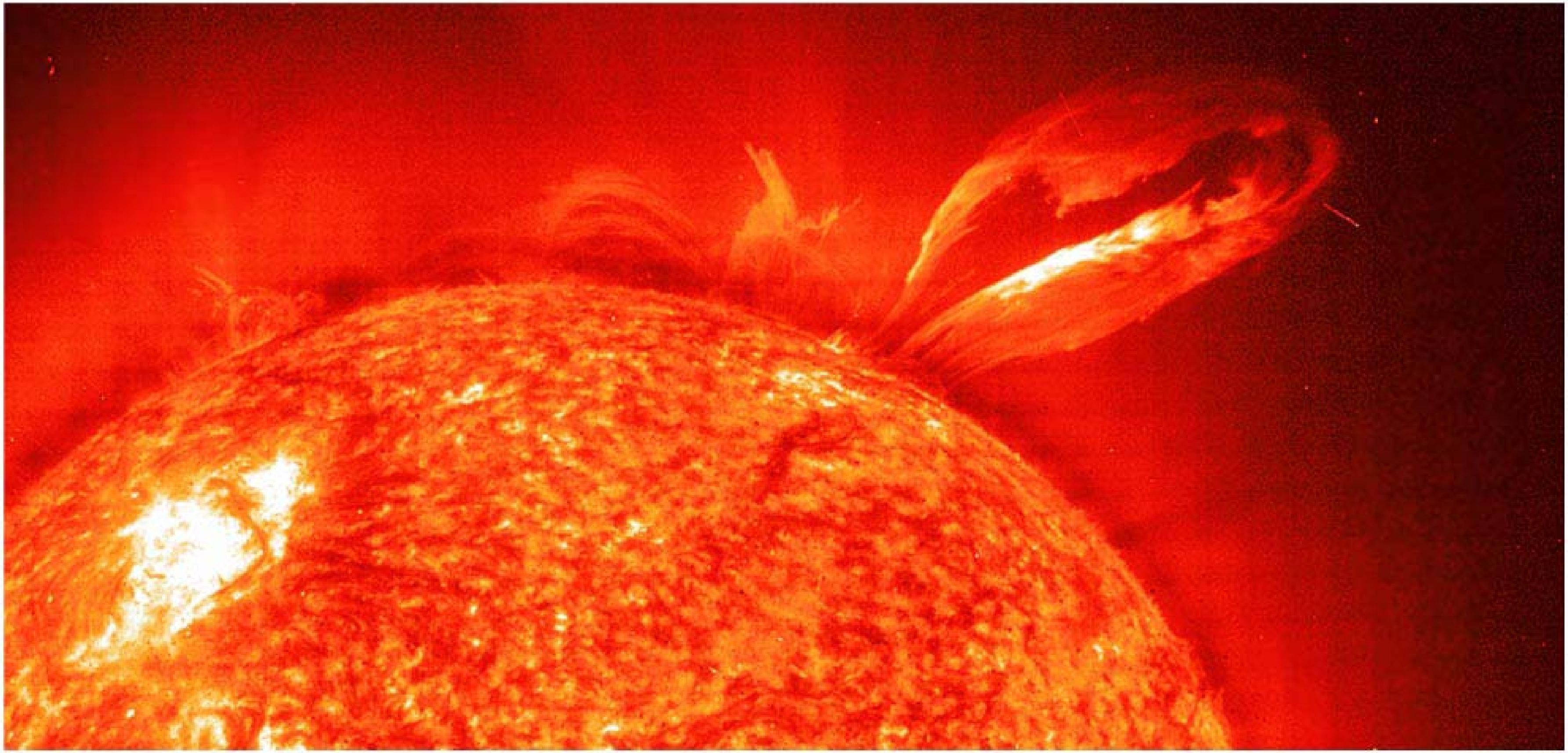
The Sun: Our Star (Chapter 14)



Based on Chapter 14

- No subsequent chapters depend on the material in this lecture
- Chapters 4, 5, and 8 on “Momentum, energy, and matter”, “Light”, and “Formation of the solar system” will be useful for understanding this chapter.

Goals for Learning

- What is the Sun's structure?
- How does the Sun produce energy?
- How does energy escape from the Sun?
- What is solar activity?

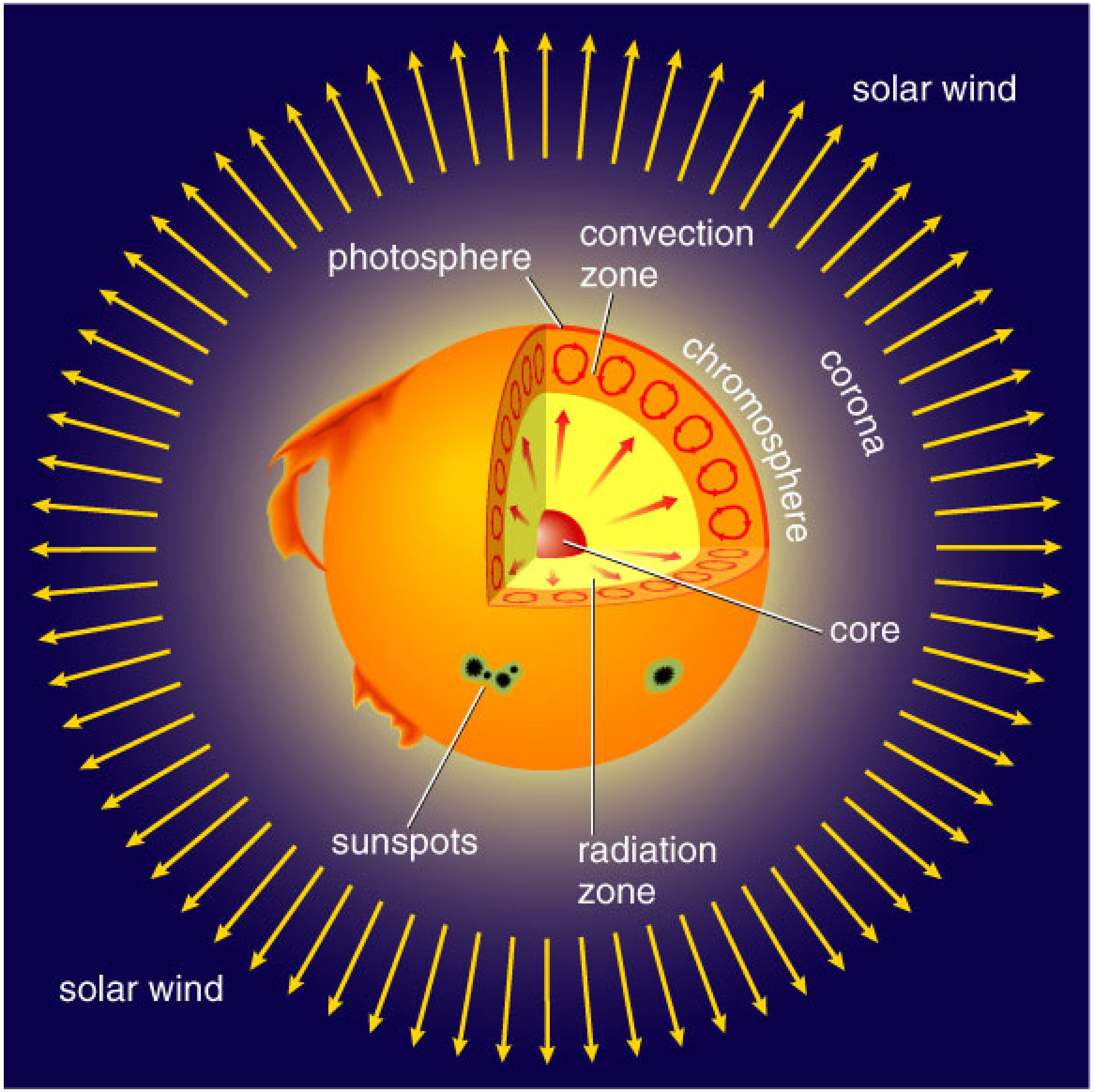
What Makes the Sun Shine?

- Sun’s size/distance known by 1850s

- Some kind of burning, chemical reaction?
  – Can’t provide enough energy
- Gravitational potential energy from contraction?
  – Sun doesn’t shrink very fast, shines for 25 million years
- Physicists like this idea. Geologists don’t, because rocks/fossils suggest age of <u>100s of millions of years</u>

$E=mc^2$ (1905, Einstein)

- Massive Sun has enough energy to shine for billions of years, geologists are happy
- But how does “m” become “E”?



