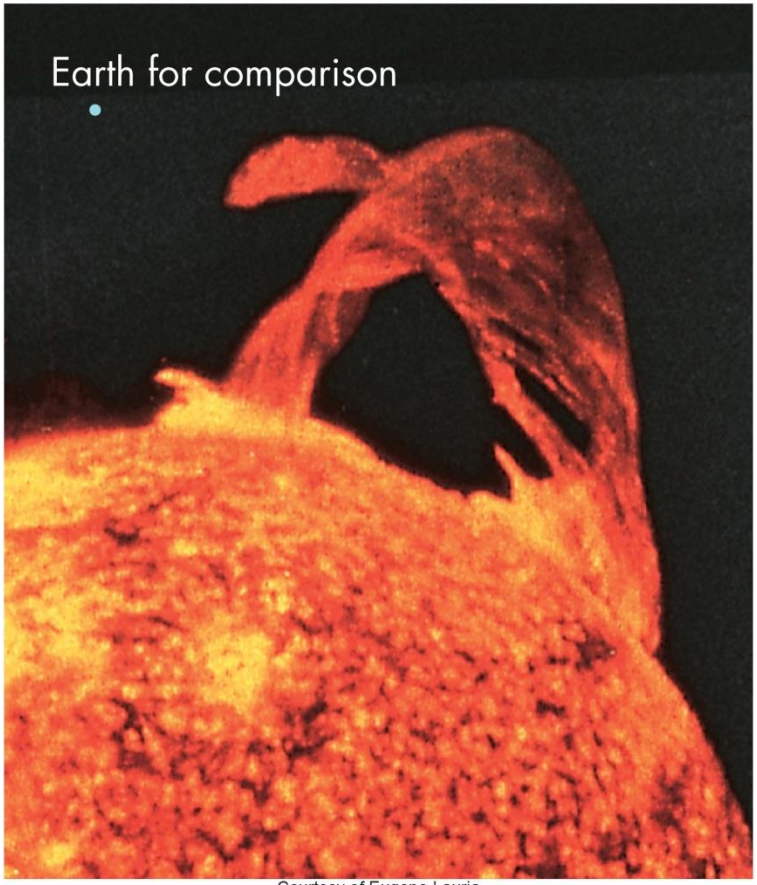
- The Sun's distance from Earth (about 150 million km or 1 AU) was once measured by triangulation, but is now done by radar
- Once the distance is known, its diameter (about 1.4 million km) can be found from its angular size (about 1/2 degree)

Mass and Temperature

- From the Sun's distance and the Earth's orbital period, Kepler's modified third law gives the Sun's mass
- From the 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

Courtesy Stefan Seip/www.astromeeting.de

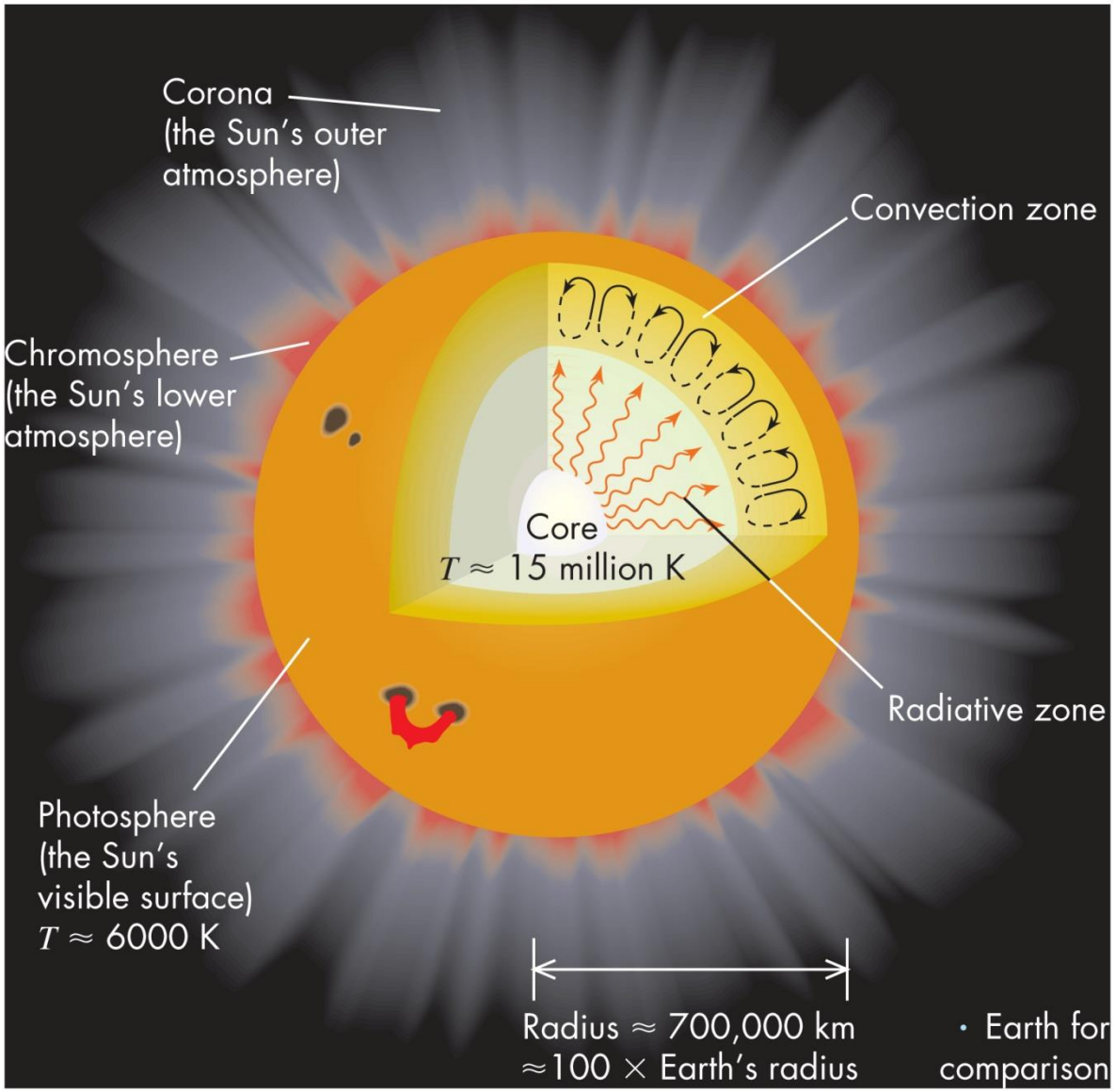
Composition and Structure



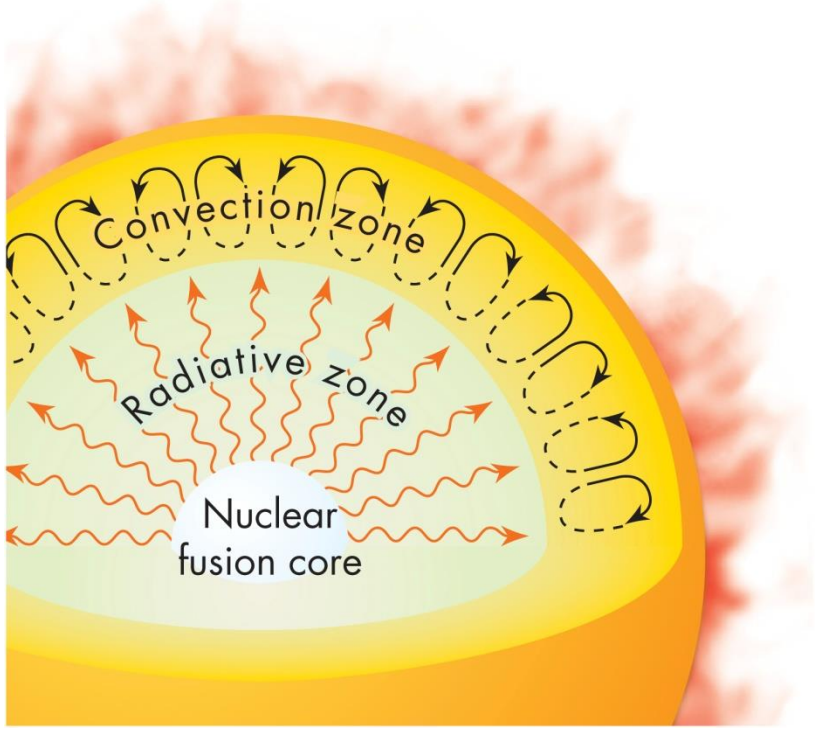
Courtesy of Eugene Lauria

- 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

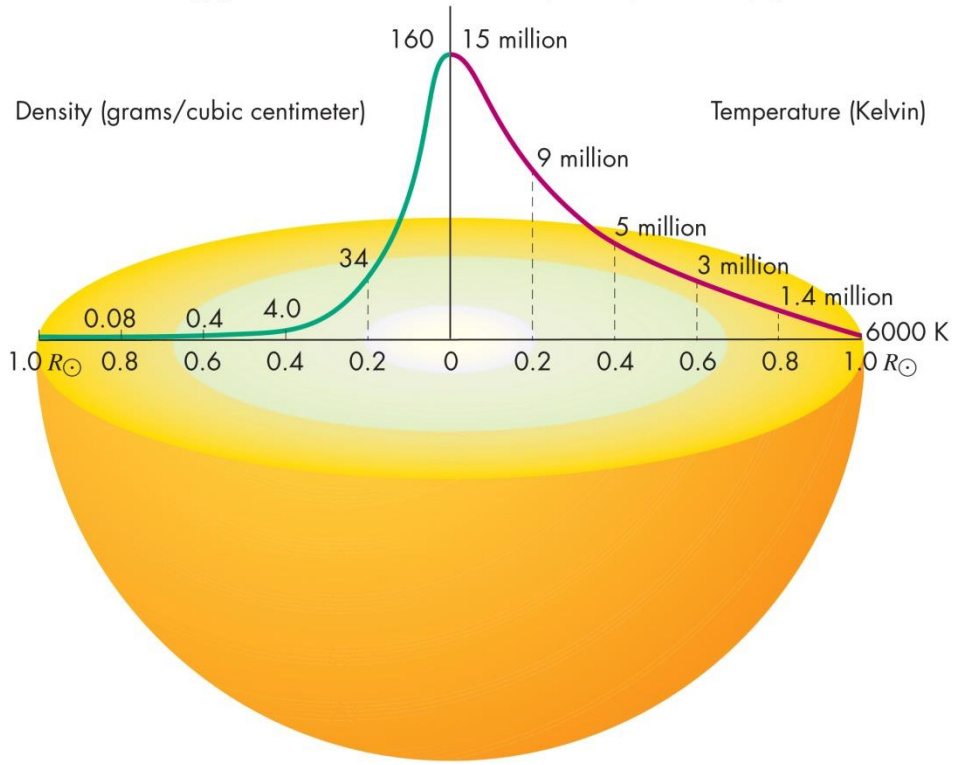


The Solar Interior



- 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 the yellow “surface.”
- Layers below the photosphere are opaque, photons created there are readily absorbed by atoms located there

