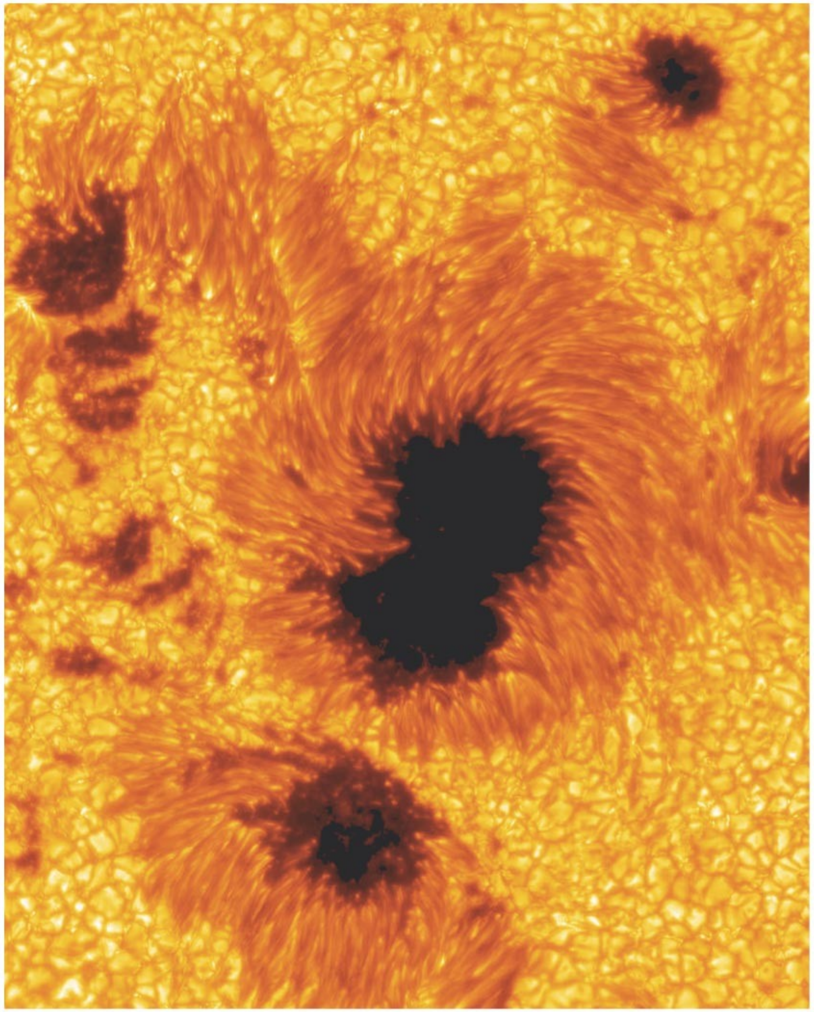
Chapter 16
The Sun



Units of Chapter 16

16.1 Physical Properties of the Sun

16.2 The Solar Interior

SOHO: Eavesdropping on the Sun

16.3 The Sun's Atmosphere

16.4 Solar Magnetism

16.5 The Active Sun

Solar–Terrestrial Relations

16.1 Physical Properties of the Sun

Radius: 700,000 km

Mass: 2.0×10^{30} kg

Density: 1400 kg/m^3

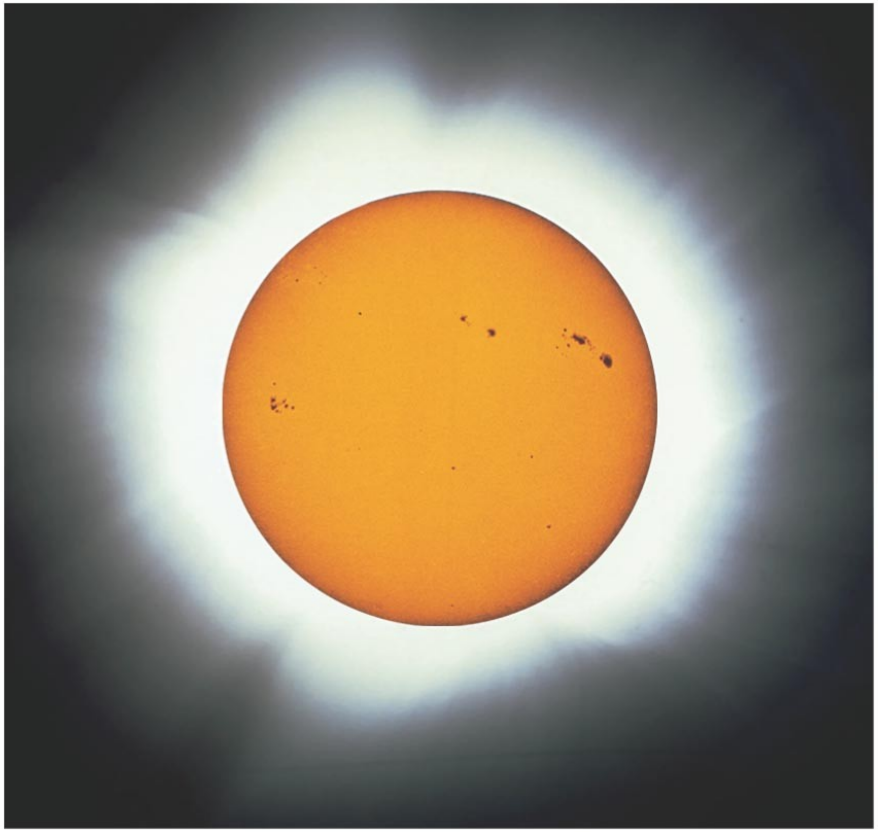
Rotation: Differential; period about a month

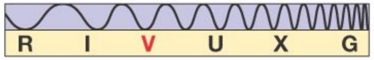
Surface temperature: 5800 K

Apparent surface of Sun is **photosphere**

16.1 Physical Properties of the Sun

This composite image shows both the filamentary corona and the sharp outline of the photosphere.





16.1 Physical Properties of the Sun

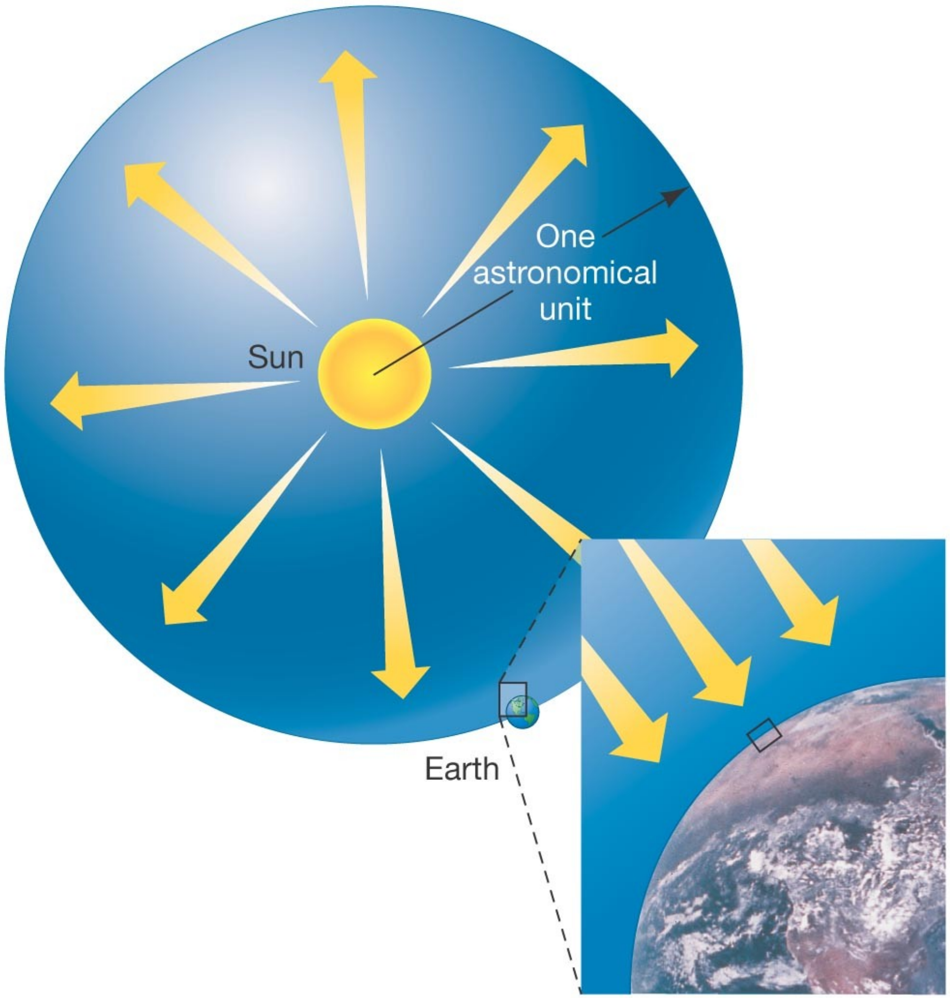
Solar constant—amount of Sun's energy passing through a square meter at 1 AU — **1400 W/m^2**.