Sun is giant ball of plasma (ionized gas)

Charged particles in plasma are affected by magnetic fields

Magnetic fields are very important in the Sun

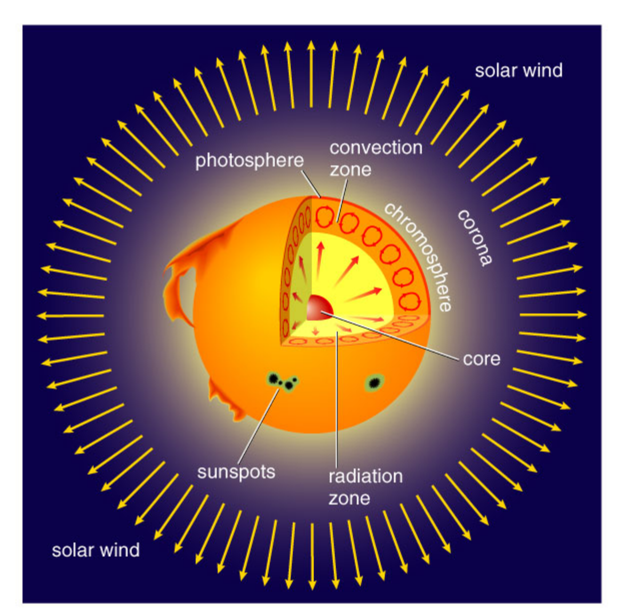
Sun = 300,000 M_E
Sun >1000 M_J
Radius = 700,000 km
Radius > 100 R_E
3.8 x 10^{26} Watts

Rotation: 25 days (Equator)
Rotation: 30 days (Poles)

Surface T = 5,800 K
Core T = 15 million K

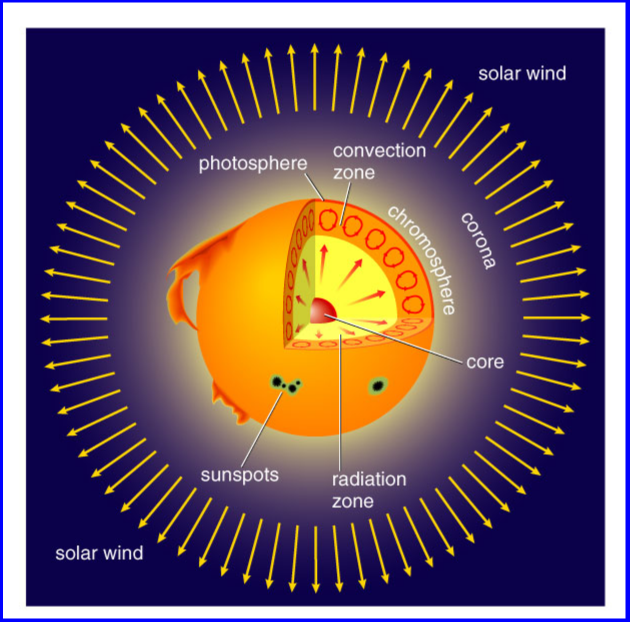
70% Hydrogen, 28% Helium, 2% heavier elements

Solar Wind

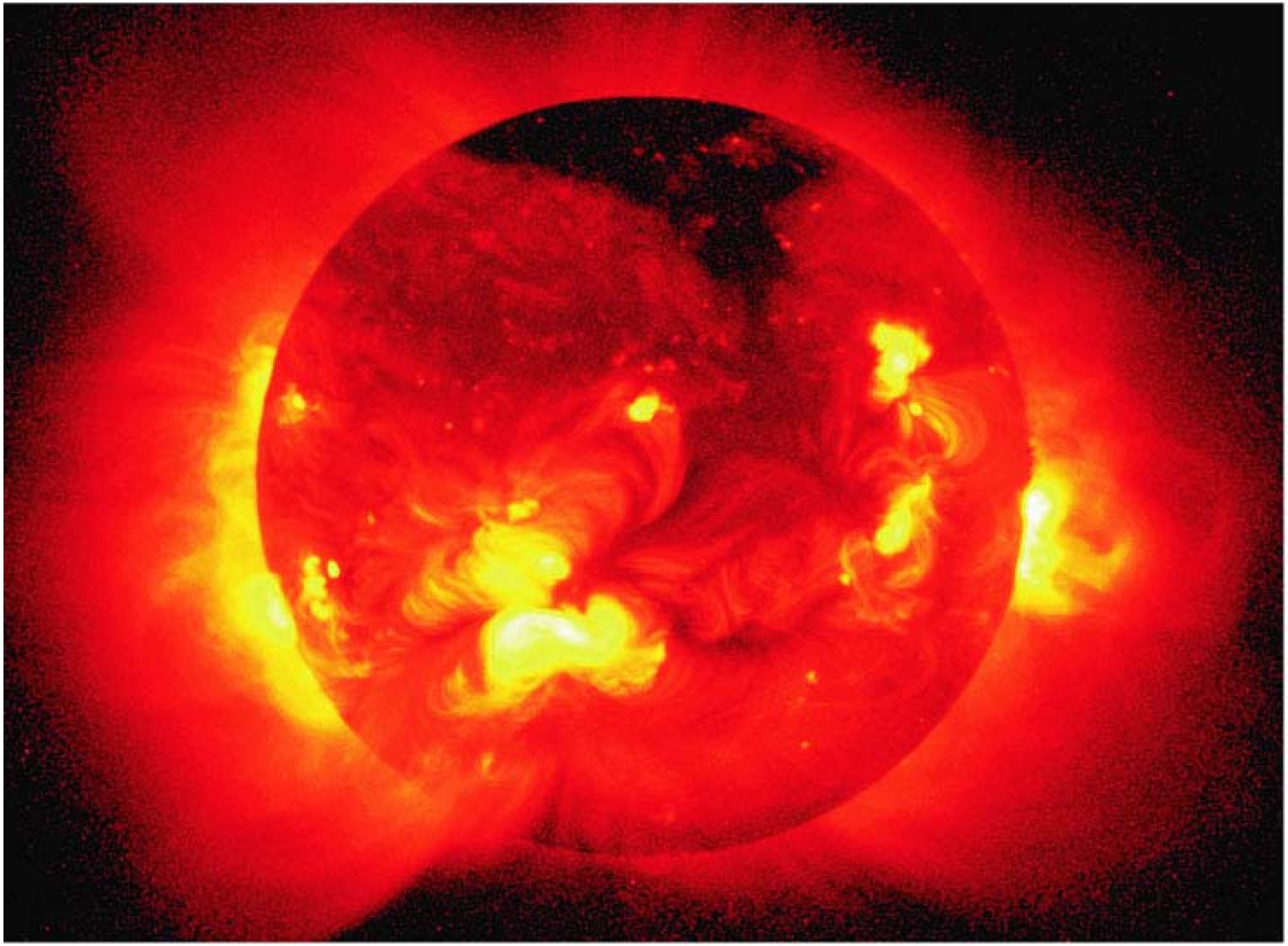


- Stream of charged particles blown continually outwards from Sun
- Shapes the magnetospheres of the planets today
- Cleared away the gas of the solar nebula 4.5 billion years ago

Corona

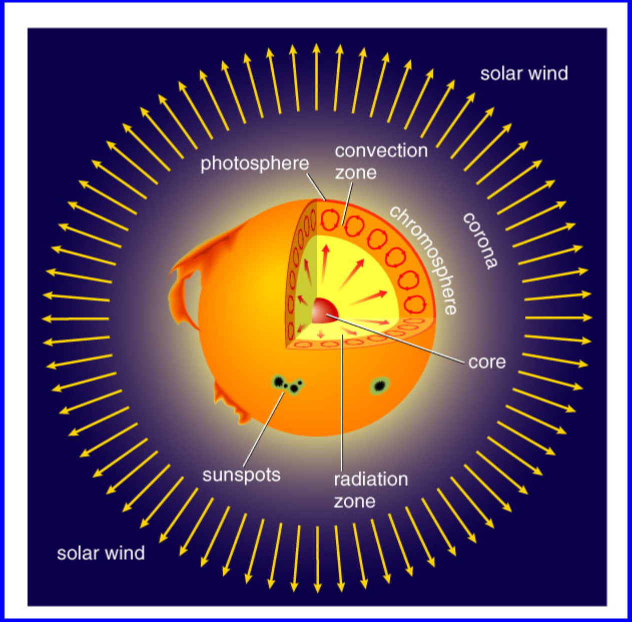


- Low density outer layer of Sun’s atmosphere
- Extends several million km high
- T = 1 million K (why?)
- Source of solar X-ray emissions
  - what wavelength?