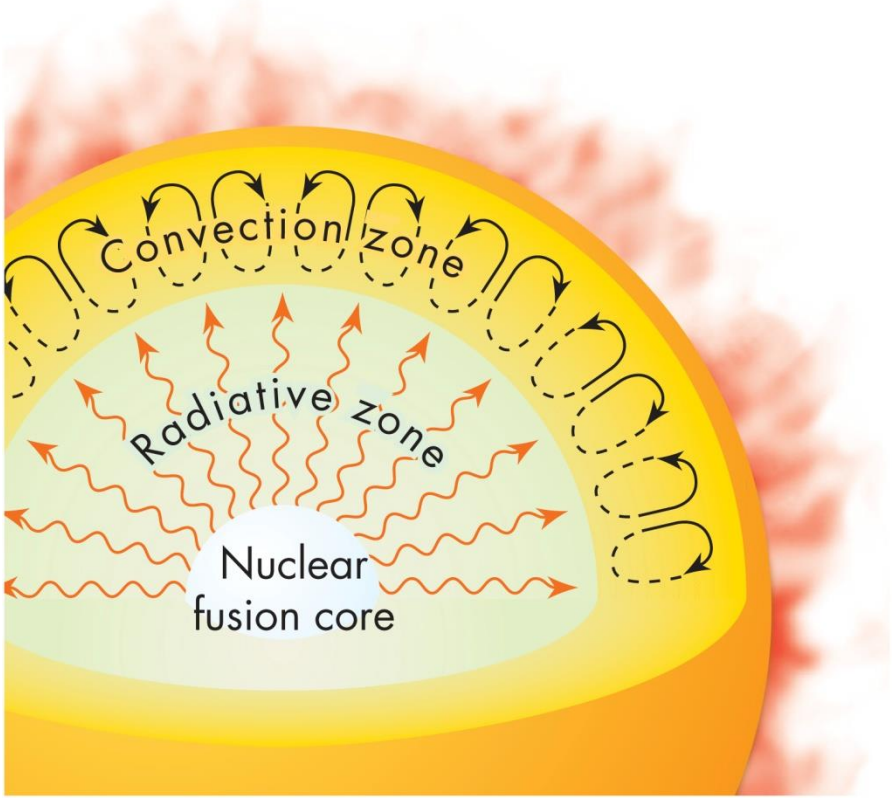
Temperature and Density Changes



- 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

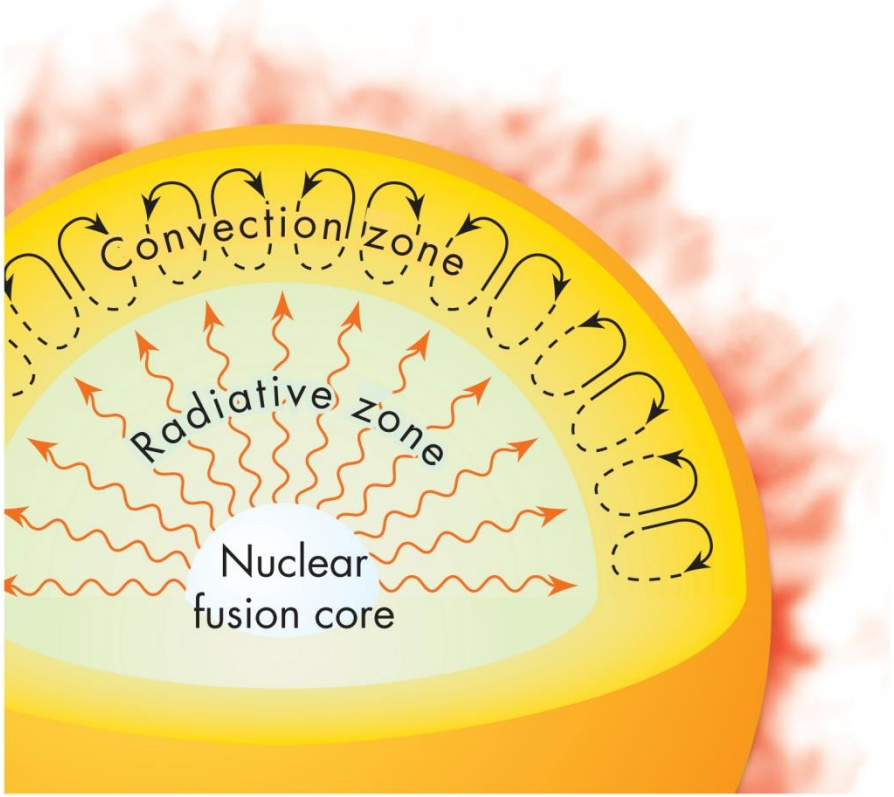
The Radiative Zone

- 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***



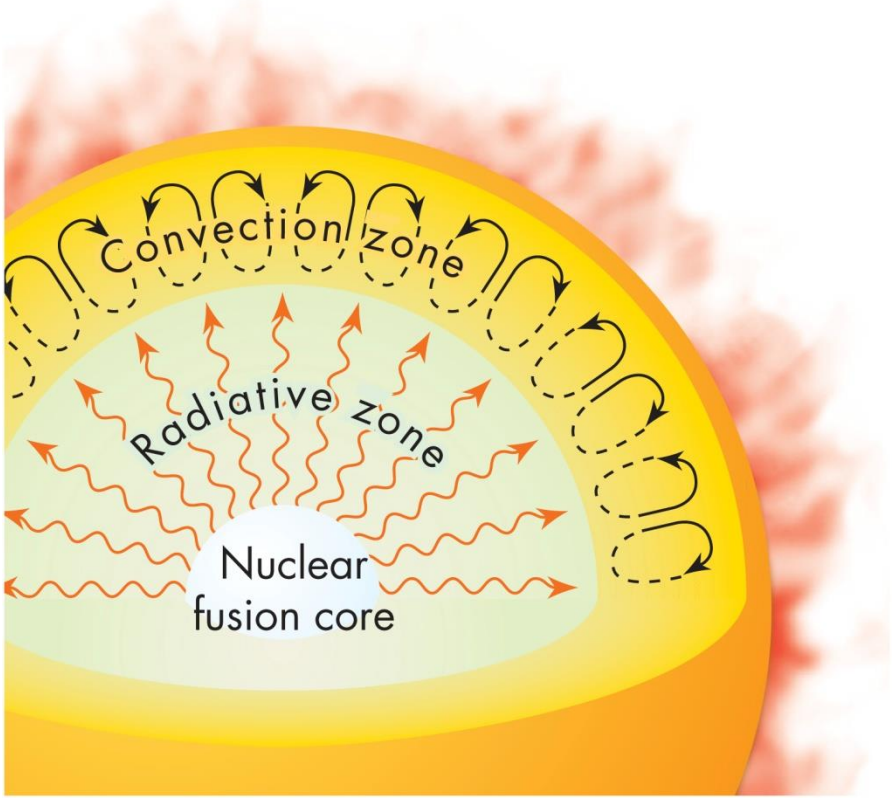
Very Old Light

- 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!

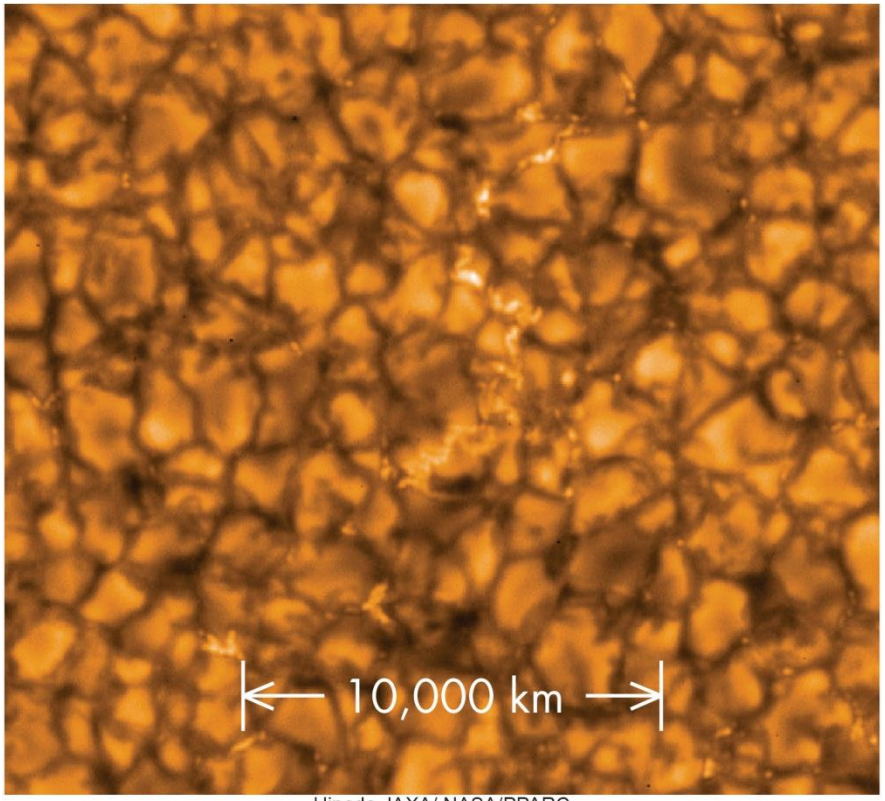


The Convection Zone

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



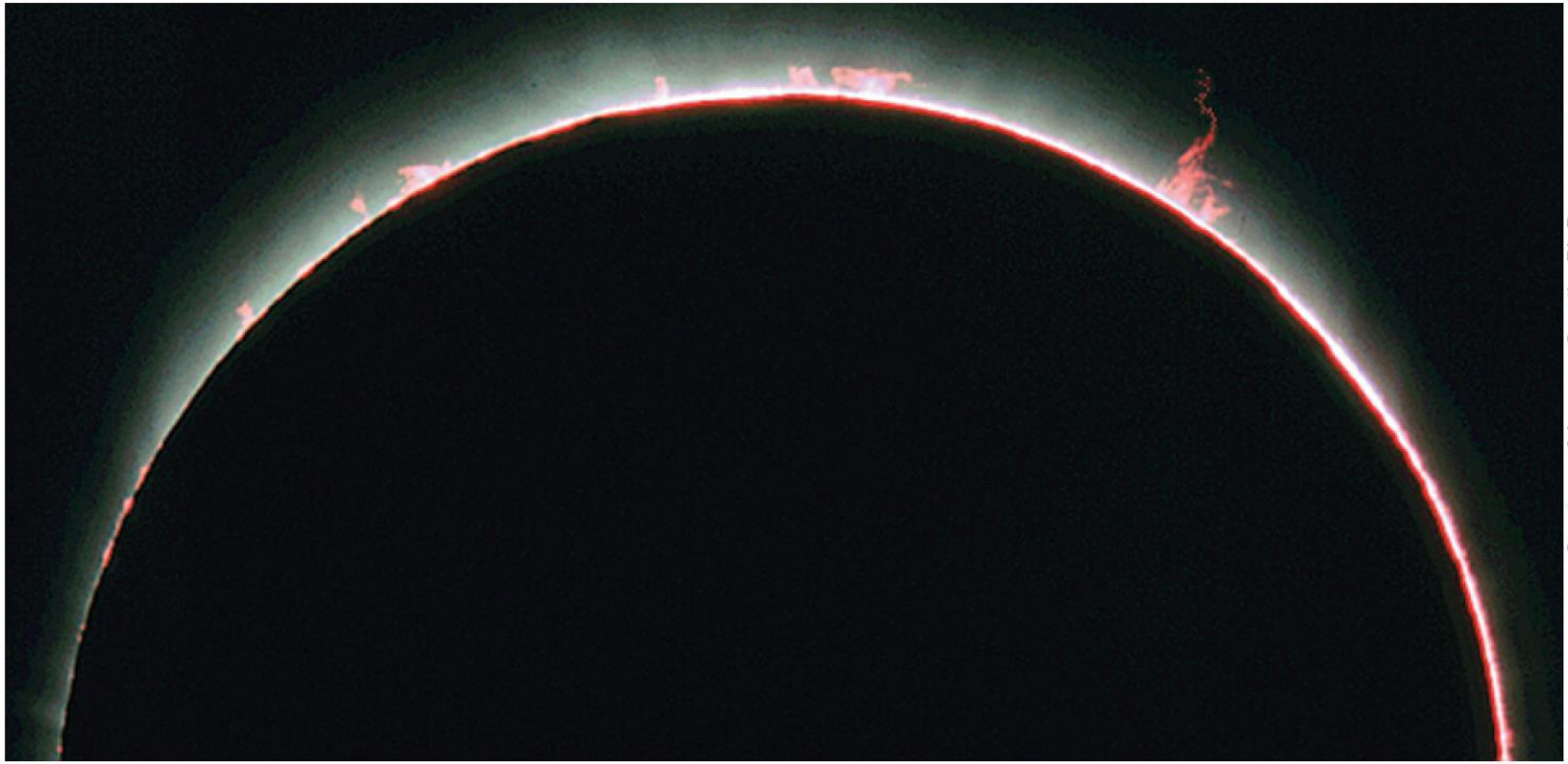
Granulation



Hinode JAXA/ NASA/PPARC

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

The Sun's Atmosphere



Courtesy of Jacques Guertin, Ph.D.