Luminosity—total energy radiated per second in all directions.

Total luminosity is about **4 × 10^{26} W**—the equivalent of 100 billion 1-megaton nuclear bombs per second.

16.1 Physical Properties of the Sun

how to extrapolate from the radiation hitting Earth to the **entire output** of the Sun ...



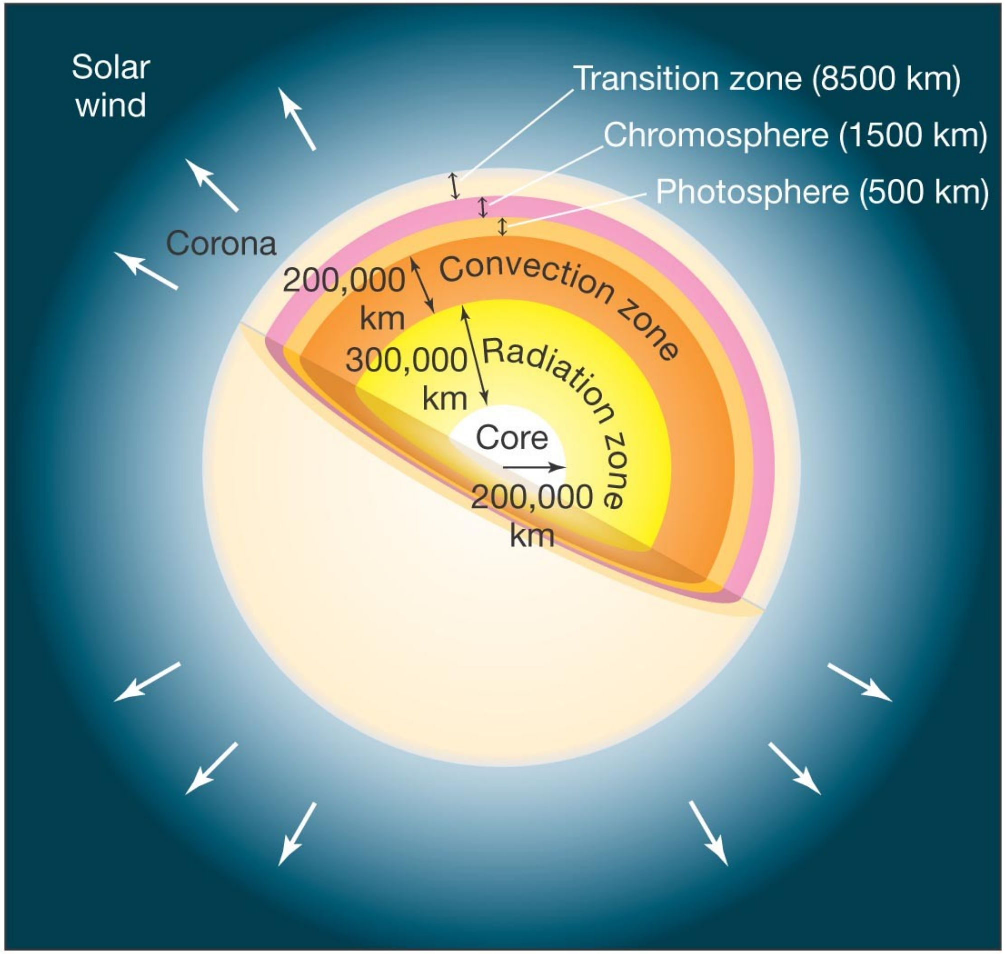
16.2 The Solar Interior

Interior structure of the Sun:

core: where energy is created (fusion)

Radiative Zone: heat transferred outward by radiation

Convective Zone heat transfer by radi- ation and convection



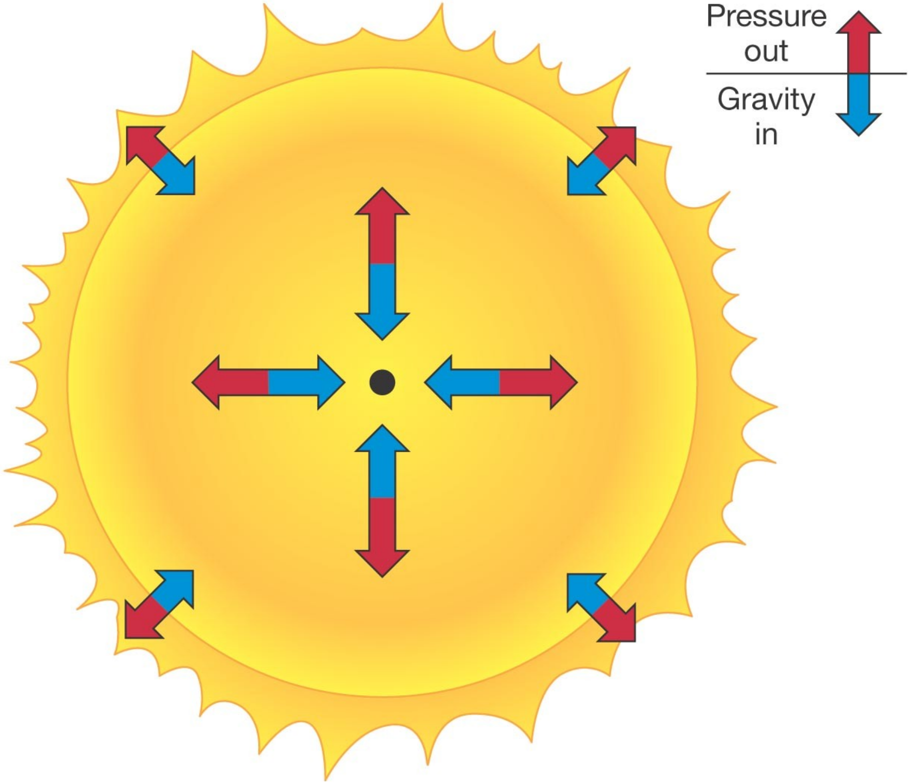
(Outer layers are not to scale.)

16.2 The Solar Interior

How do we know about the interior?

Method 1: Astrophysics uses 4 "structural equations" which help us estimate temp, density, pressure, etc. in the Sun's interior.

One is called **hydrostatic equilibrium**: for a stable star, inward **gravitational force** must be balanced by outward **pressure**.