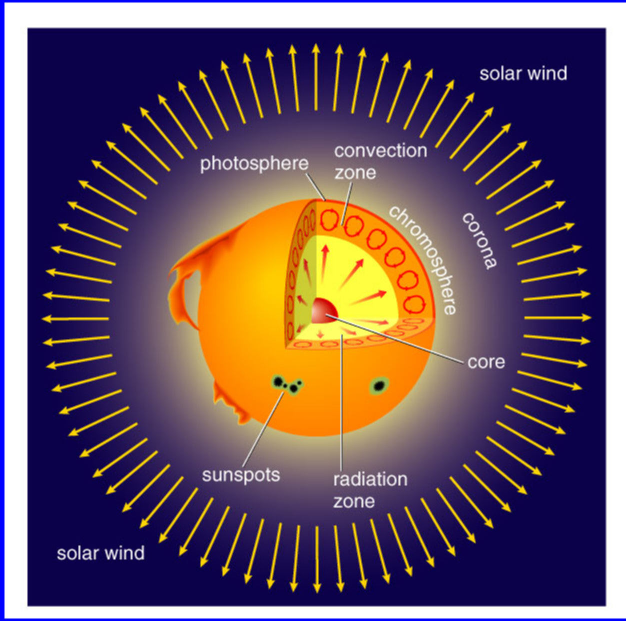
X-ray image of solar corona. Yellow = hotter, stronger X-ray emission

Chromosphere



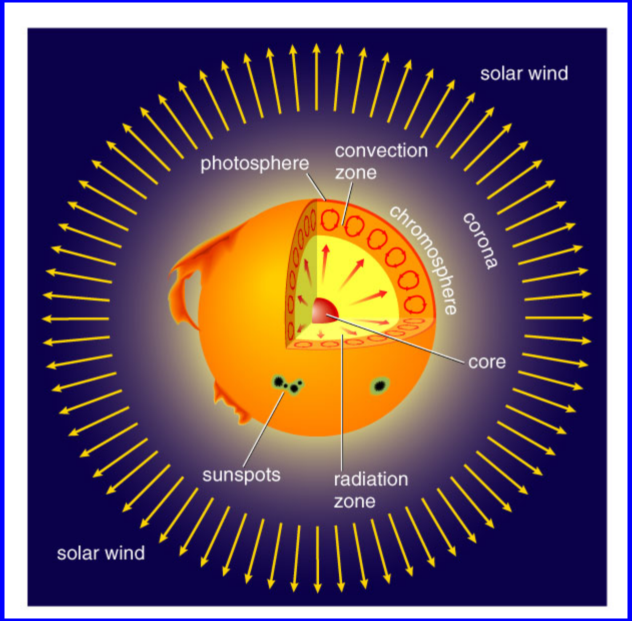
- Middle layer of Sun’s atmosphere
- Temperature drops to 10,000 K
- Region that radiates most of Sun’s UV light

Photosphere



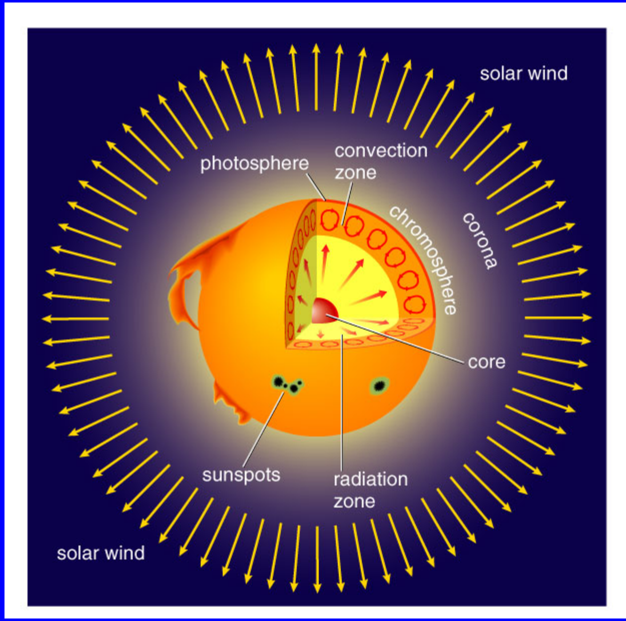
- Lowest layer of the atmosphere
- Visible surface of the Sun, with sunspots
- Temperature is 5,800 K
- Vigourously convecting, very dynamic
- Can’t see outside from below the photosphere, can’t see inside from above it

Convection Zone



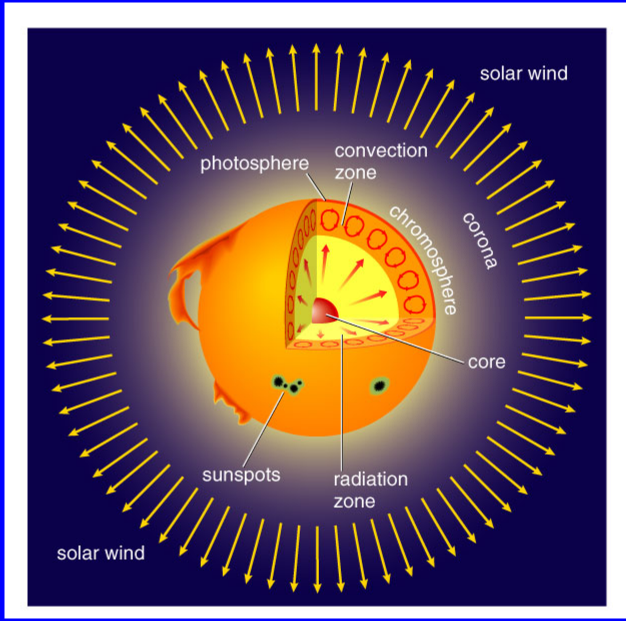
- Upper layer of solar interior, turbulent
- Energy generated in solar core is transported upwards by convection, rising hot plasma, falling cool plasma
- 2 million K at bottom, 5800 K at top
- Seething surface of photosphere is the top of the convection zone
- Extends from 0.7 R_{Sun} to surface (1.0 R_{Sun})

Radiation Zone



- Middle layer of solar interior, not turbulent
- Energy is carried outwards by X-ray photons, not physical movement of hot and cold gas particles
- 10 million K at bottom, 2 million K at top
- Extends from 0.2 R_{Sun} to 0.7 R_{Sun}

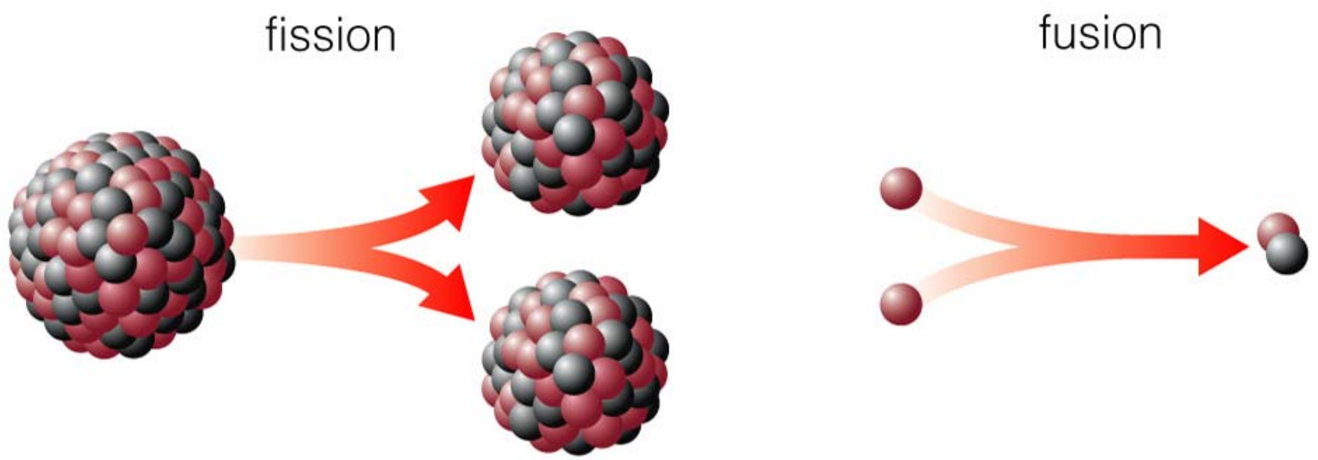
Core



- Inner layer of solar interior
- 15 million K, density 100x that of water, pressure is 200 billion x Earth's surface
- Hydrogen fuses into helium, releasing energy
- Energy takes $>10^5$ years to reach surface
- Extends out to 0.2 R_{Sun}

Interior Layering

- Convection zone, radiation zone, core
- Not compositional differences, unlike terrestrial planets
- Not phase (gas/liquid/metallic) differences, unlike jovian planets
- Differences between layers are related to energy production and transport within the layers