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

Temperature Profile

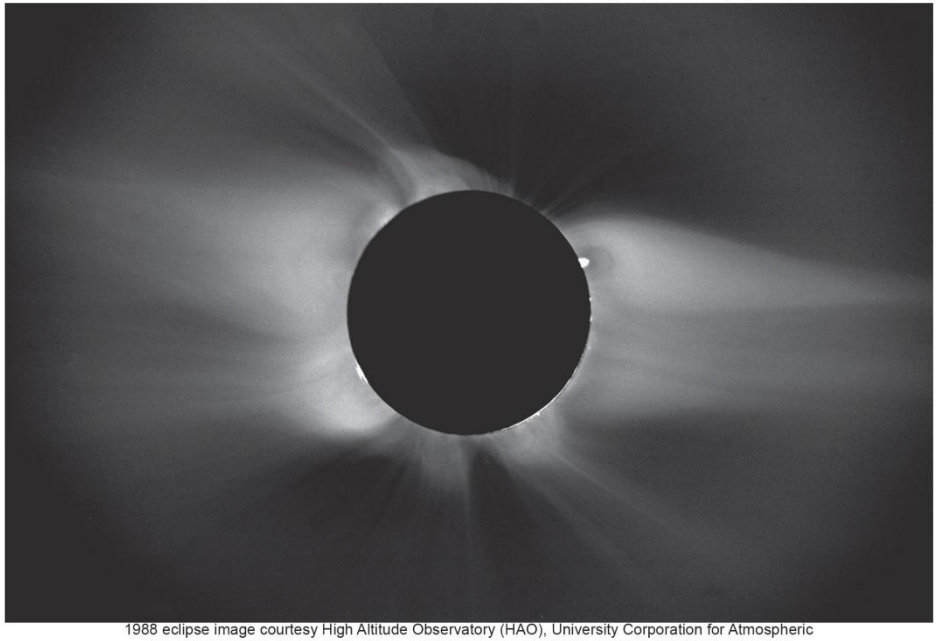
- The density of the atmosphere decreases steadily with altitude and eventually merges with the near-vacuum of space.
- Immediately above the photosphere, the temperature of the atmosphere decreases but at higher altitudes, the temperature grows hotter, reaching temperatures of several million Kelvin.
- 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.

Courtesy of NOAO/AURA/NSF

The Corona

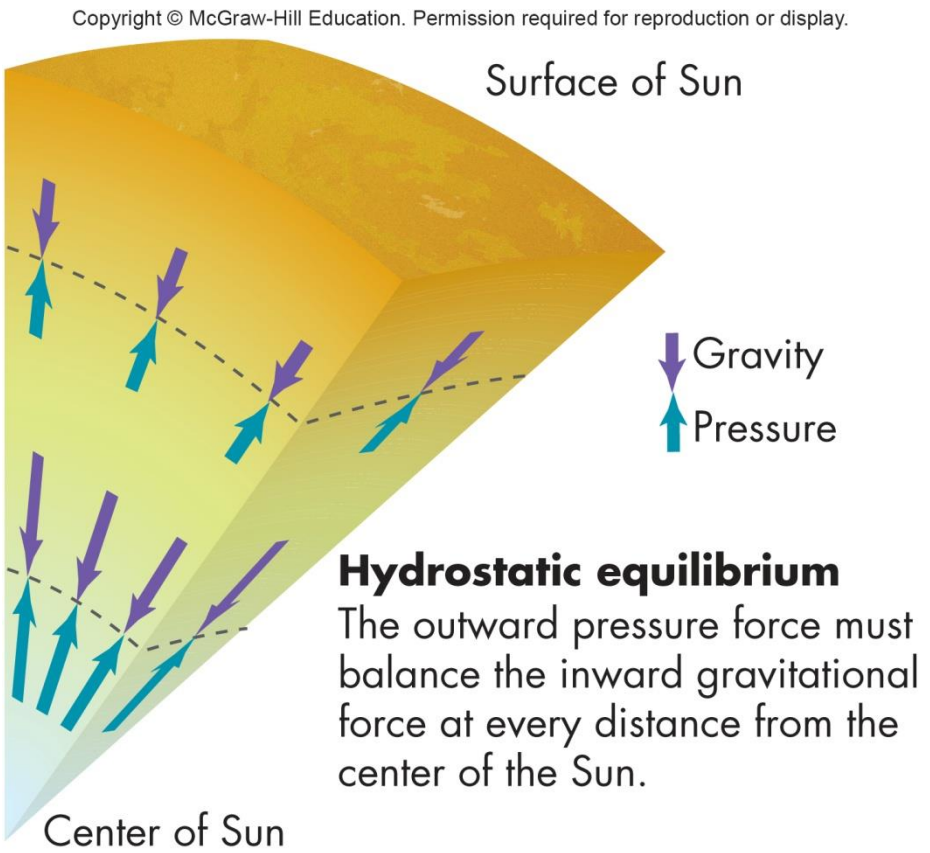


1988 eclipse image courtesy High Altitude Observatory (HAO), University Corporation for Atmospheric Research (UCAR), Boulder, Colorado. UCAR is sponsored by the National Science Foundation

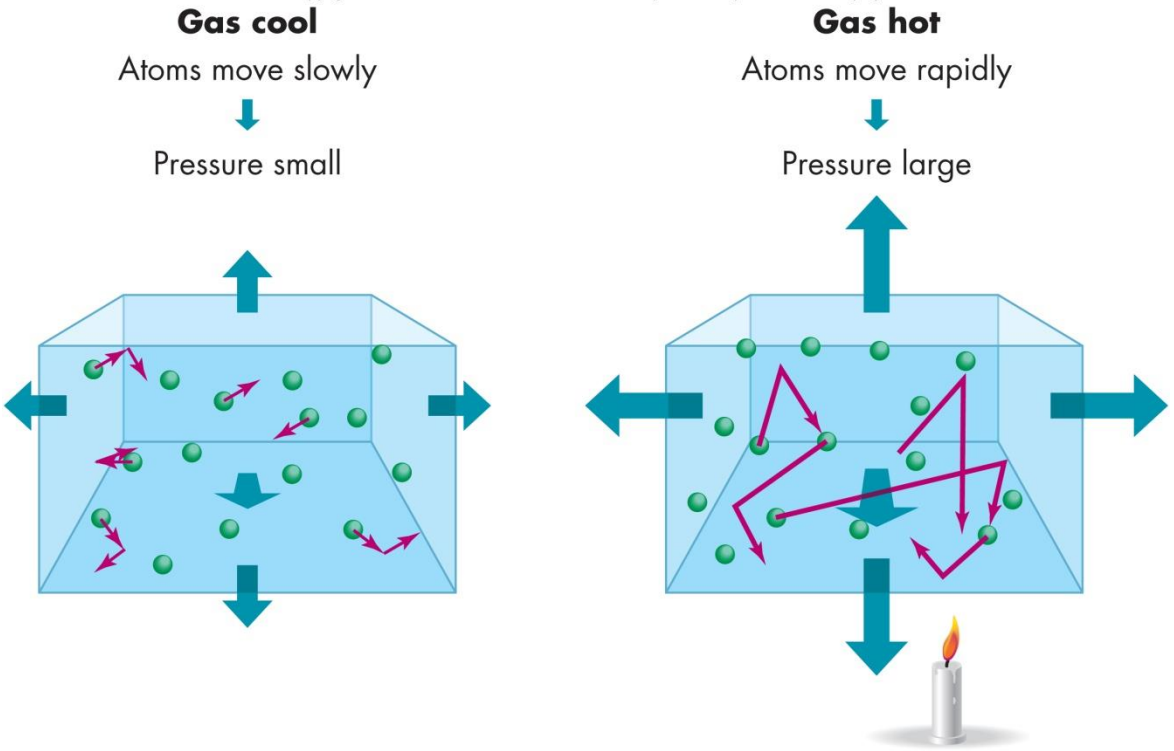
- Temperature in the corona eventually reaches about 1 million K (not much energy though due to low density)
- The corona, visible in a total solar eclipse, can be seen to reach altitudes of several solar radii
- The corona is not uniform but has streamers and *coronal holes* dictated by the Sun's magnetic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

$E = mc^2$

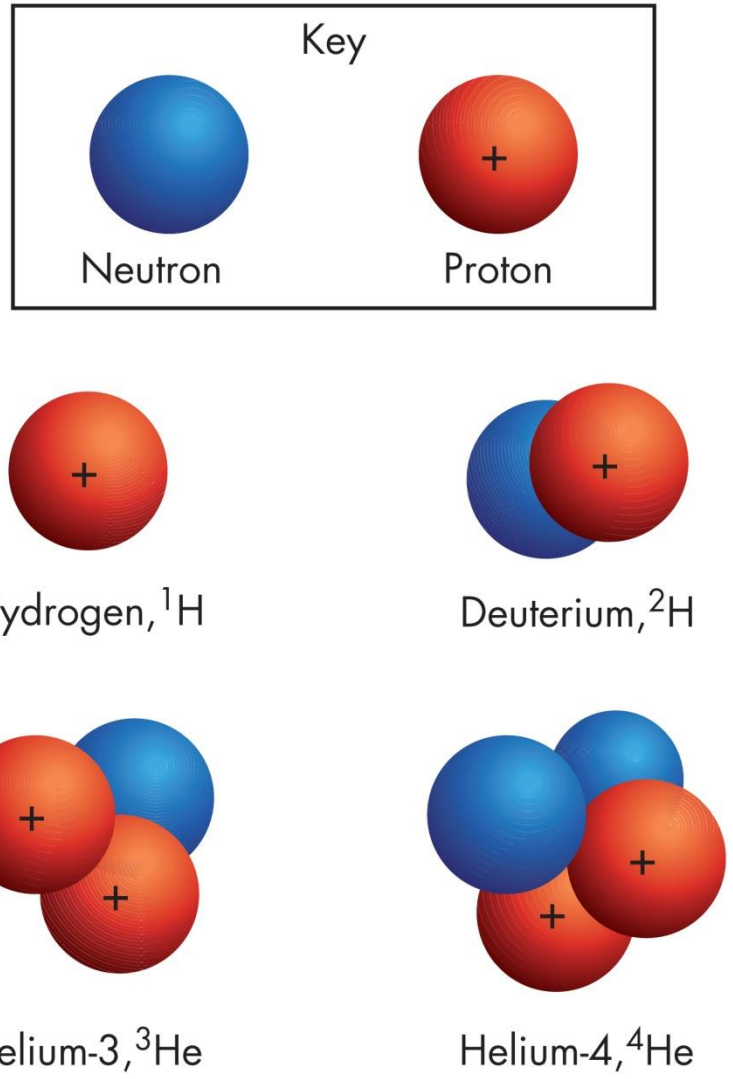
- Mass-energy is the key
  - In 1905, Einstein showed that energy and mass were equivalent through his famous $E = mc^2$ equation
  - 1 gram of mass is equivalent to the energy of a small nuclear weapon
  - The trick is finding a process to convert mass into other forms of energy