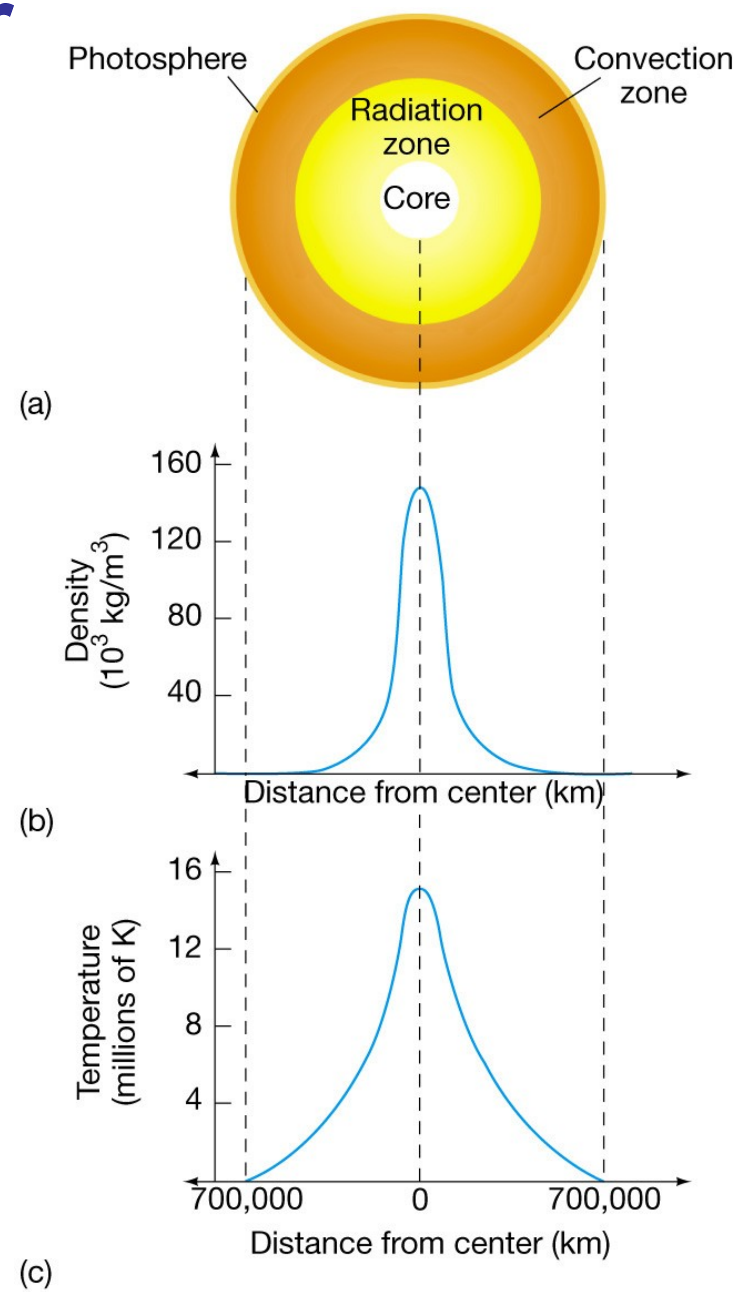


16.2 The Solar Interior

Solar density and temperature, according to the standard solar model:

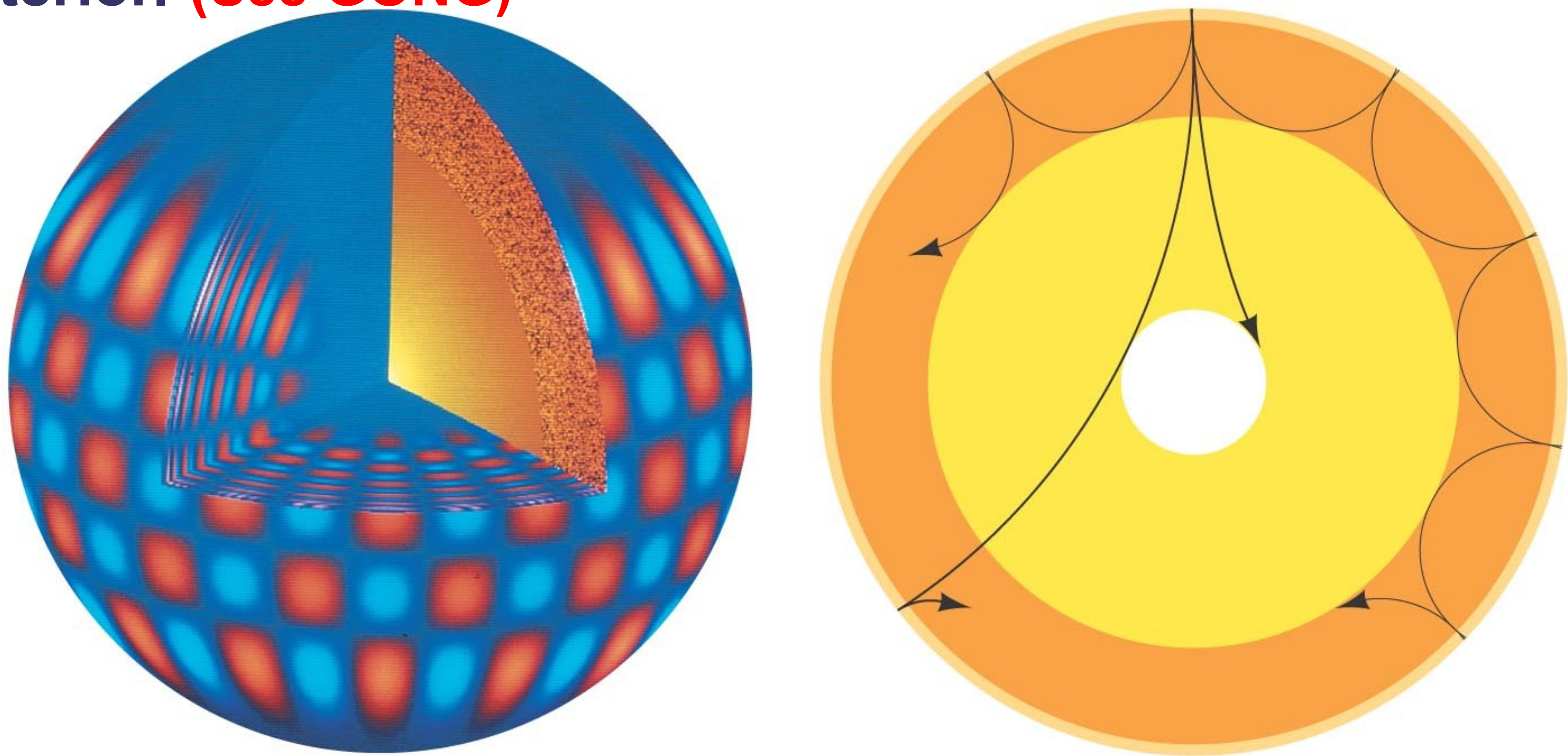
The structural equations are combined with just a few key observations to make a solar model. Those include:

1) the radius of the Sun
2) the total luminosity of Sun
3) the total mass of the Sun



16.2 The Solar Interior

Method 2: Helioseismology, the study of oscillation modes of the Sun, gives additional clues about the interior. (See GONG)



(a) (b)

Doppler shifts of solar spectral lines indicate a complex pattern of **vibrations**.

16.2 The Solar Interior

Helioseismology

Different modes of oscillation analogous to standing waves on a string (harmonics) and on a metal (Chladni) plate. (See YouTube demo)

Resonance amplifies the “white noise” of convection and other solar activity.

Waves propagate in curved lines b/c of gradually changing density.

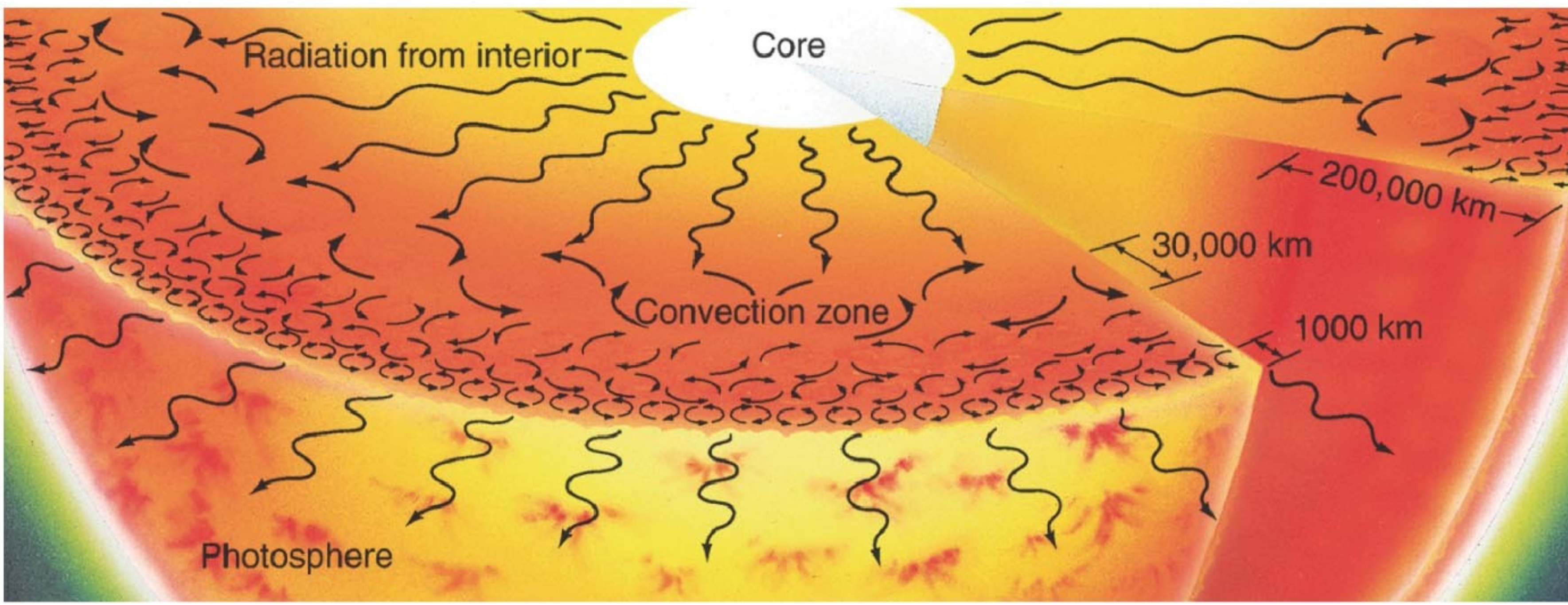
Main p-mode oscillation = 3.3 mHz, 5-minute period!