Nuclear reactions – electrons just follow along to balance charge

High pressure and temperature at core of Sun

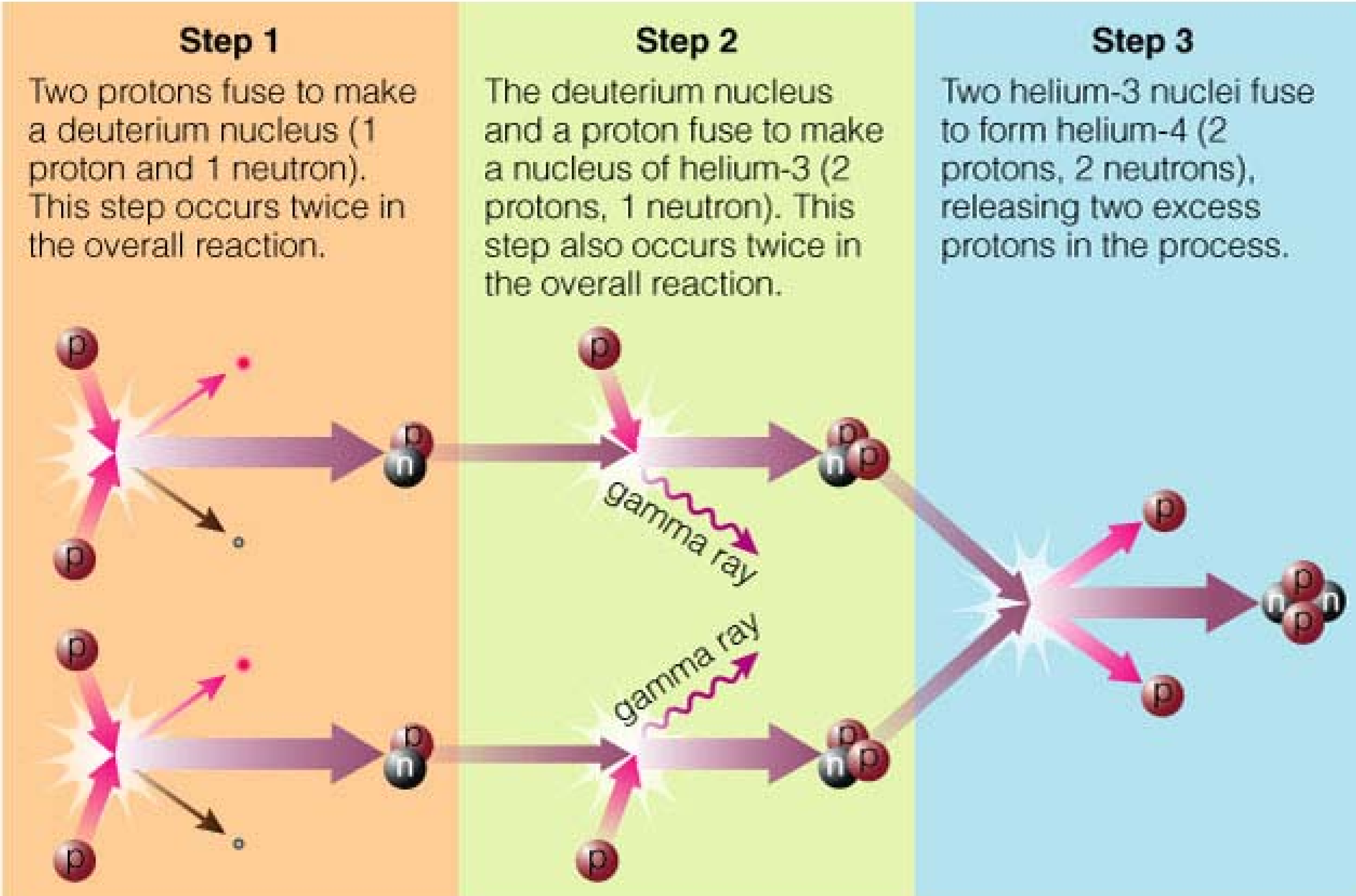
Atoms are fully ionized
Nuclei are moving at high speeds
Nuclei are very close together

<u>Will collisions be frequent?</u>

Hydrogen into Helium?

- p + p + p + p = p + p + n + n?
- p -> n + positron + neutrino
- n -> p + electron + neutrino
- Positron has same mass as electron
- Neutrinos have almost no mass
- Positrons and electrons annihilate
- Neutrinos don’t do much

Hydrogen Fusion by the Proton-Proton Chain



Follow the Energy

- Mass of four protons > mass of one helium nucleus
- Where can the energy go?
  - Radiative?
  - Kinetic?
  - Potential?

Follow the Charge

- 4 electrons, 4 protons present at start
- 2 electrons, 2 protons present at end

- 2 positrons are produced when 2 protons change into 2 neutrons
- 2 of the electrons and the 2 positrons annihilate each other, matter converted into pure radiative energy

The First Sunshine

- Sun born 4.6 billion years ago from cloud of collapsing gas (solar nebula)
- Contraction of cloud released gravitational potential energy
  - Most radiated away as thermal radiation
  - Some trapped inside, raising interior temperature of baby Sun
- Core temperature and pressure slowly rise
- Fusion starts
- Balance reached between energy generated and energy radiated

Why does the Sun shine?

- Gravitational contraction 4.6 billion years ago made the Sun hot enough to sustain nuclear fusion in its core

- Energy released by fusion maintains the Sun's gravitational/pressure equilibrium and keeps it shining steadily today

The Long March Outwards

Energy takes >100,000 years to travel from the core to the photosphere and out

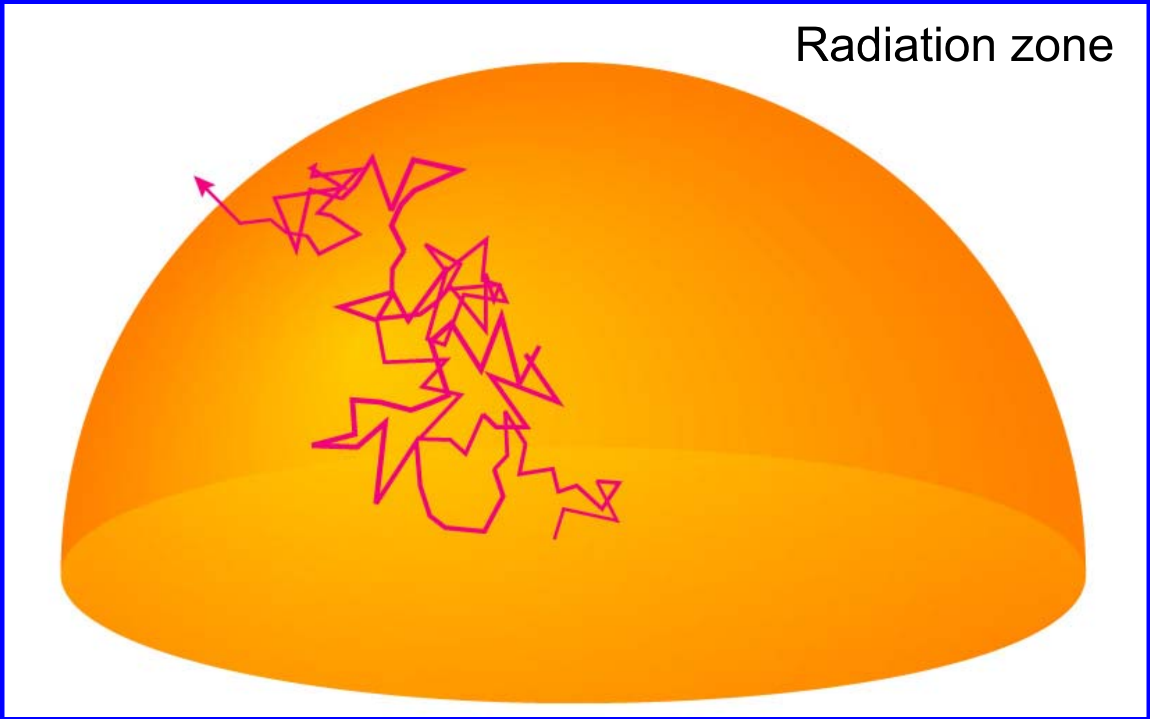
Most energy starts its journey out of the solar core as photons travelling at the speed of light

Densities are so high that photon travels less than 1 mm before interacting with an electron and "bouncing" off it