Nuclear Fusion

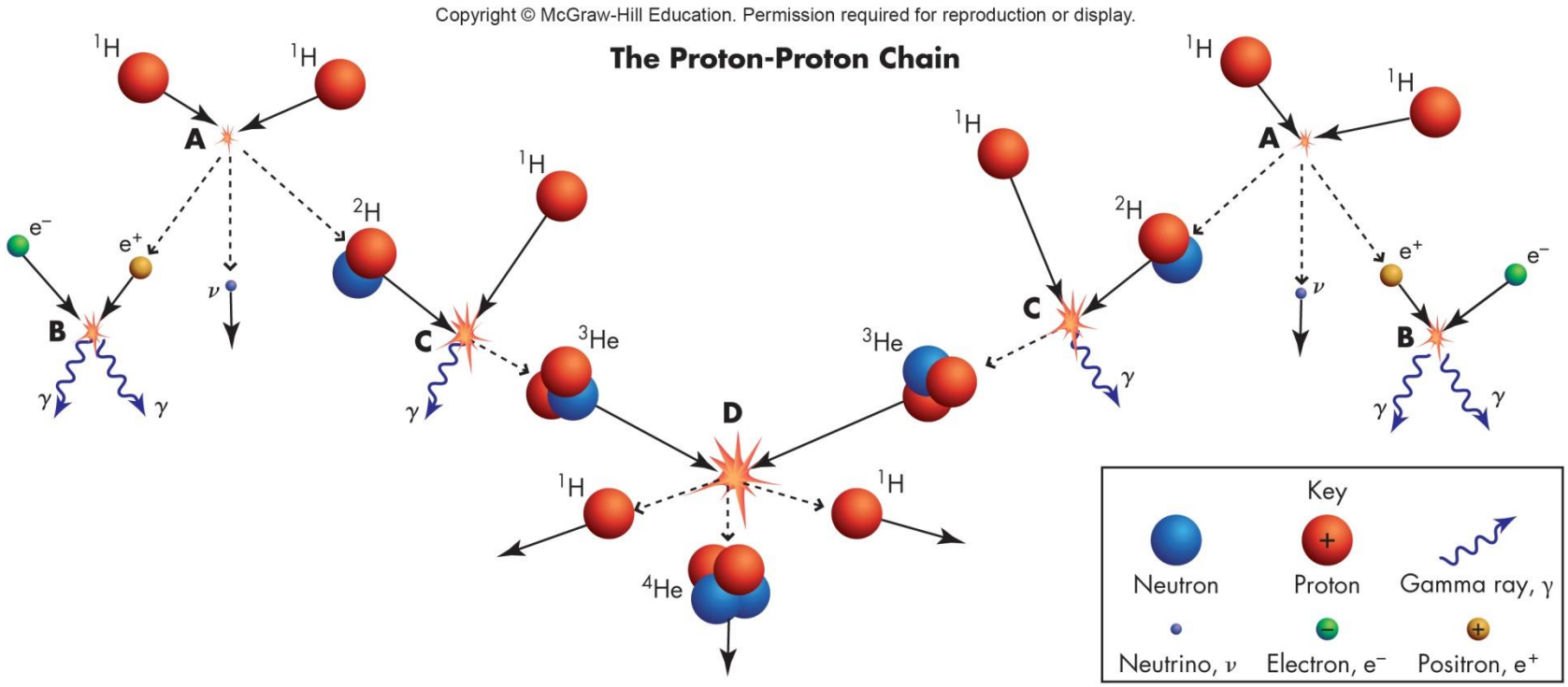
- A detailed process for mass conversion in the Sun called ***nuclear fusion*** was found:
  - Sun's core temperature is high enough to force positively charged protons close enough together to bind them together via the ***nuclear*** or ***strong force***
  - The net effect is that four protons are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

Isotopes

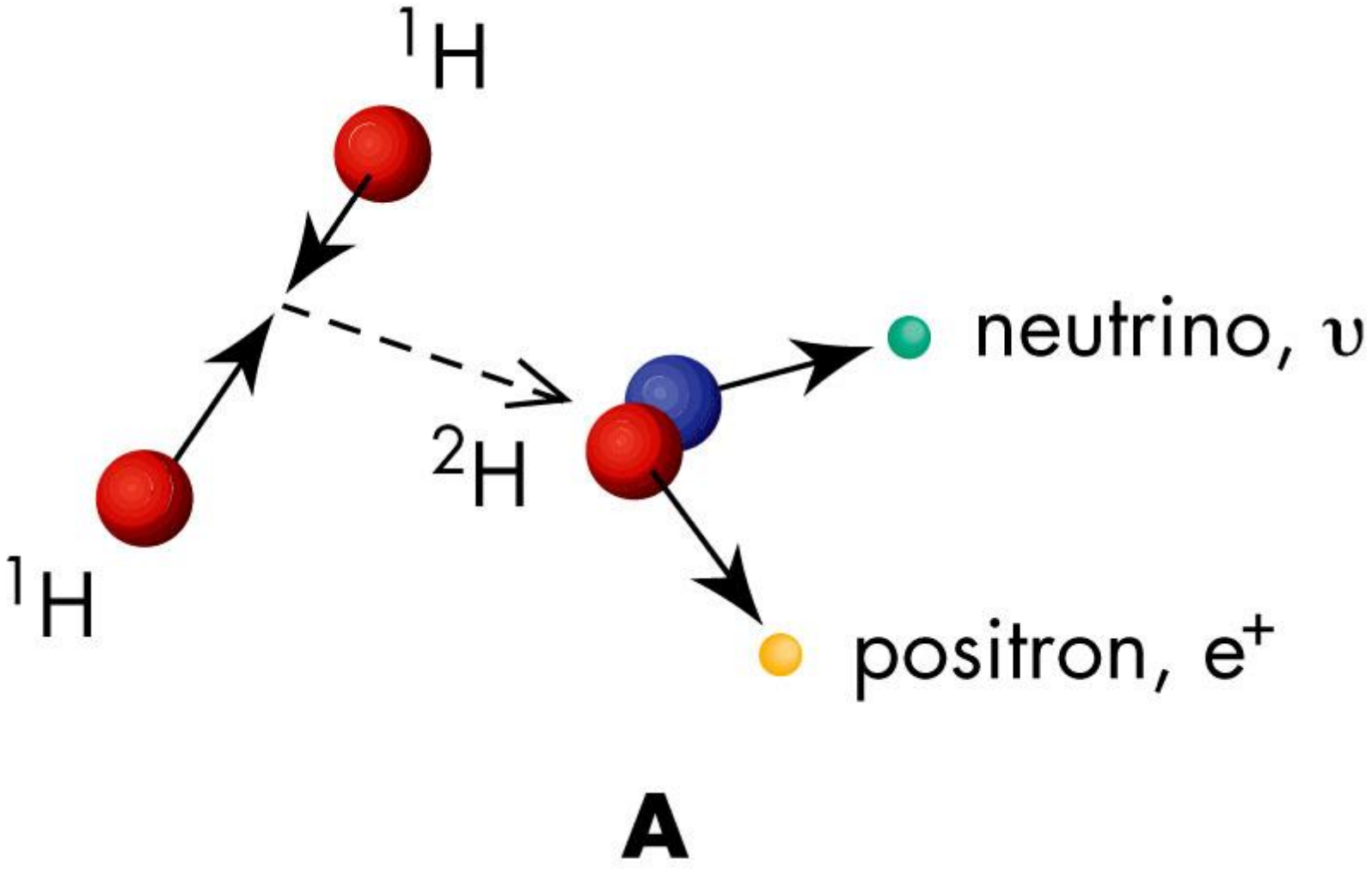
- In the proton-proton cycle, isotopes are intermediate steps between protons and their ultimate fusion into ^{4}He.