Equator to pole “conveyor belt” discovered.

16.2 The Solar Interior

Zones defined by energy transport:

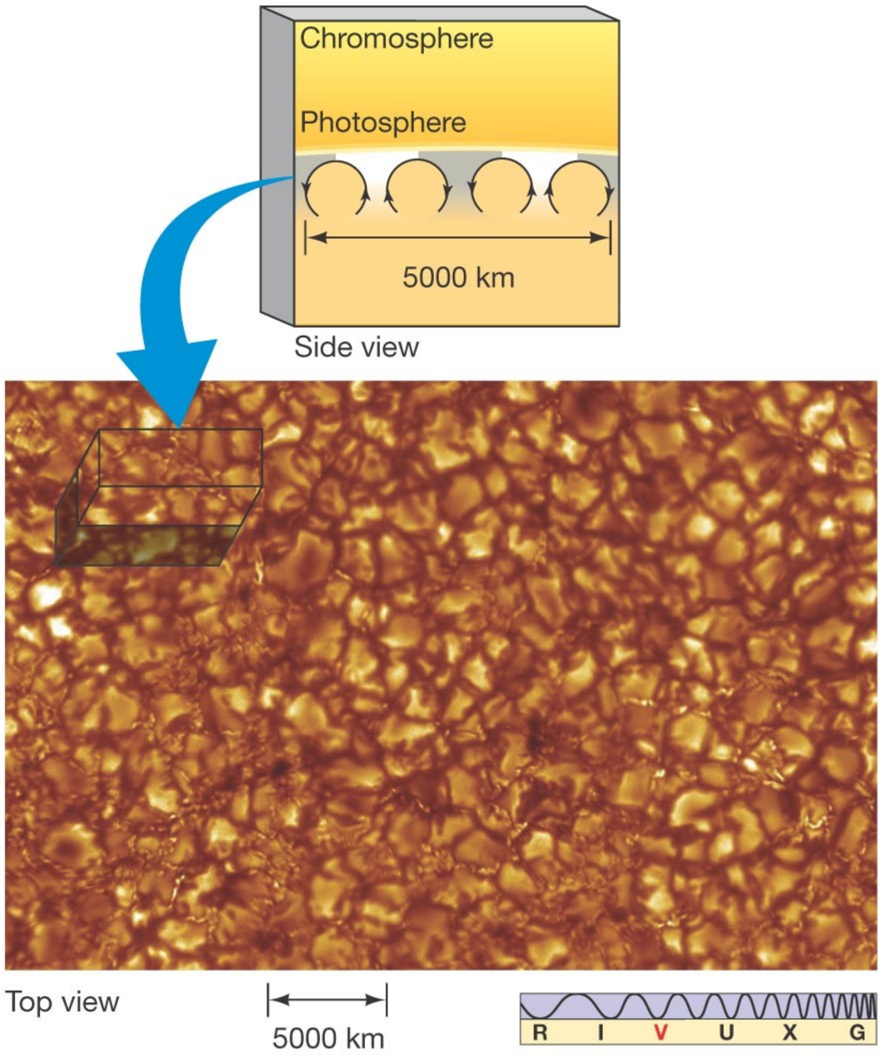
The **radiation zone** is relatively transparent; the cooler **convection zone** is opaque



16.2 The Solar Interior

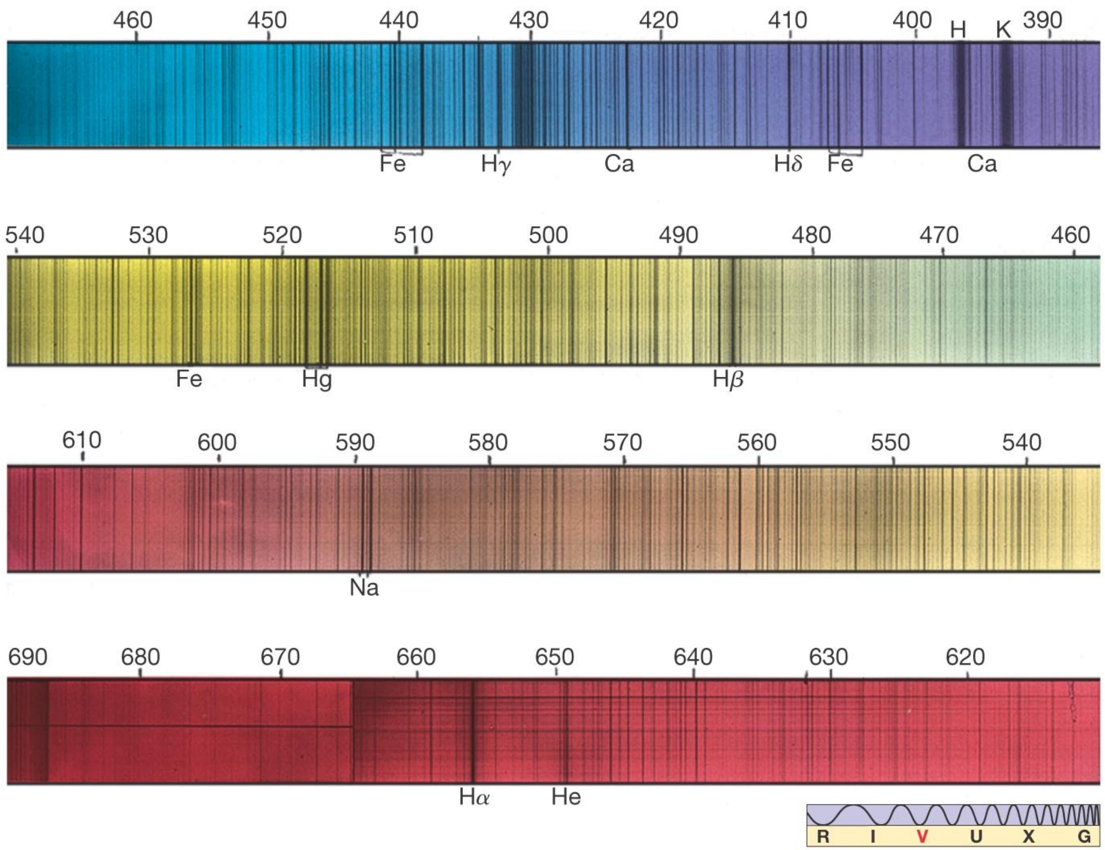
Signs of convection: the photosphere appears granulated.