Photons are not absorbed by the plasma, so keep bouncing around

Travel a long distance at the speed of light, but don't get very fare

Eventually reaches bottom of the convection zone



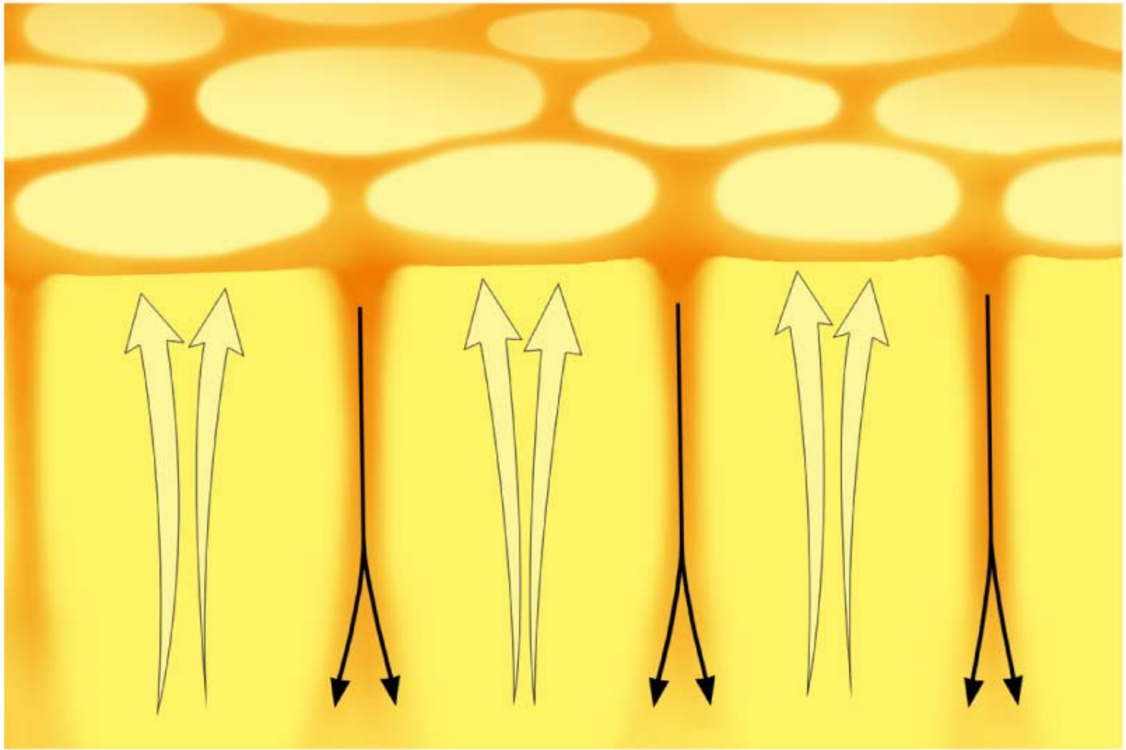
Convection Zone

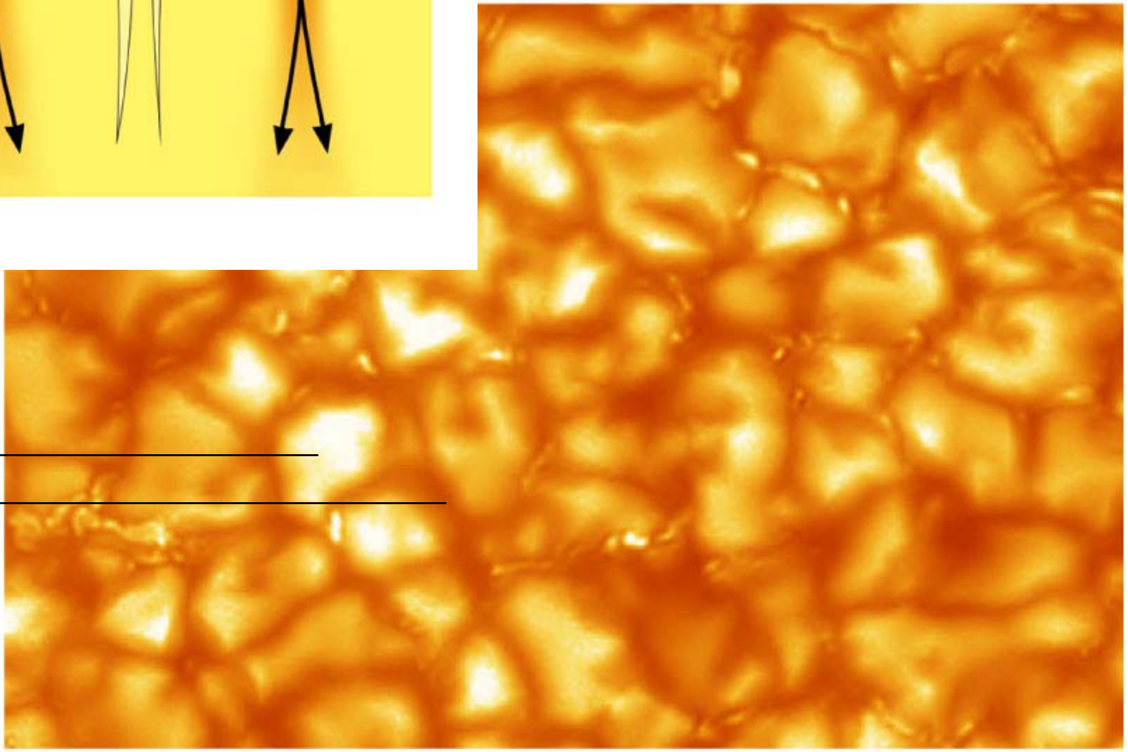
- Temperatures are cooler, 2 million K
- Plasma can absorb photons now (why?)

- Plasma is heated by upwelling photons
- Hot plasma rises, cool plasma falls
- Energy is moved outwards by a conveyor belt of hot material replacing cool material

Bright spots appear on Sun's surface where hot gas is rising

Then the gas sinks after it cools off





Real photo

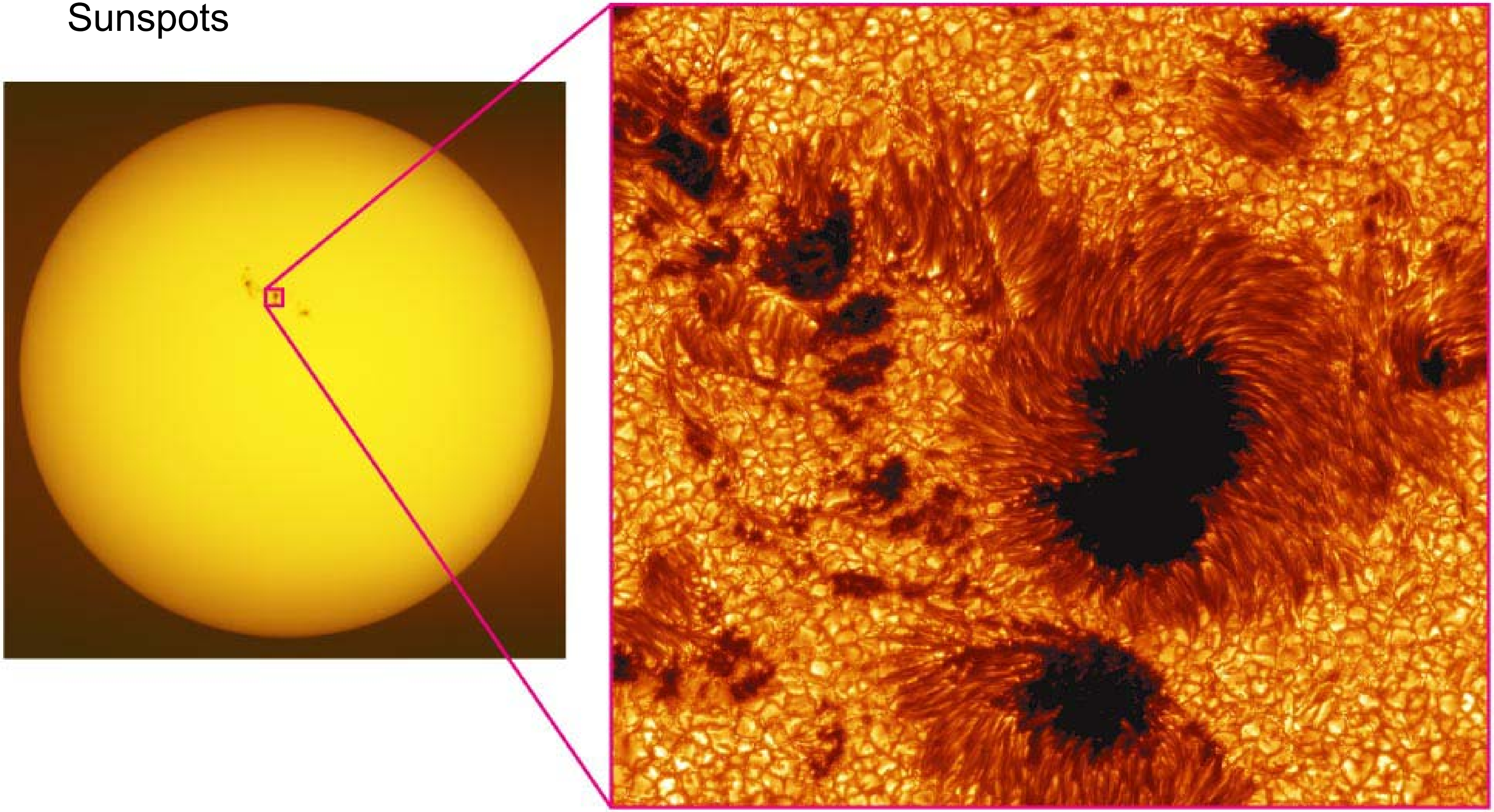
Photosphere

- At top of convection zone, densities are low
- Photons emitted by thermal radiation can escape to space, so material cools
- Is thermal radiation emitted when material is deep in convection zone? What happens?
- Temperature is 5800 K
- Interactive Figure: SVST granulation