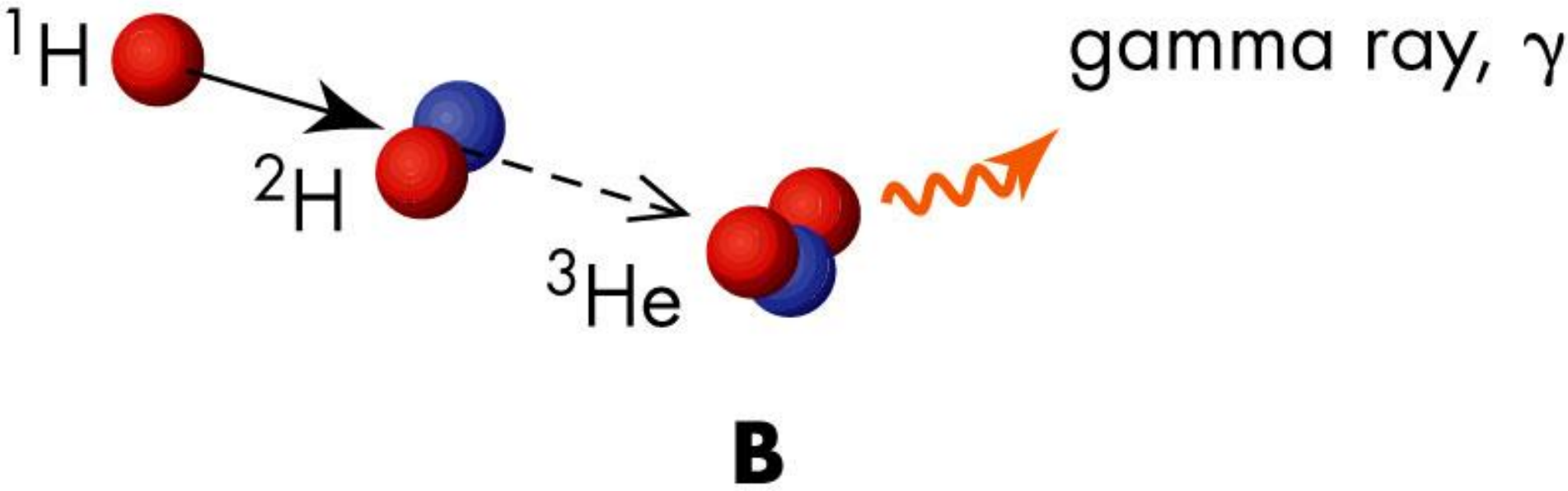
The Proton-Proton Chain



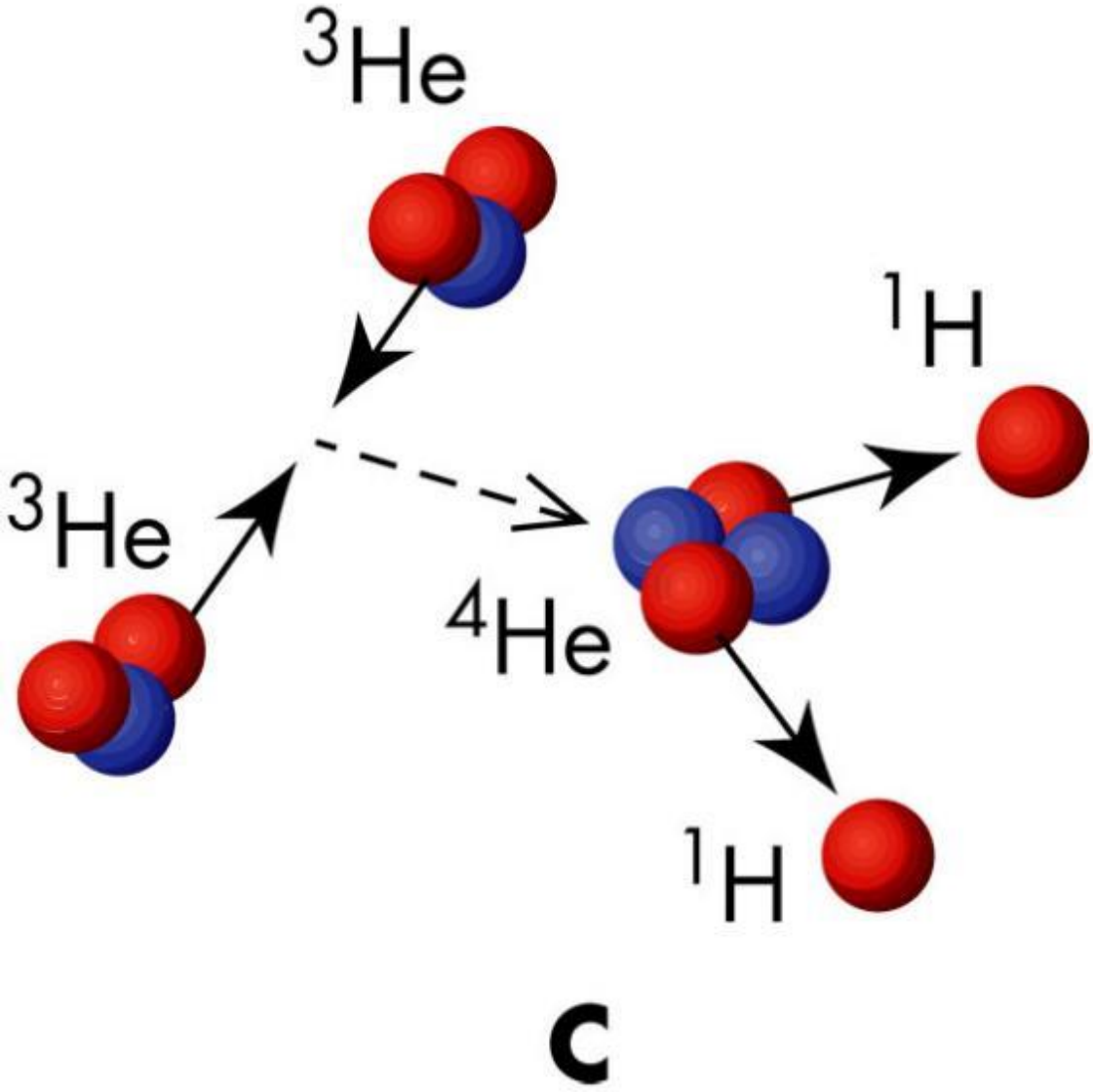
The Proton-Proton Chain: Step 1



The Proton-Proton Chain: Step 2

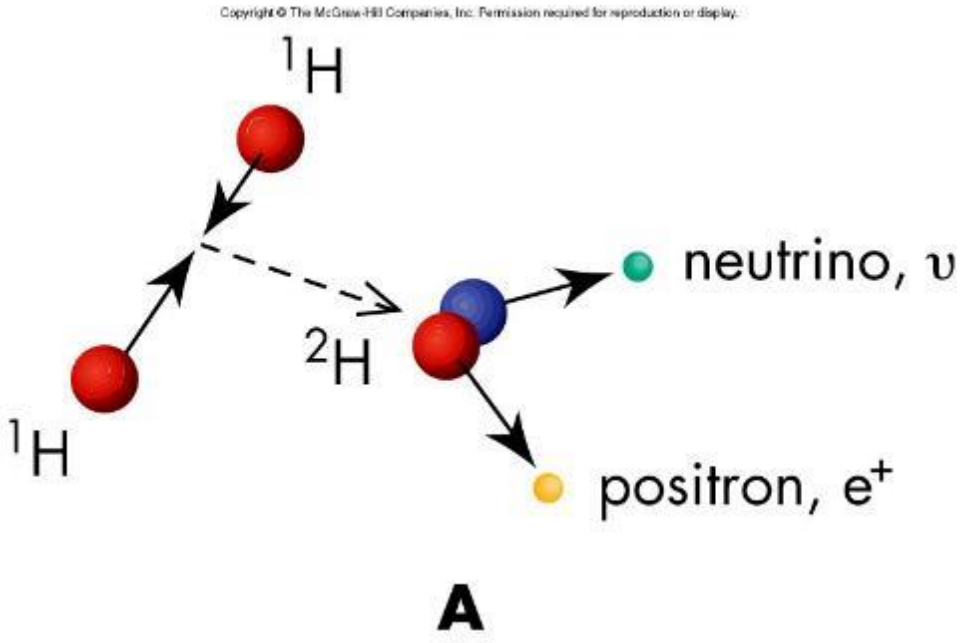


The Proton-Proton Chain: Step 3

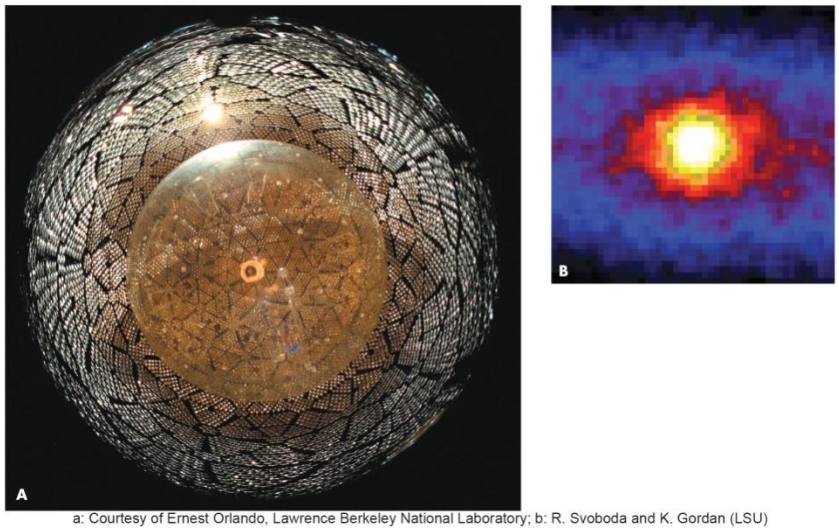


Solar Neutrinos

- 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).



Difficult to Detect



a: Courtesy of Ernest Orlando, Lawrence Berkeley National Laboratory; b: R. Svoboda and K. Gordan (LSU)

- 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

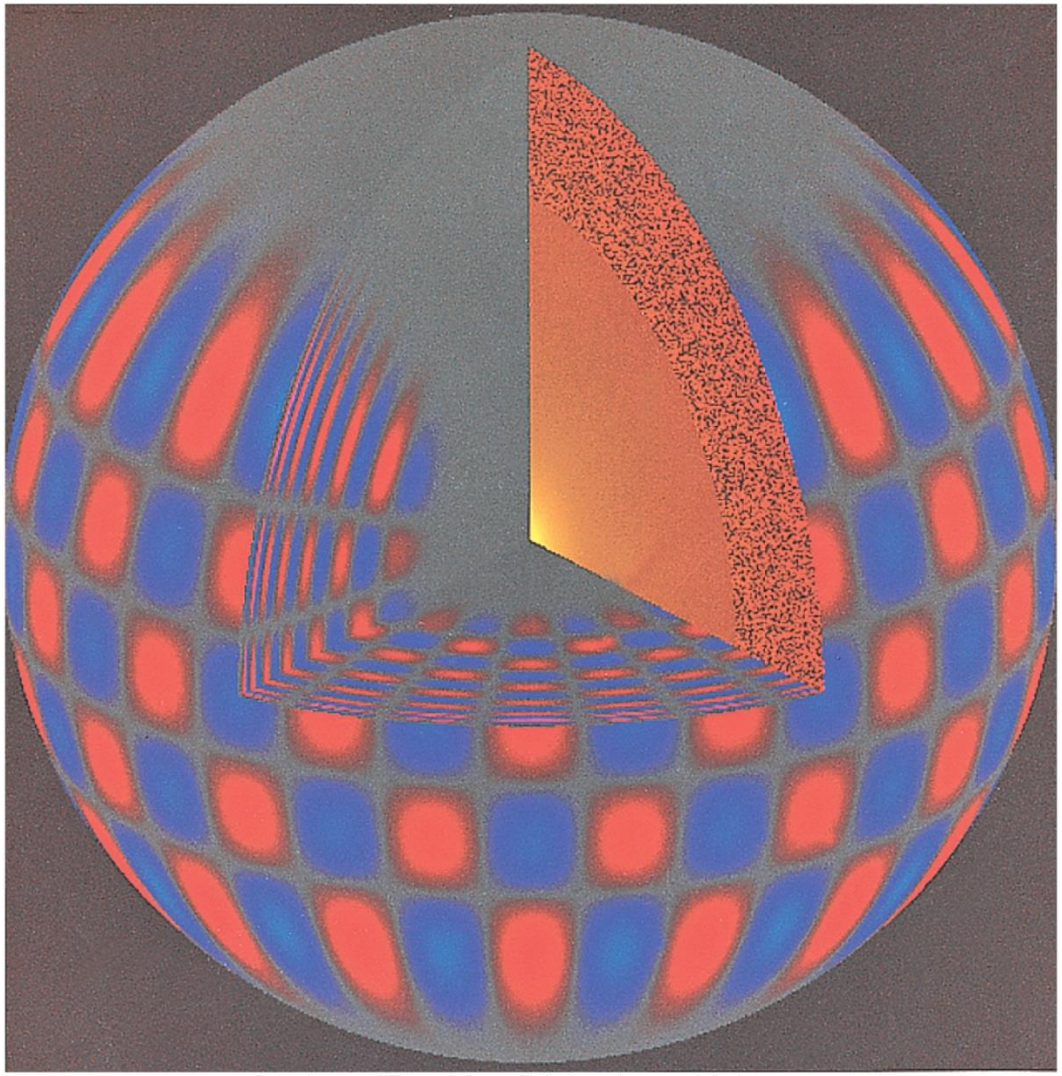
The Neutrino Crisis

- 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 first detectors could not detect all varieties.
- Subsequent observations with new detectors found all three types of neutrinos.