Upwelling gas - hot sinking gas - cool



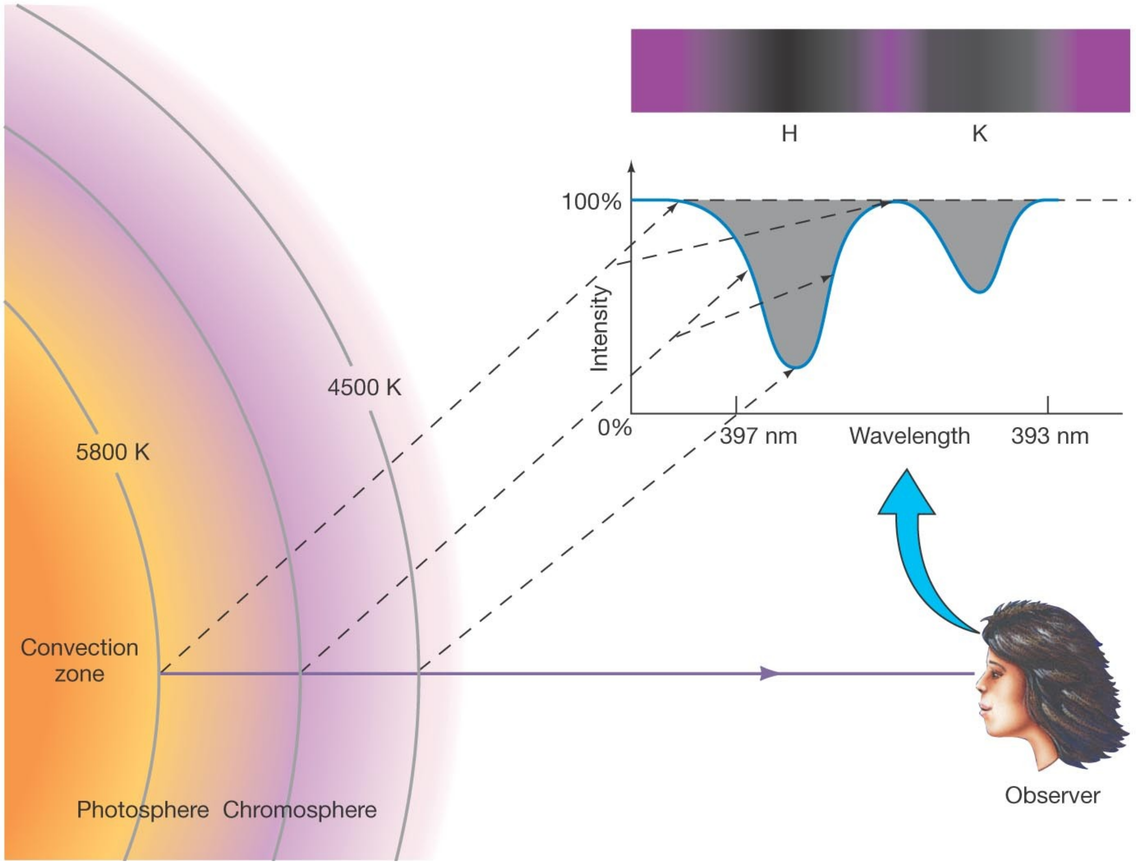
16.3 The Sun's Atmosphere

Spectral analysis can tell us what elements are present in the chromosphere and photosphere of the Sun. This spectrum has lines from 67 different elements:



16.3 The Sun's Atmosphere

Spectral absorption lines. We can't see as deep into the Sun at the wavelengths being absorbed.



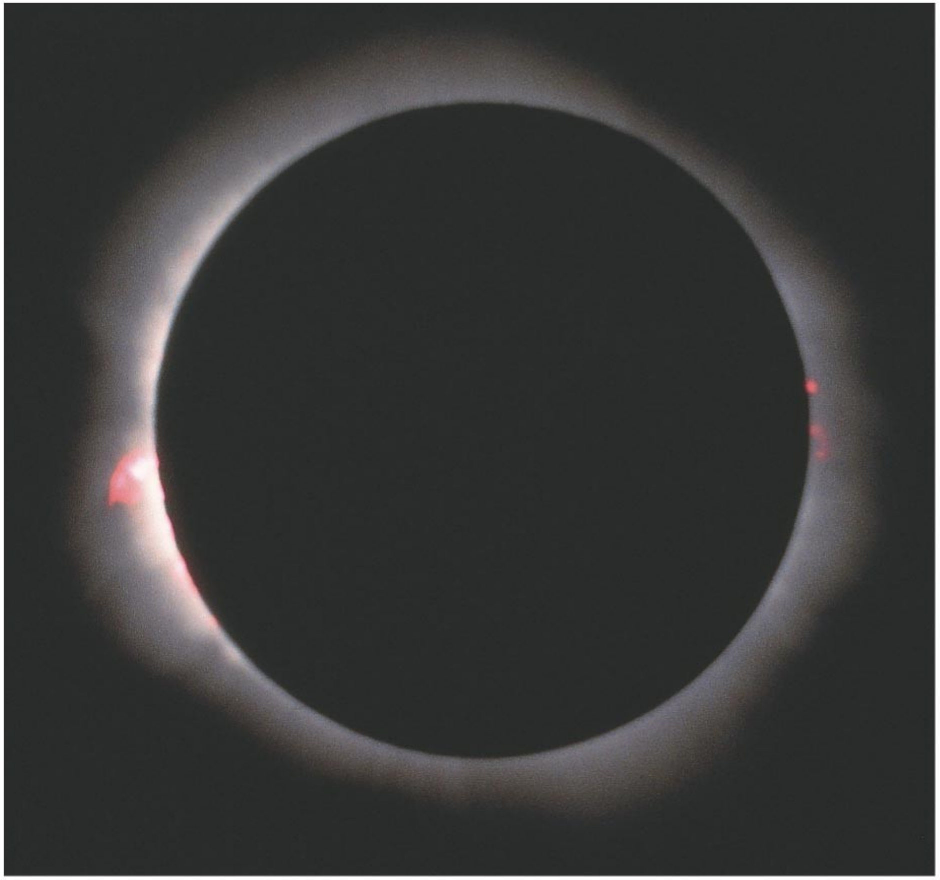
16.3 The Sun's Atmosphere

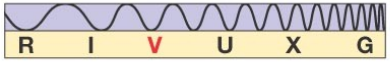
The colorful chromosphere is above the photosphere.

The chromosphere is reddish-pink.

Lower density than photosphere.

Temp increases with height from 4400 K to 25,000 K in ~2000 km.





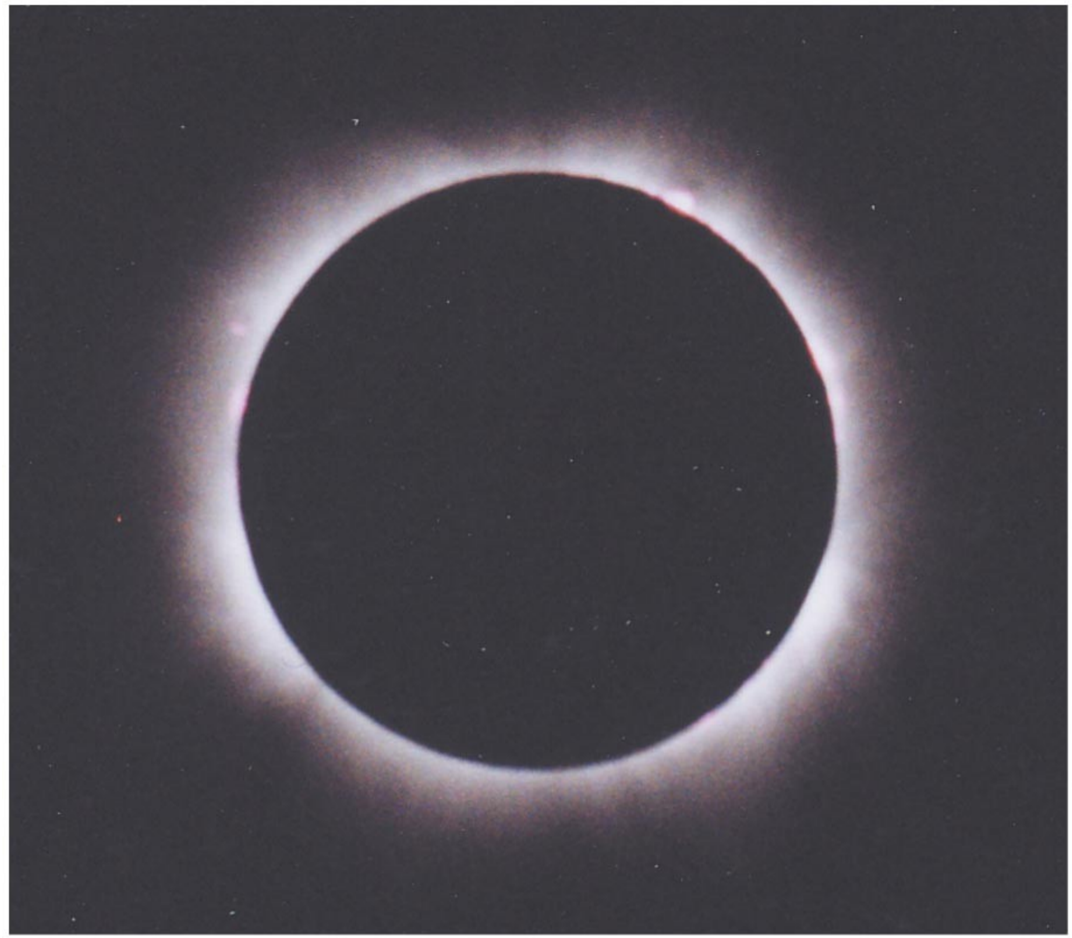
16.3 The Sun’s Atmosphere

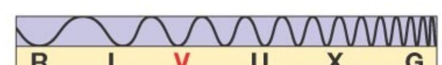
Solar corona

Hottest (10^6 K) and thinnest part of the Sun's atmosphere.

Spectrum shows emission lines from highly ionized species of iron and helium.