Solar Activity

- Some aspects of the Sun's release of energy change with time
- Some of them have effects on Earth – "space weather"

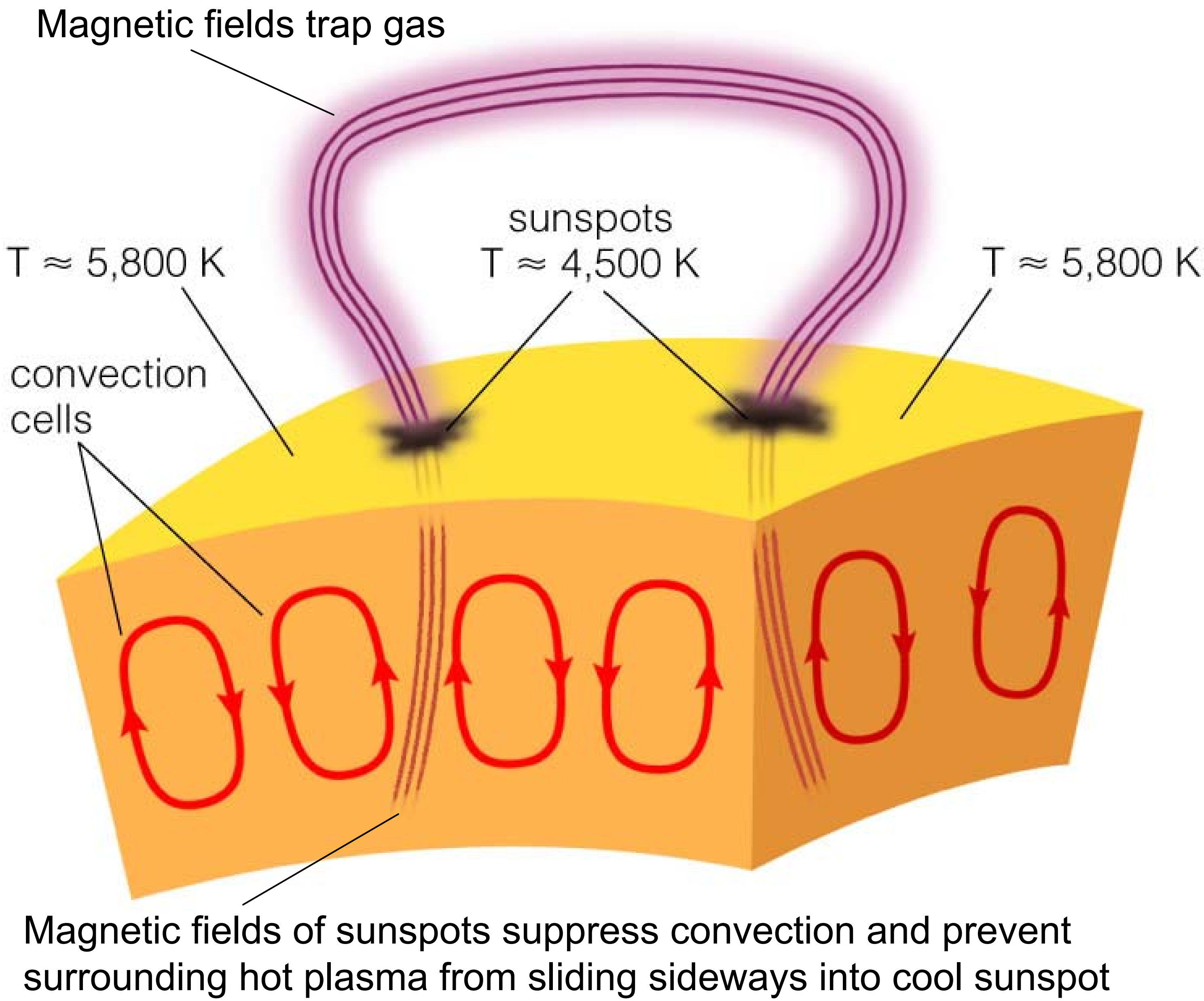
Sunspots



Video – SOHO-MDI views the Sun

Sunspots

- Very bright. Appear dark in photos because they are less bright than surrounding regions
- Temperature of plasma in sunspots is 4000 K
- Temperature of plasma outside sunspots is 5800 K
- Can last for weeks. Why doesn't hot plasma mix with cool plasma?



Very strong magnetic fields affect solar spectrum, so magnetic field can be mapped across the solar surface

Sunspots have strong magnetic fields

Sunspots come in pairs, connected by a loop of magnetic field

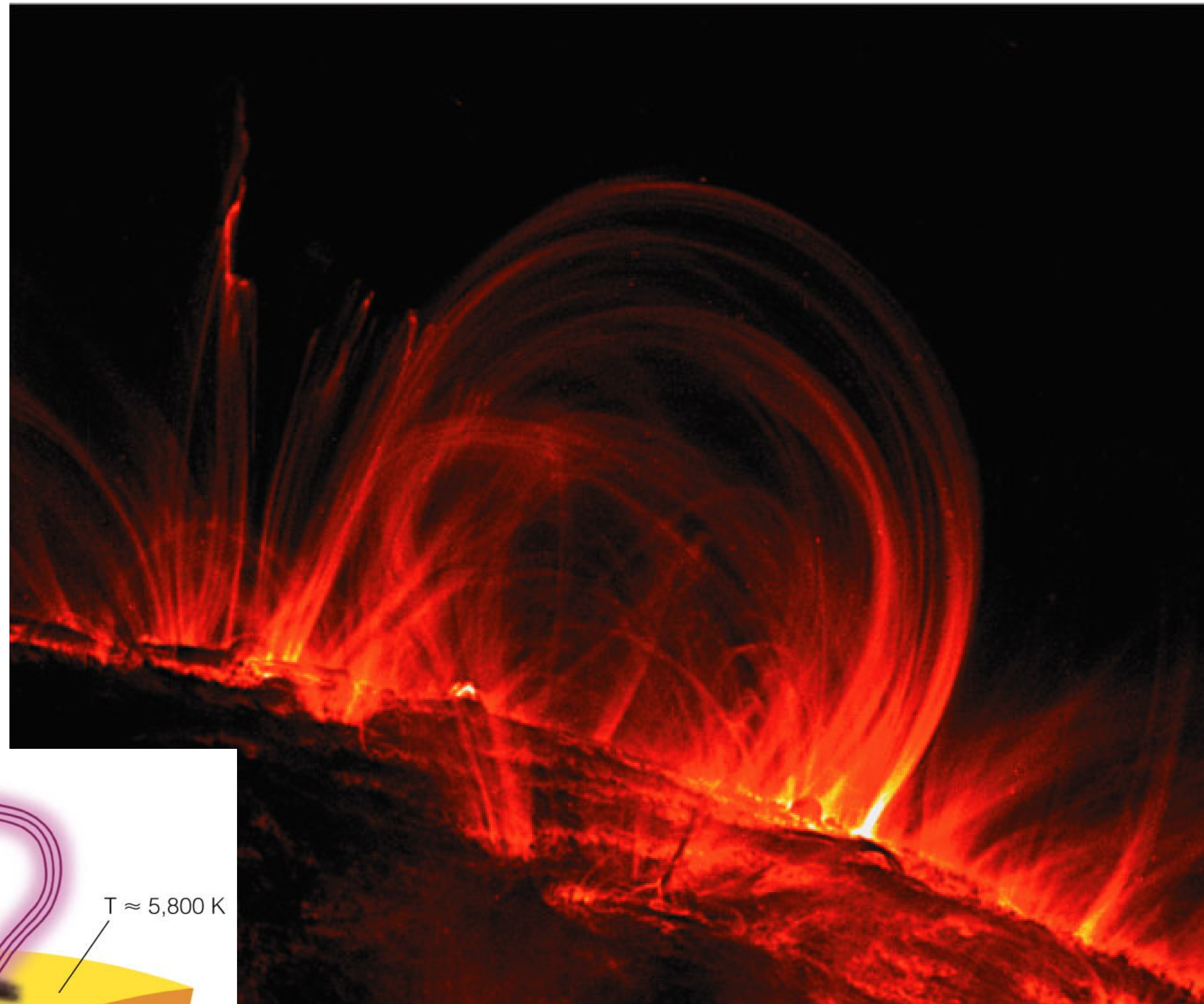
Why are sunspots cool?