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

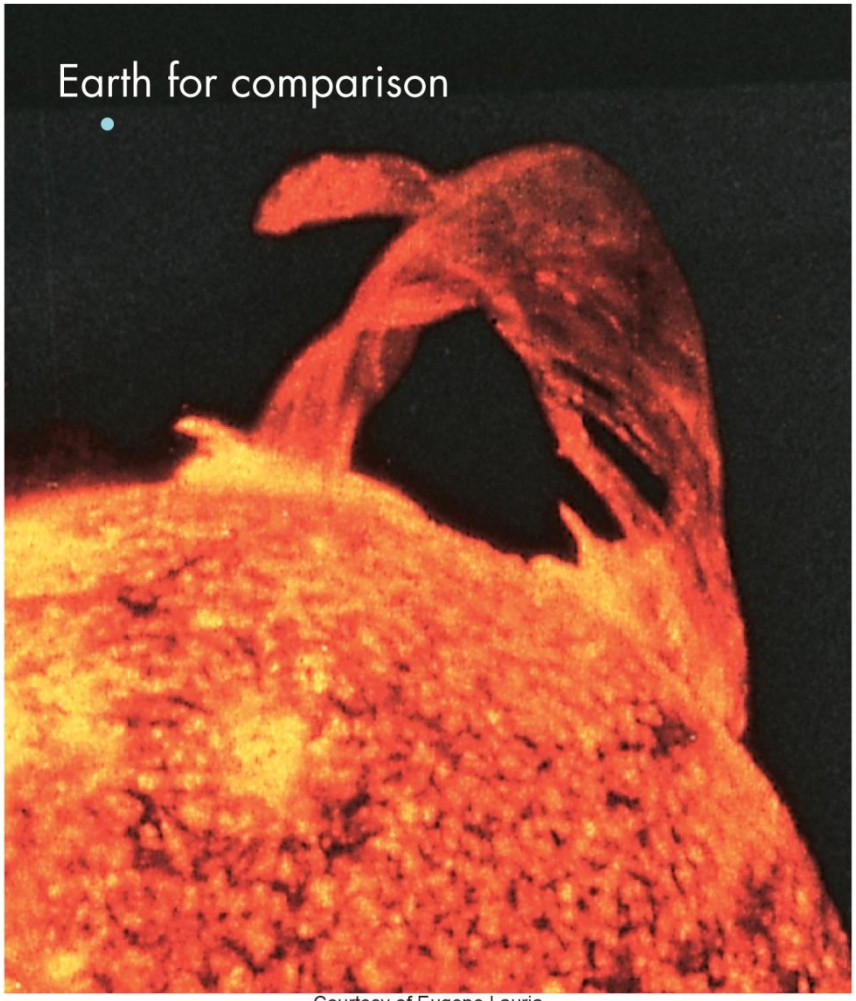
Peering Inside the Sun



Courtesy of Royal Swedish Academy of Sciences

Solar Magnetic Activity

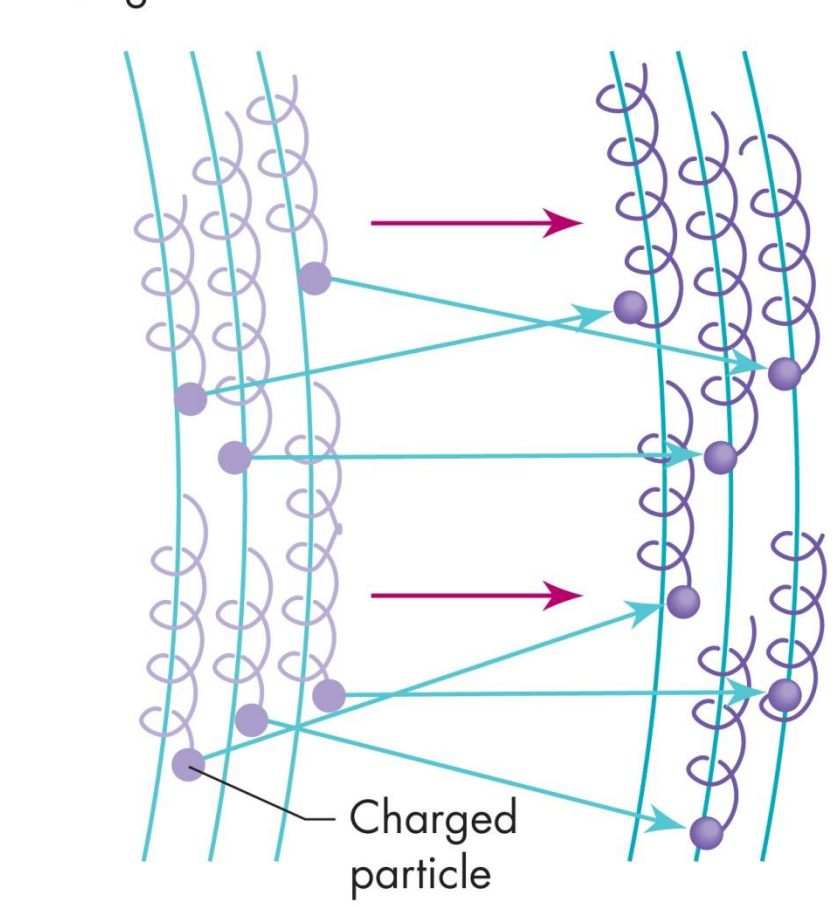
- Surface waves are but one type of disturbance in the Sun's outer layers
- A wide class of dramatic and lovely phenomena occur on the Sun and are caused by its magnetic field.



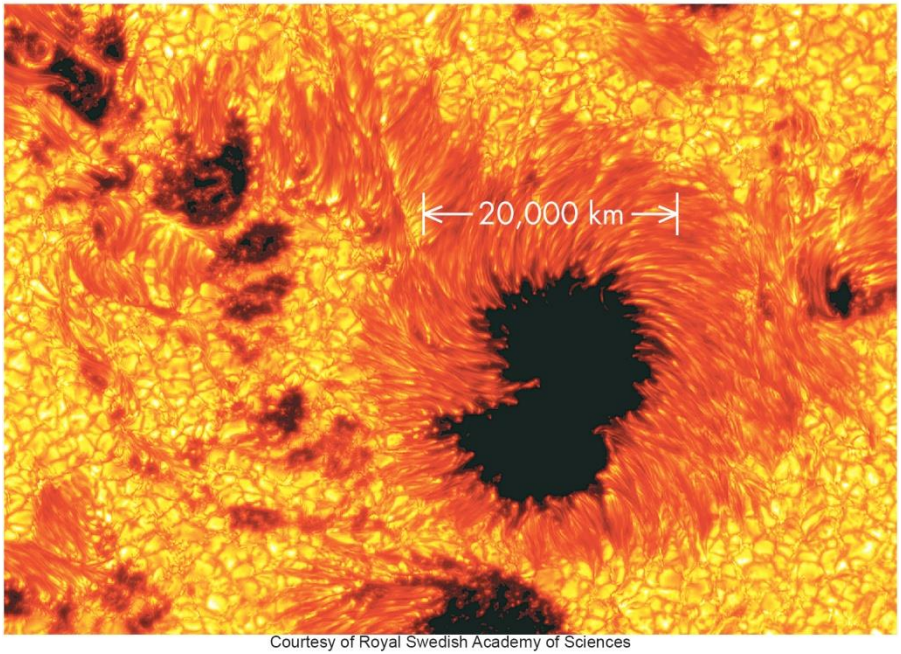
Courtesy of Eugene Lauria

Interaction of Fields and Particles

- Charged particles tend to spiral along magnetic field lines easier than they drift across them.
- Bulk motion of plasma carries the field along with it.
- Motion of the field carries particles along with it.