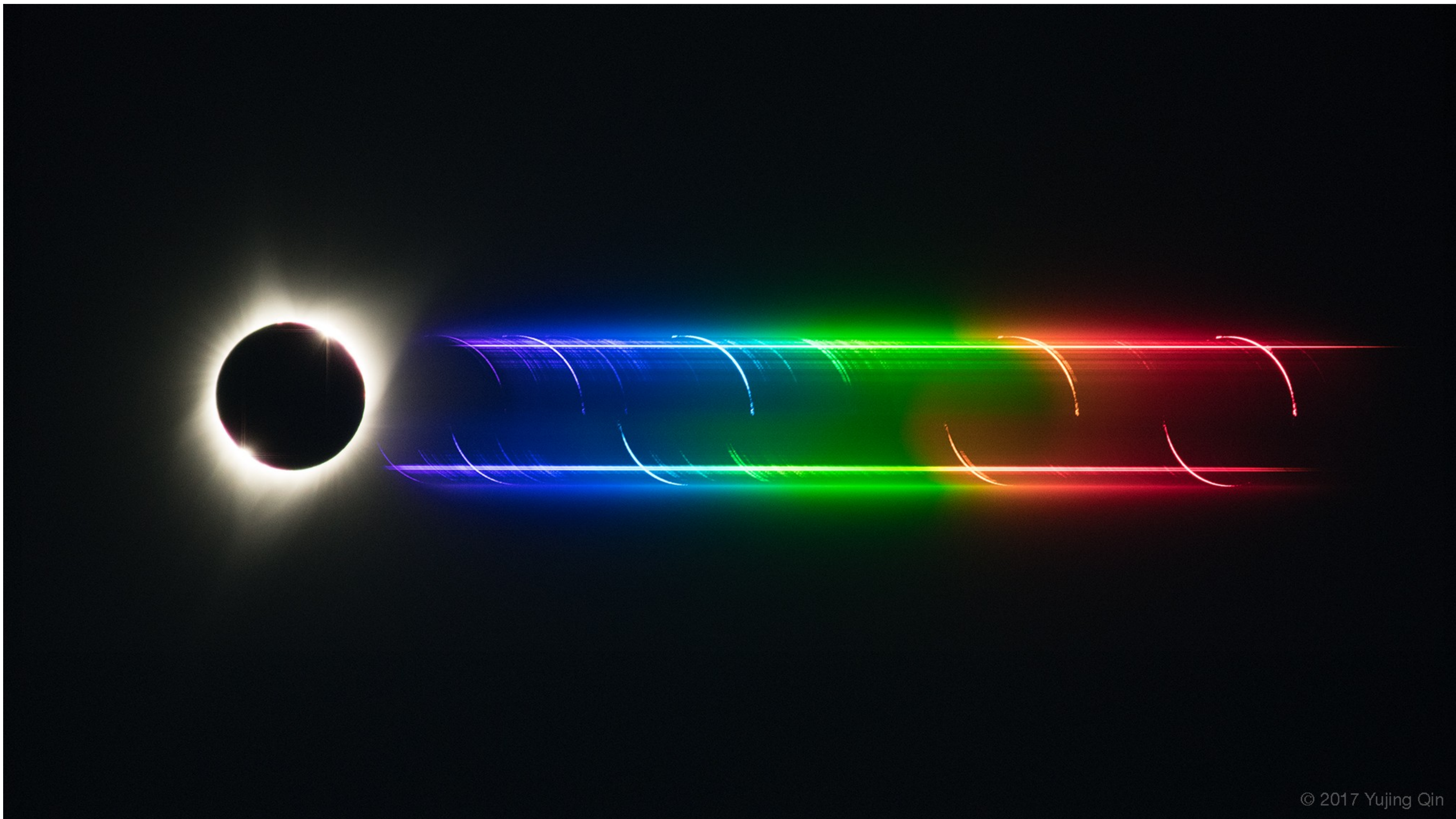
(“coronium”)





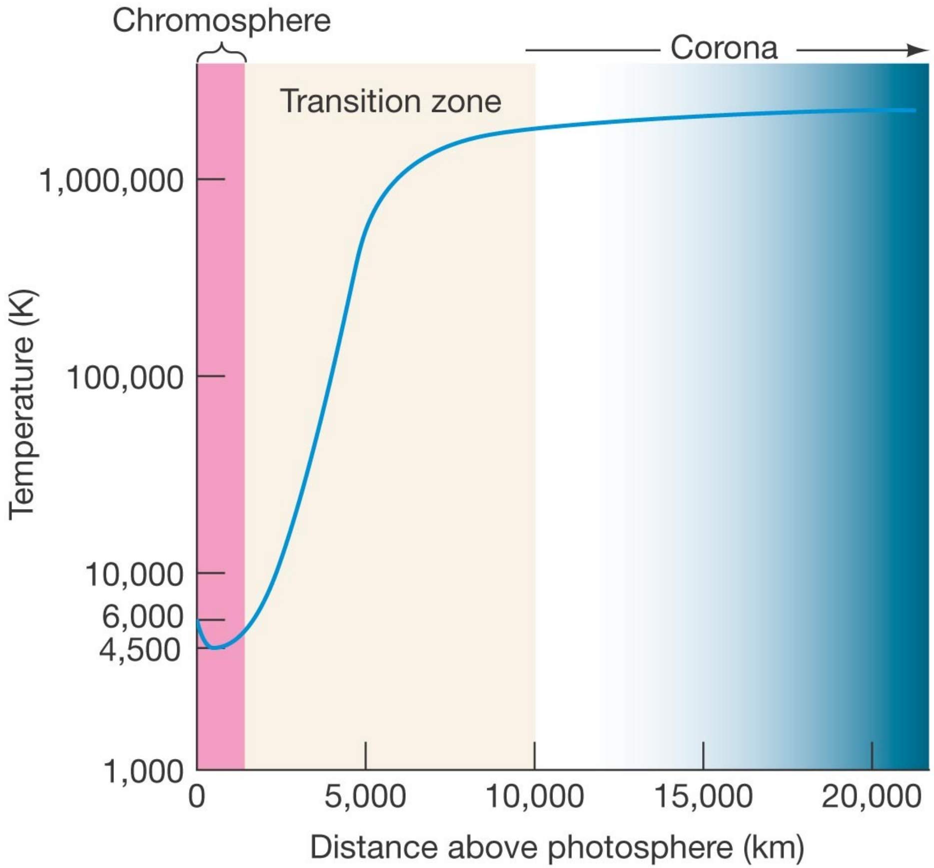
16.3 The Sun's Atmosphere

"Flash" spectrum (slitless) showing spectra of Solar corona, chromosphere, and photosphere.