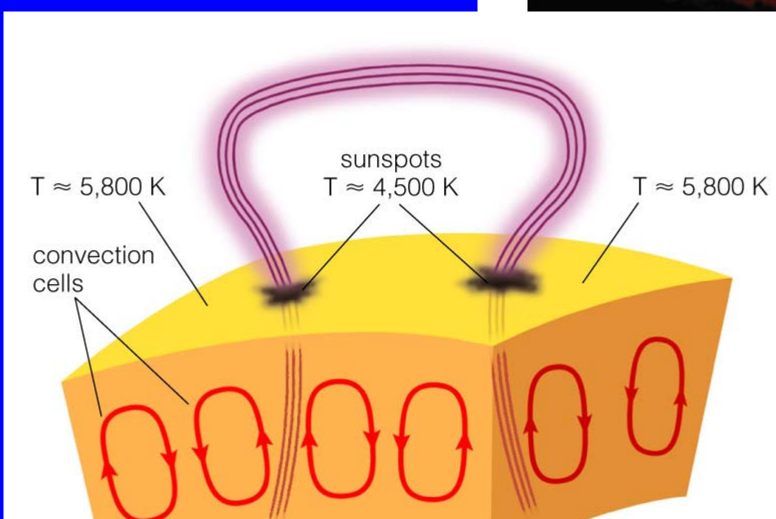
- Strong magnetic fields cause cool plasma, not the other way around
- Strong magnetic fields restrict the inflow of hot plasma to replace plasma that has been sitting on the surface, radiating to space, and cooling down

- Sunspots typically last a few weeks

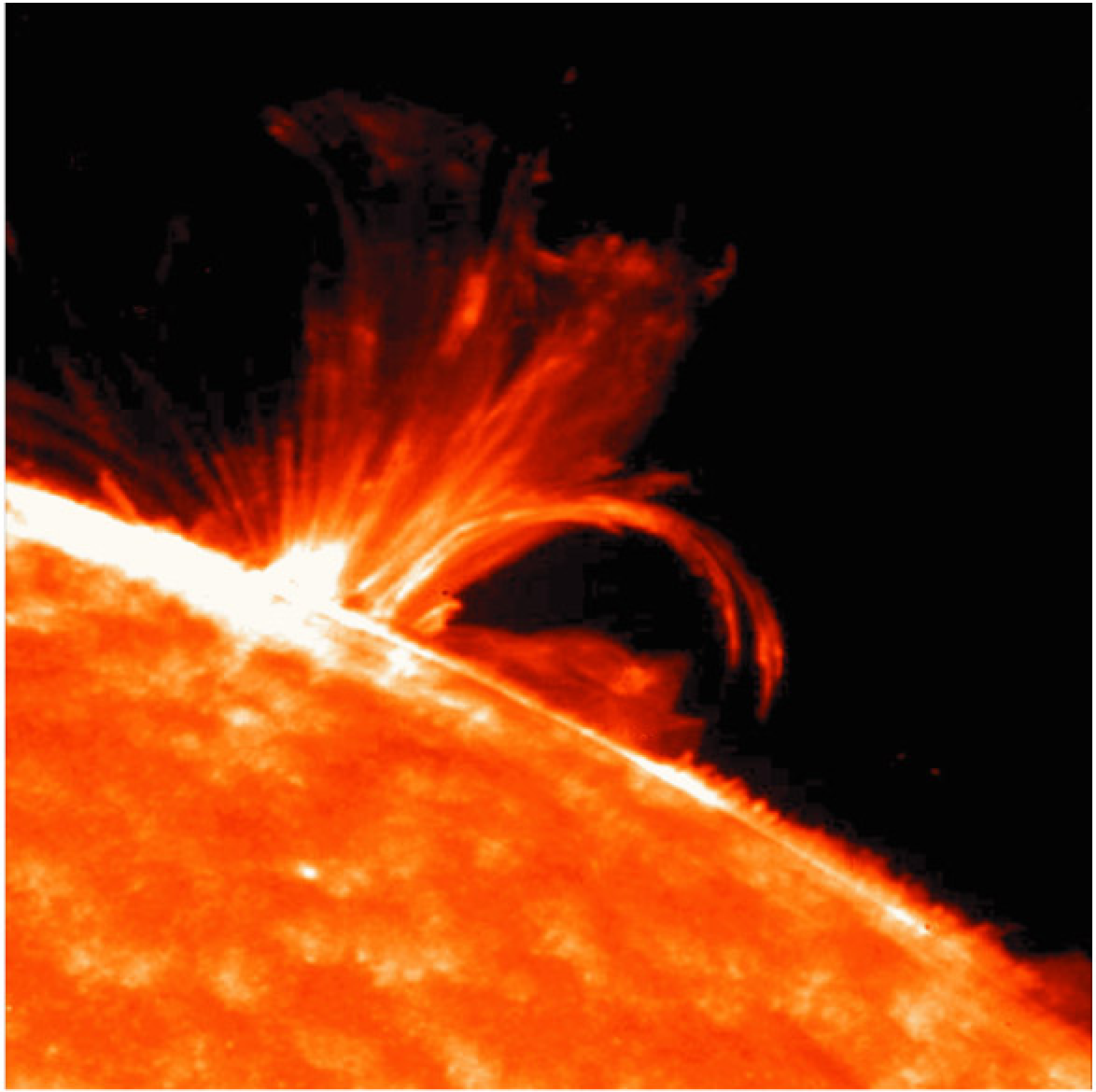
Plasma from the photosphere is forced to move along this looped magnetic fieldline

It travels far above its usual altitudes





X-ray image of hot gas trapped within magnetic field lines



UV image of a solar flare

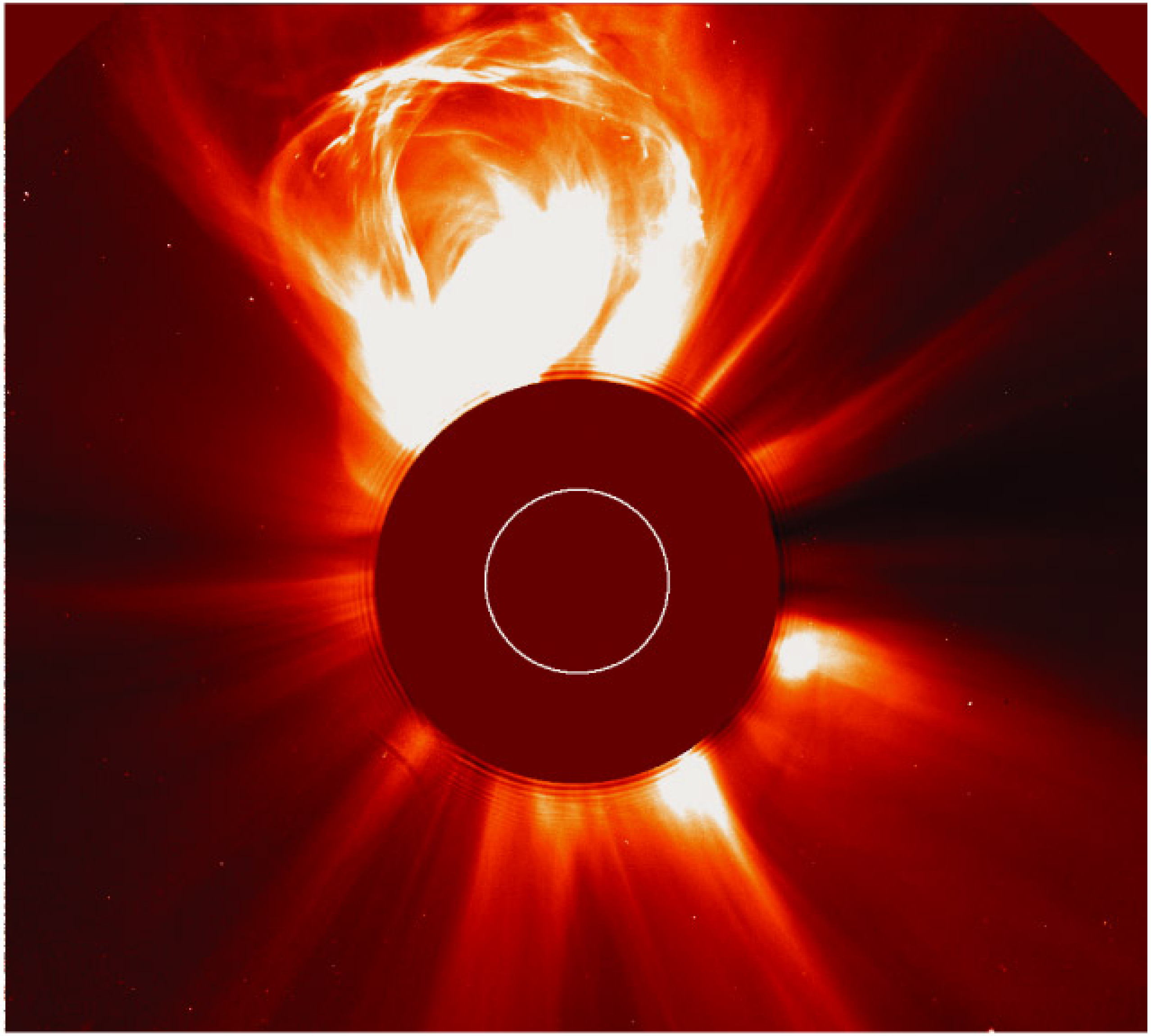
Solar flare

Potential energy stored in the magnetic field is released, heats nearby plasma to 100 million K