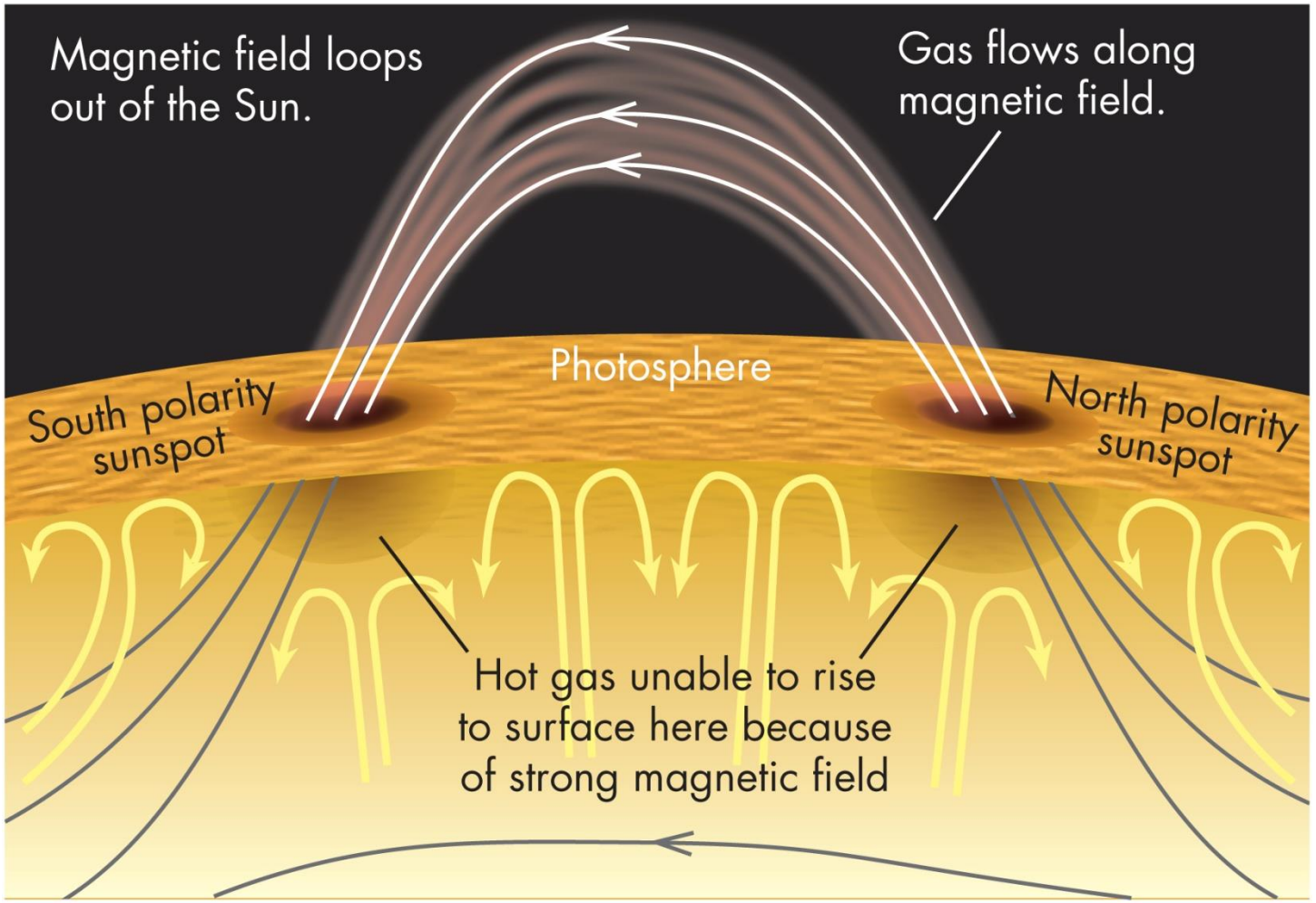
Sunspots



Courtesy of Royal Swedish Academy of Sciences

- 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

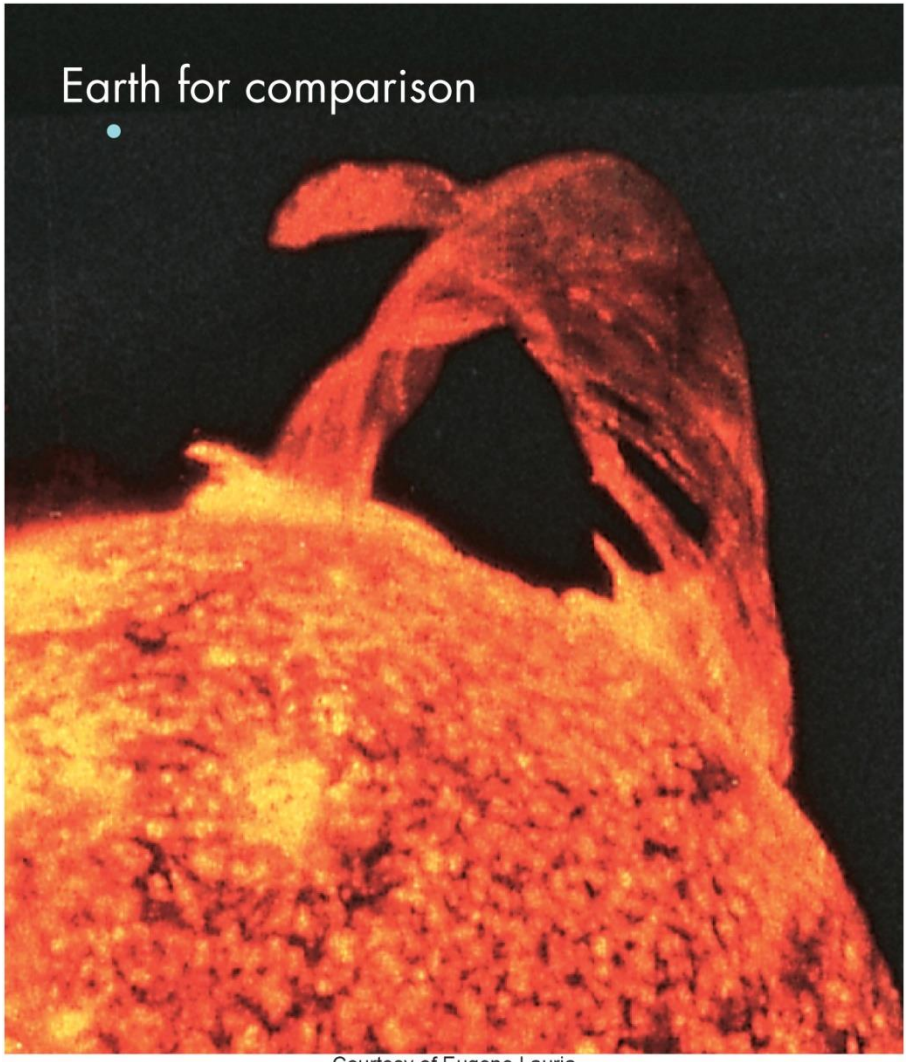
Origin of Sunspots



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

Prominences

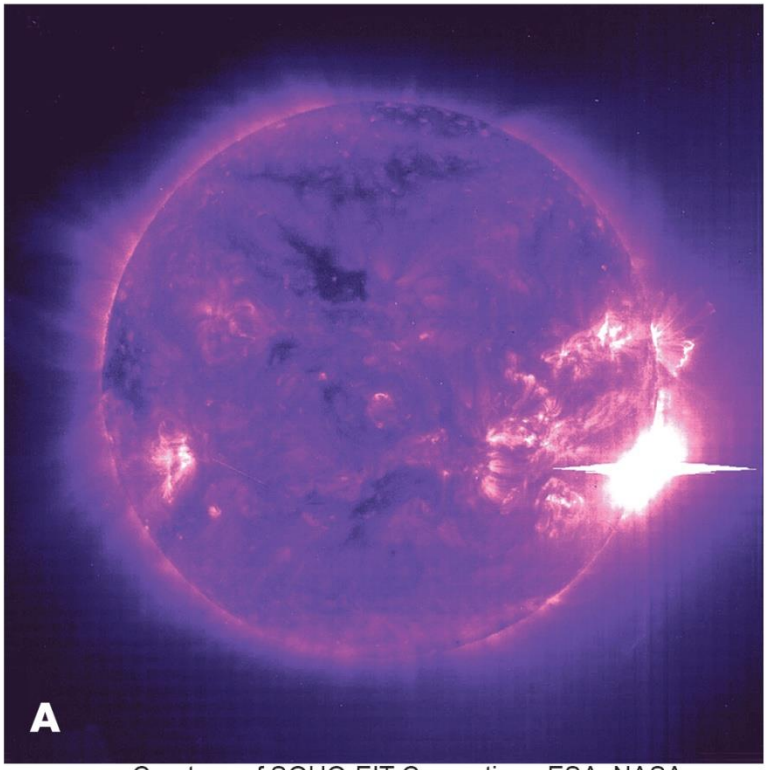
- ***Prominences*** are huge glowing gas plumes that jut from the lower chromosphere into the corona



Courtesy of Eugene Lauria

Solar Flares

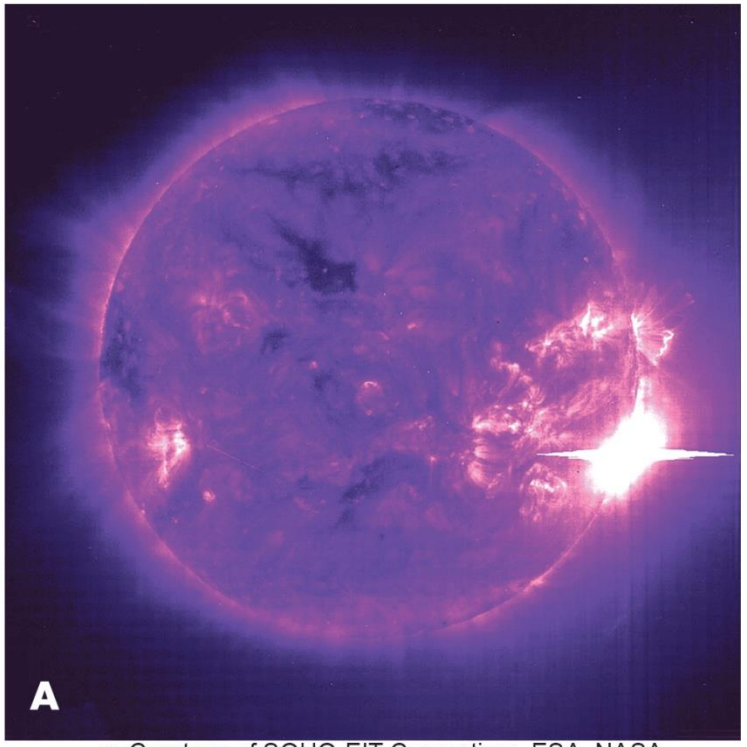
- Sunspots give birth to ***solar flares,*** brief but bright eruptions of hot gas in the chromosphere.
- Hot gas brightens over minutes or hours, but not enough to affect the Sun's total light output.



a: Courtesy of SOHO-EIT Consortium, ESA, NASA

Source of Flares

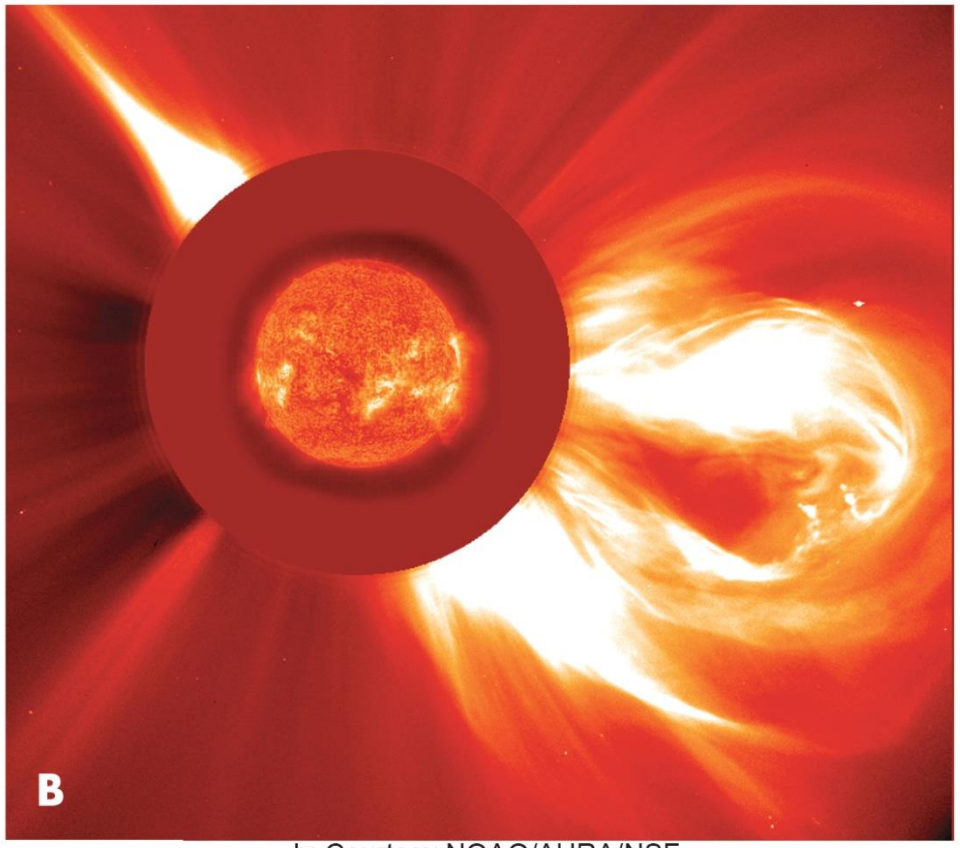
- Strong increase in radio and x-ray emissions
- Intense twisting and "breakage" of magnetic field lines is thought to be the source of flares



a: Courtesy of SOHO-EIT Consortium, ESA, NASA

Coronal Mass Ejections

- *Coronal mass ejections* can explosively shoot gas across the Solar System and result in spectacular auroral displays



b: Courtesy NOAO/AURA/NSF

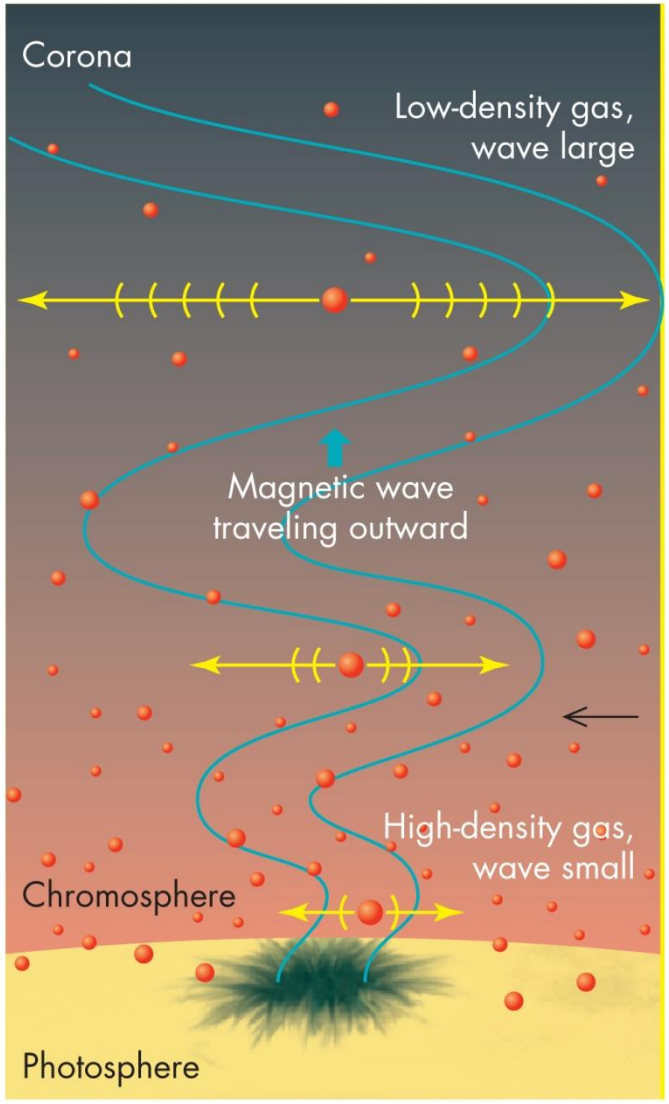
Impact of Solar Flares

Courtesy of Eugene Lauria

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.