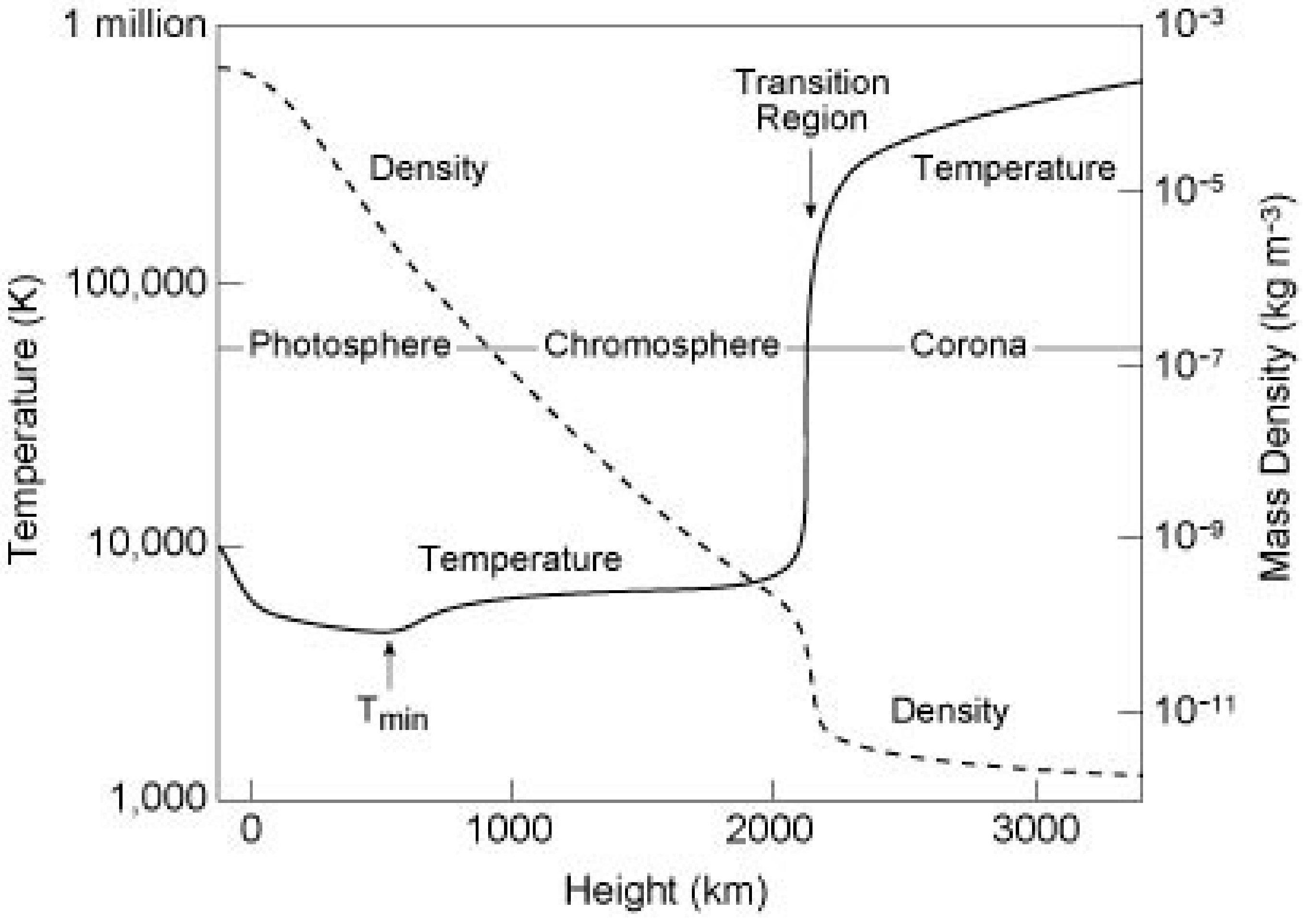
16.3 The Sun's Atmosphere

The textbook's plot of T vs height has mistakes: 1) Temp minimum is really at the top of the photosphere, 2) Chromospheric temperatures can exceed 10,000 K, 3) transition zone is only about 100 km thick.



16.3 The Sun’s Atmosphere

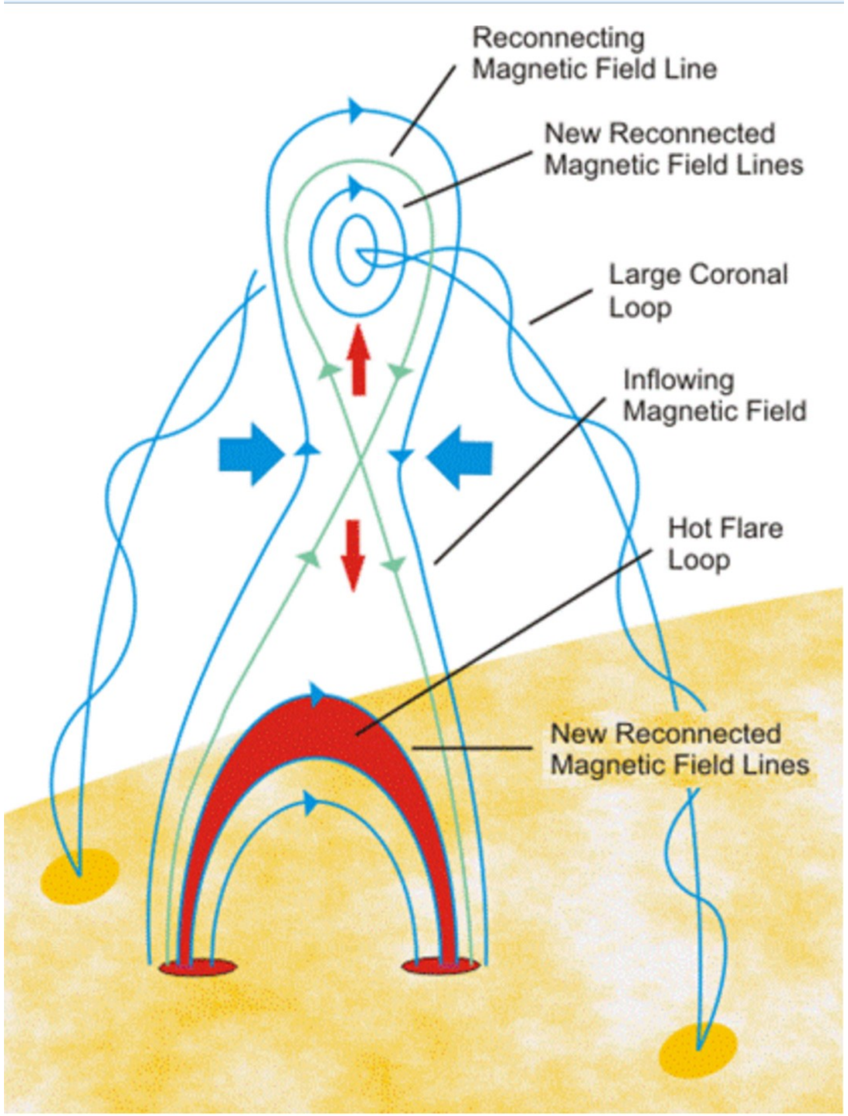
Better plot of Temperature vs height:



16.3 The Sun's Atmosphere

A big question is "what makes the corona so hot?"

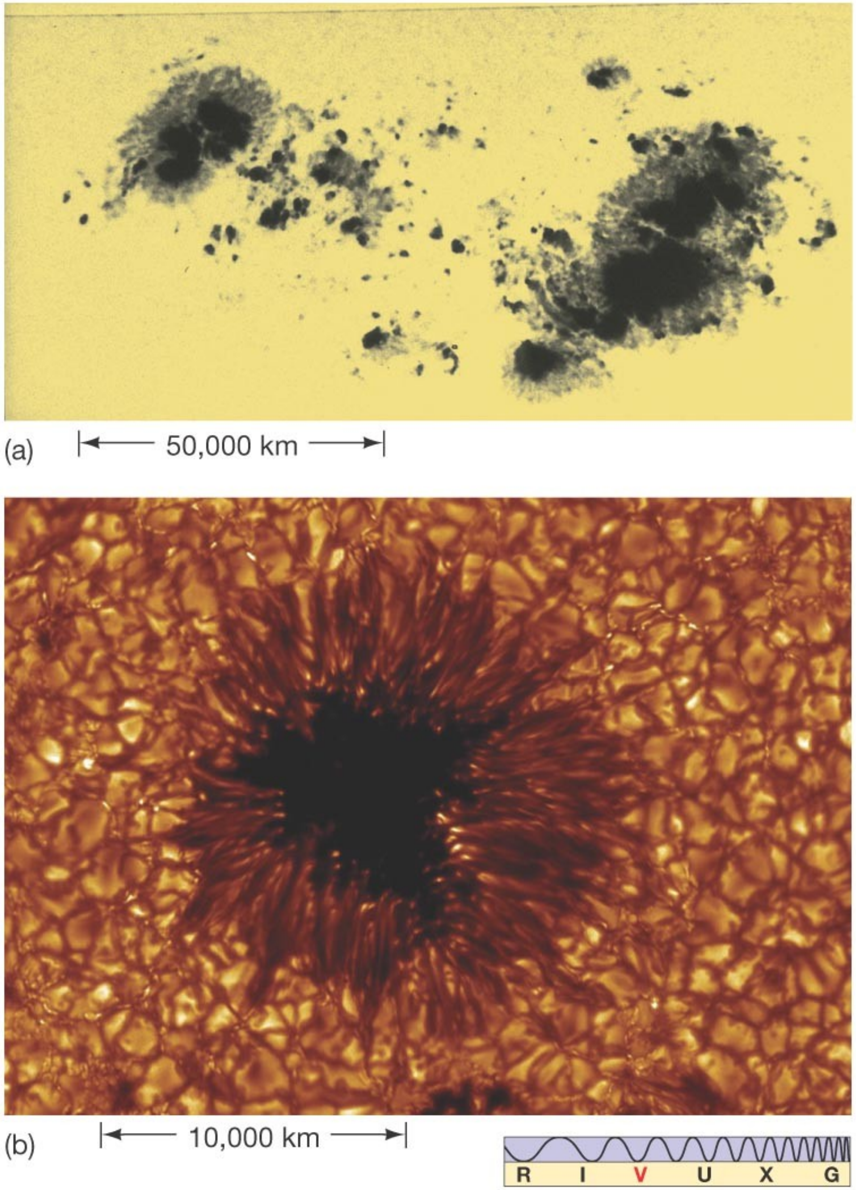
One candidate is heating by **magnetic reconnection** (probable mechanism behind solar flares).