Plasma emits X-rays and UV photons

Large blobs of material sometimes ejected from the Sun as well

Solar flares occur above sunspots, evidence for involvement of magnetic fields



X-ray image of a "coronal mass ejection"

Blob of material ejected from Sun is called a "coronal mass ejection"

Full of protons and electrons

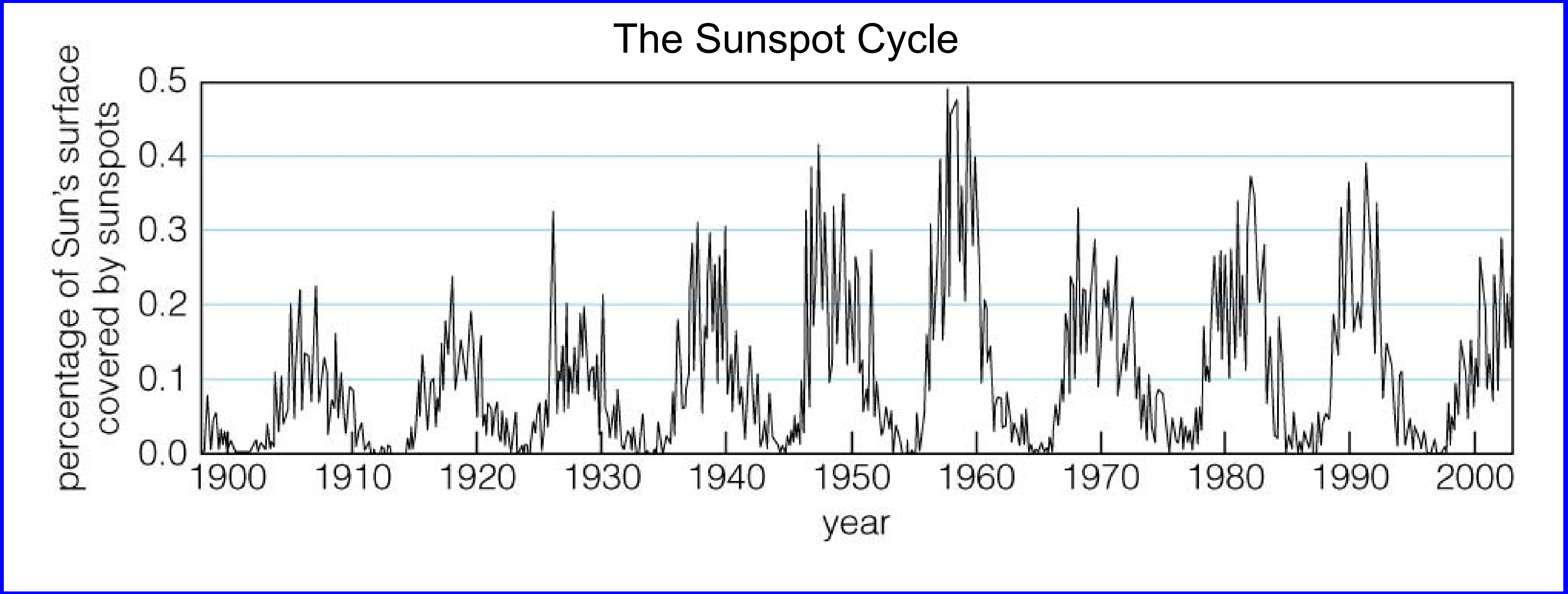
Carries some magnetic field along as well

Coronal mass ejections lead to aurora on Earth
Can also damage communications systems, power grids, satellites

Movie – coronal mass ejection gif file

Visible, UV, X-ray

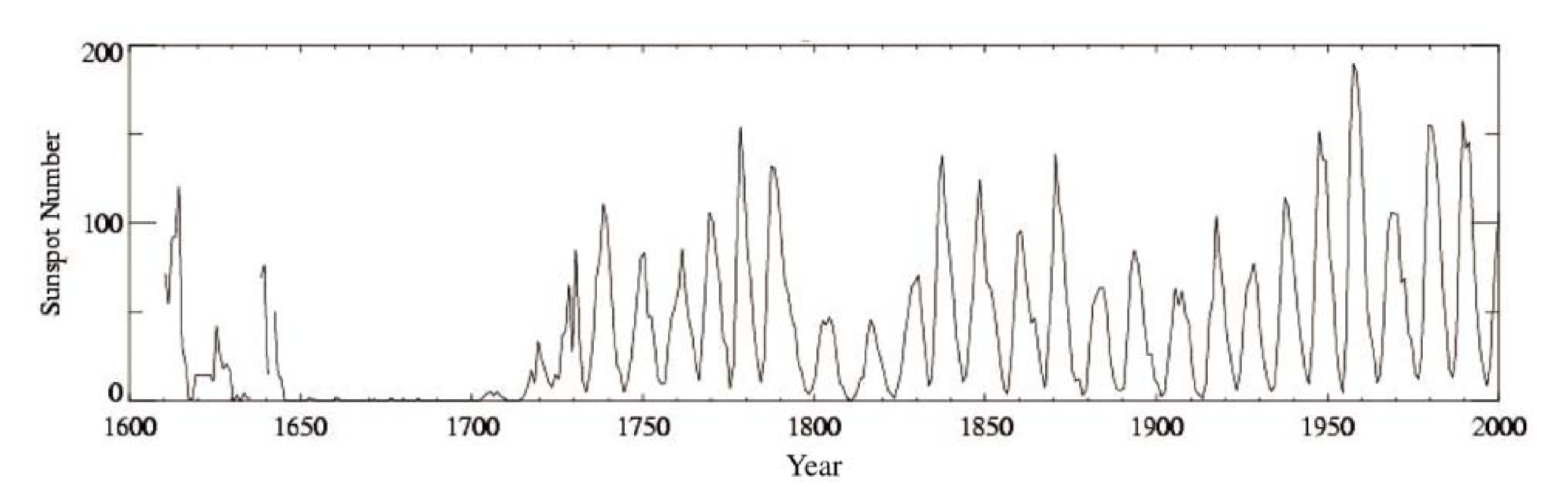
- 5800 K photosphere – visible
- 10,000 K chromosphere – UV
- 1 million K corona – X-ray



Many sunspots are seen at solar maximum
Few sunspots are seen at solar minimum
11 year period (approximately)
2006 is around solar minimum, not maximum

Solar Changes and Climate

- Total solar power varies by <0.1% over the sunspot cycle
- Visible output barely changes
- Solar UV and X-ray output varies much more significantly (double?)
- Do these have any effects on Earth's climate?
  - Typical 11-year sunspot cycle doesn't seem to have any effects



Galileo uses telescope to discover sunspots around 1609

Virtually no sunspot activity between 1645-1715 (Maunder Minimum)
Cold temperatures in Europe and North America at the same time

What about the rest of the world?
Were these changes in Earth's climate due to solar changes?

Was long absence of sunspots due to some long-period solar variability or just a fluke?
When will it happen again?

We don't know what past solar activity has been like
We don't know how changes in solar activity lead to changes in Earth's climate

Goals for Learning

- What is the Sun’s structure?
- How does the Sun produce energy?
- How does energy escape from the Sun?
- What is solar activity?

Goals for Learning

- What is the Sun's structure?
  - Very hot, very dense core where fusion occurs
  - Radiation zone
  - Convection zone
  - Photosphere, visible surface, 5800 K
  - Chromosphere, 10000 K
  - Corona, 1 million K
  - Solar wind, escaping protons and electrons

Goals for Learning

- How does the Sun produce energy?
  - Nuclear fusion, $E=mc^2$
  - 4 protons combine to form 2 protons and 2 neutrons in a helium nucleus
  - Requires high temperatures and pressures

Goals for Learning

- How does energy escape from the Sun?
  - Slowly
  - Photon bounces around in radiation zone for 100,000 years
  - Upwelling hot plumes and downwelling cool regions transport heat upwards by convection in convection zone
  - Thermal radiation from photosphere (visible), chromosphere (UV), and corona (X-rays)

Goals for Learning

- What is solar activity?
  - Sunspots vary on 11-year cycle
  - Sun’s UV and X-ray output also varies
  - Coronal mass ejections can “burp” large blobs of protons and electrons into space, which can affect aurora and electrical systems at Earth
  - Magnetic fields play a major role

- http://quake.stanford.edu/~sasha/CDROM/fig1.gif
- http://solar.physics.montana.edu/sxt/Images/The_Solar_Cycle_XRay_med.jpg