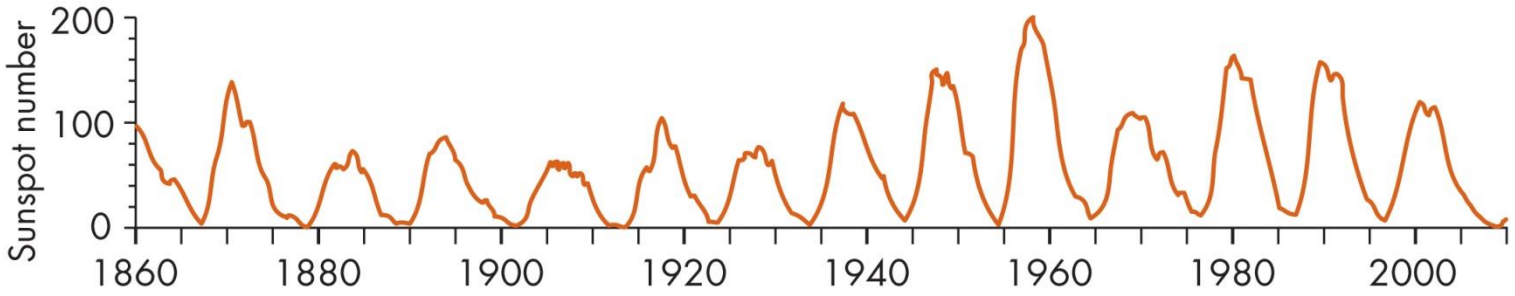
Magnetic Waves



The Solar Wind

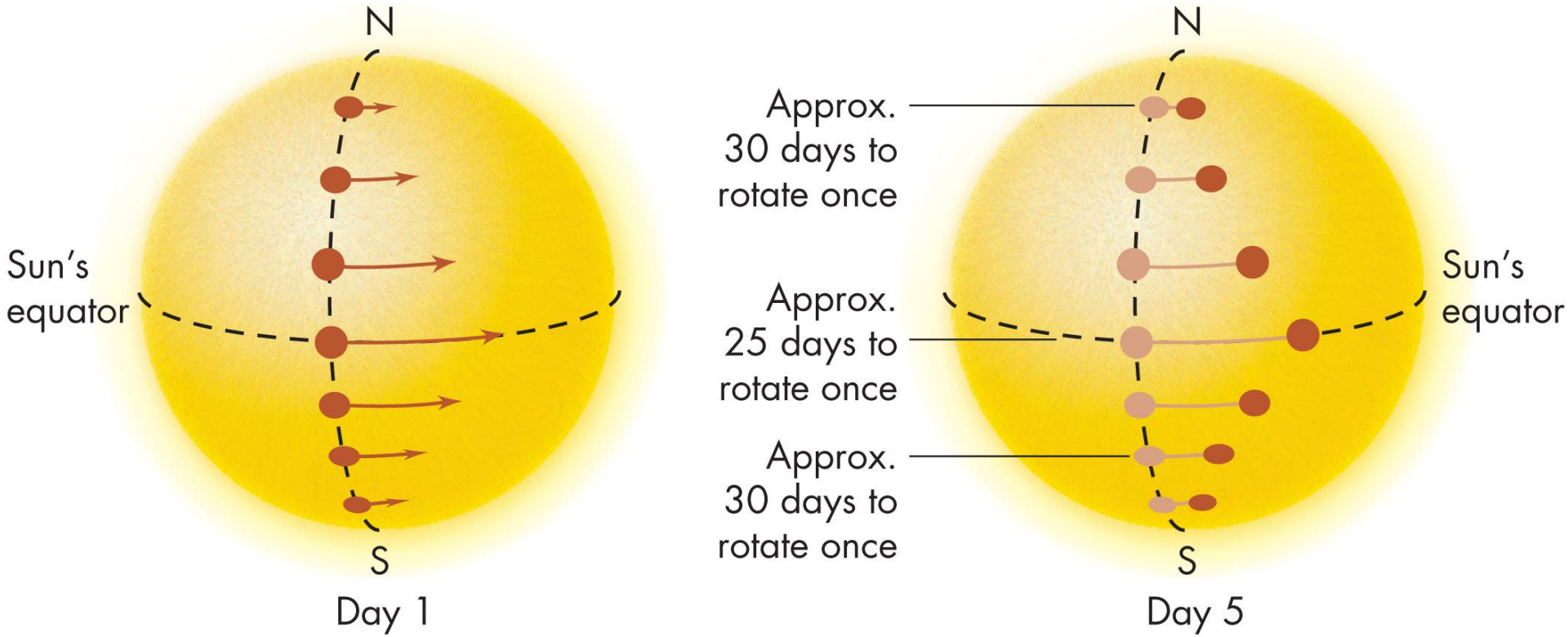
- The corona's high temperature gives its atoms enough energy to exceed the escape velocity of the Sun.
- As these atoms stream into space, they form the ***solar wind,*** a tenuous gas of hydrogen and helium that sweeps across the entire Solar System.
- The amount of material lost from the Sun via the 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 merges with interstellar space.

The Solar Cycle



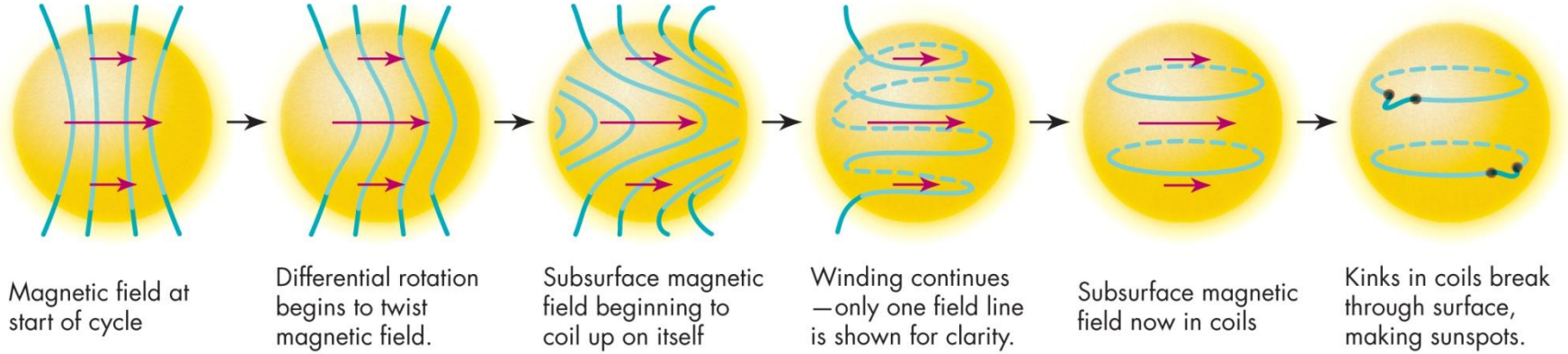
- Sunspot, flare, and prominence activity change yearly in a pattern called the ***solar cycle.***
- Over the last 140 years or so, sunspots peak in number about every 11 years.
- Climate patterns on Earth may also follow the solar cycle.

Differential Rotation



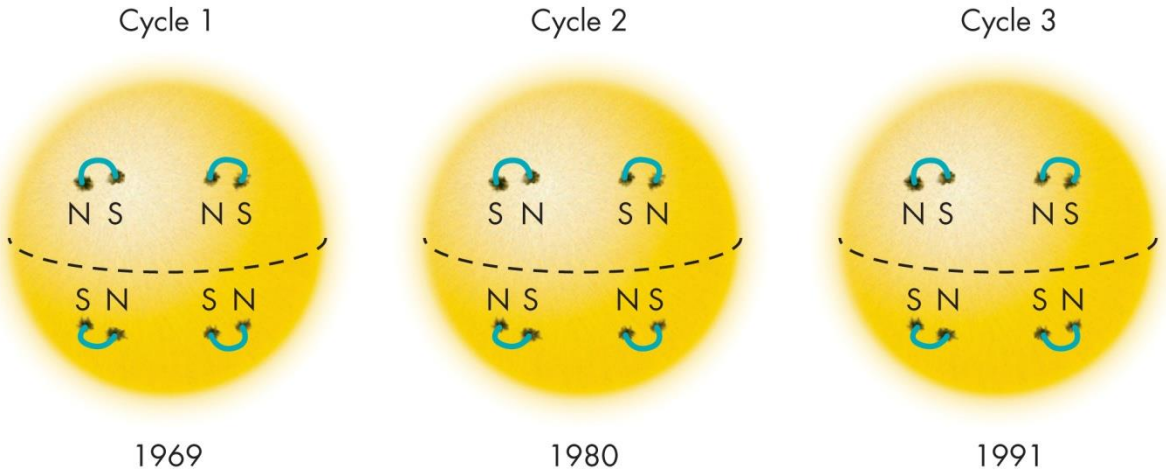
- The Sun undergoes differential rotation, 25 days at the equator and 30 at the poles.

Cause of the Solar Cycle



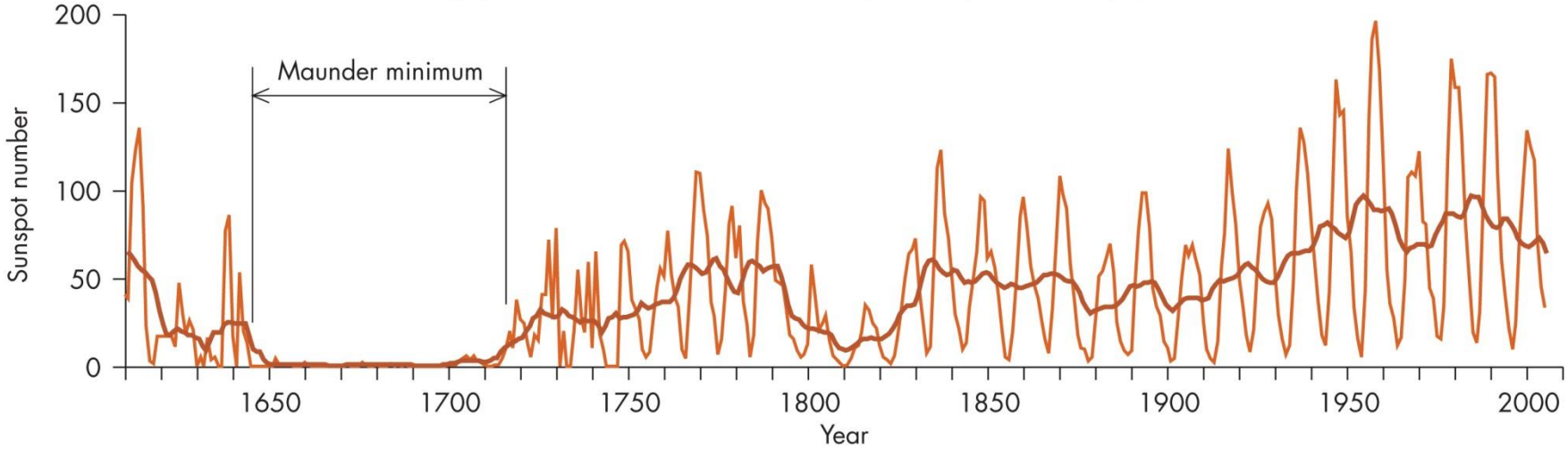
- This rotation causes the Sun's magnetic field to "wind up," increasing solar activity (magnetic field "kinks" that break through the surface).
- The cycle ends when the field twists too "tightly" and collapses – the process then repeats

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.