Another recent candidate is "**nano flares**" (unresolved flares).

16.4 Solar Magnetism

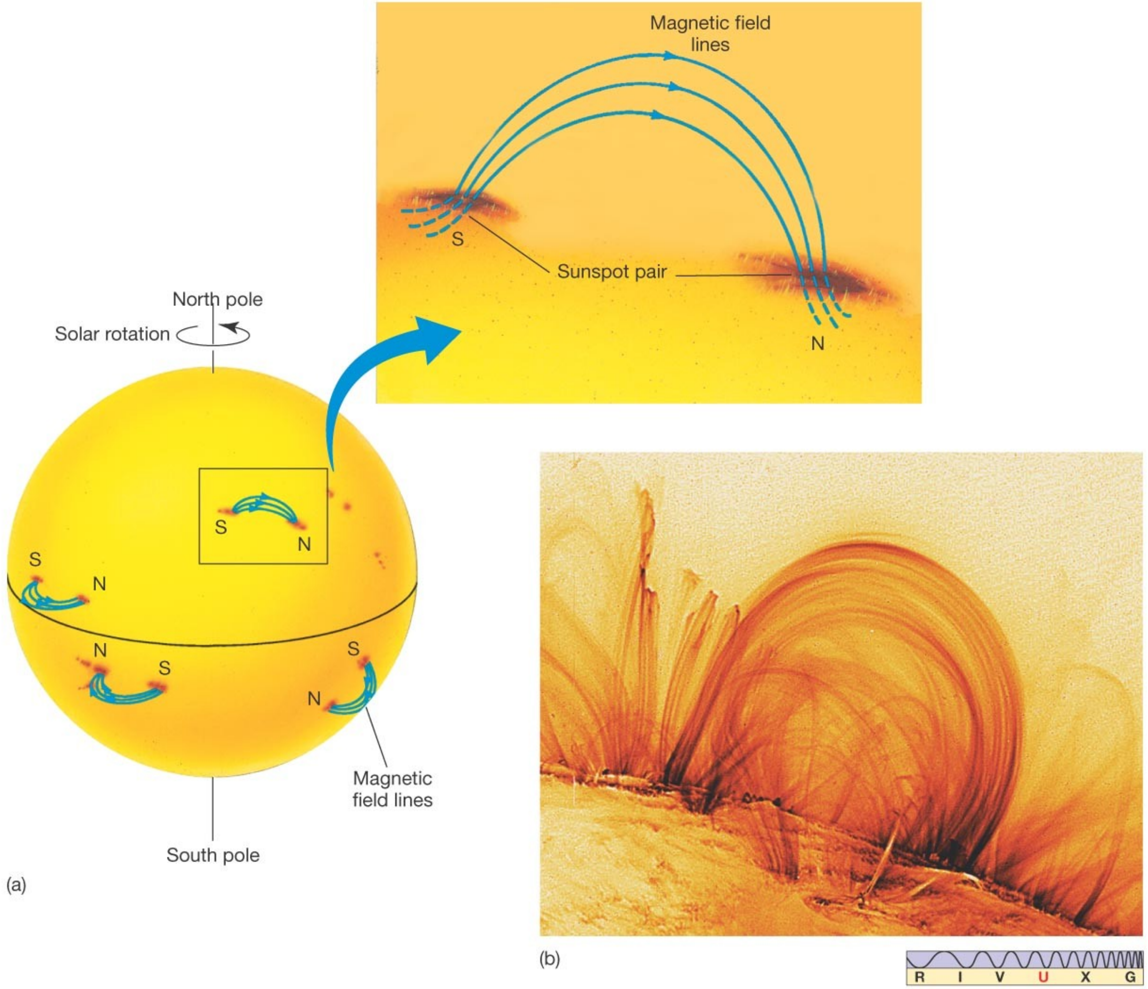
Sunspots: Appear dark because slightly cooler than surroundings



16.4 Solar Magnetism

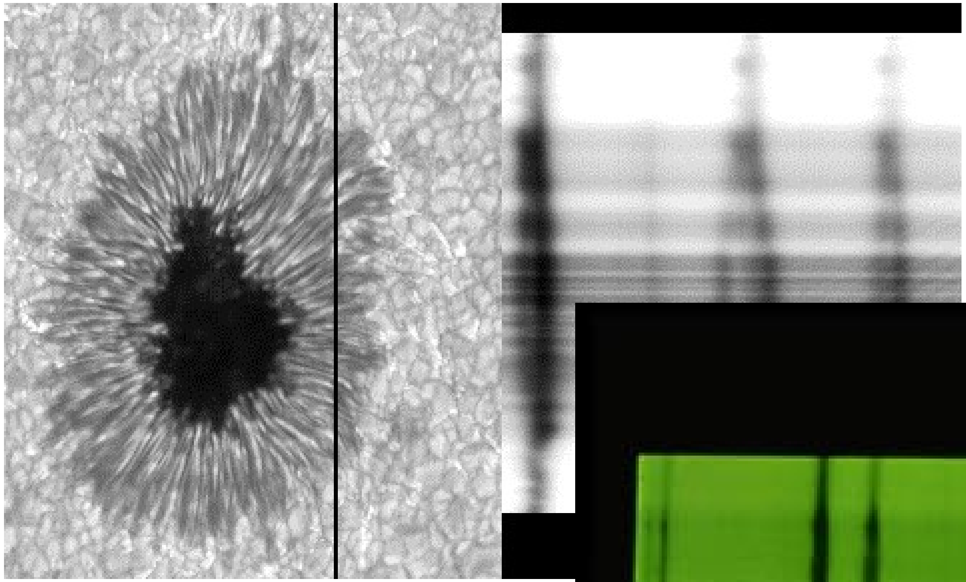
Sunspots come and go, typically in a few days.

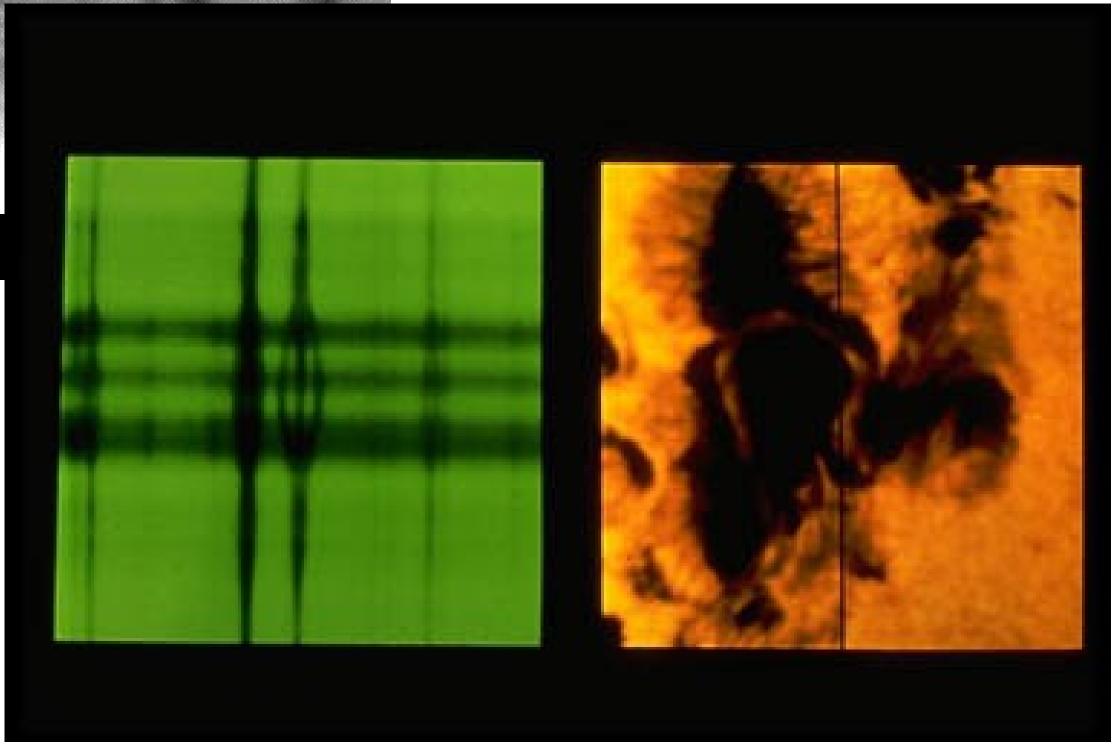
Pairs of sunspots are linked by **magnetic field lines**:



16.4 Solar Magnetism

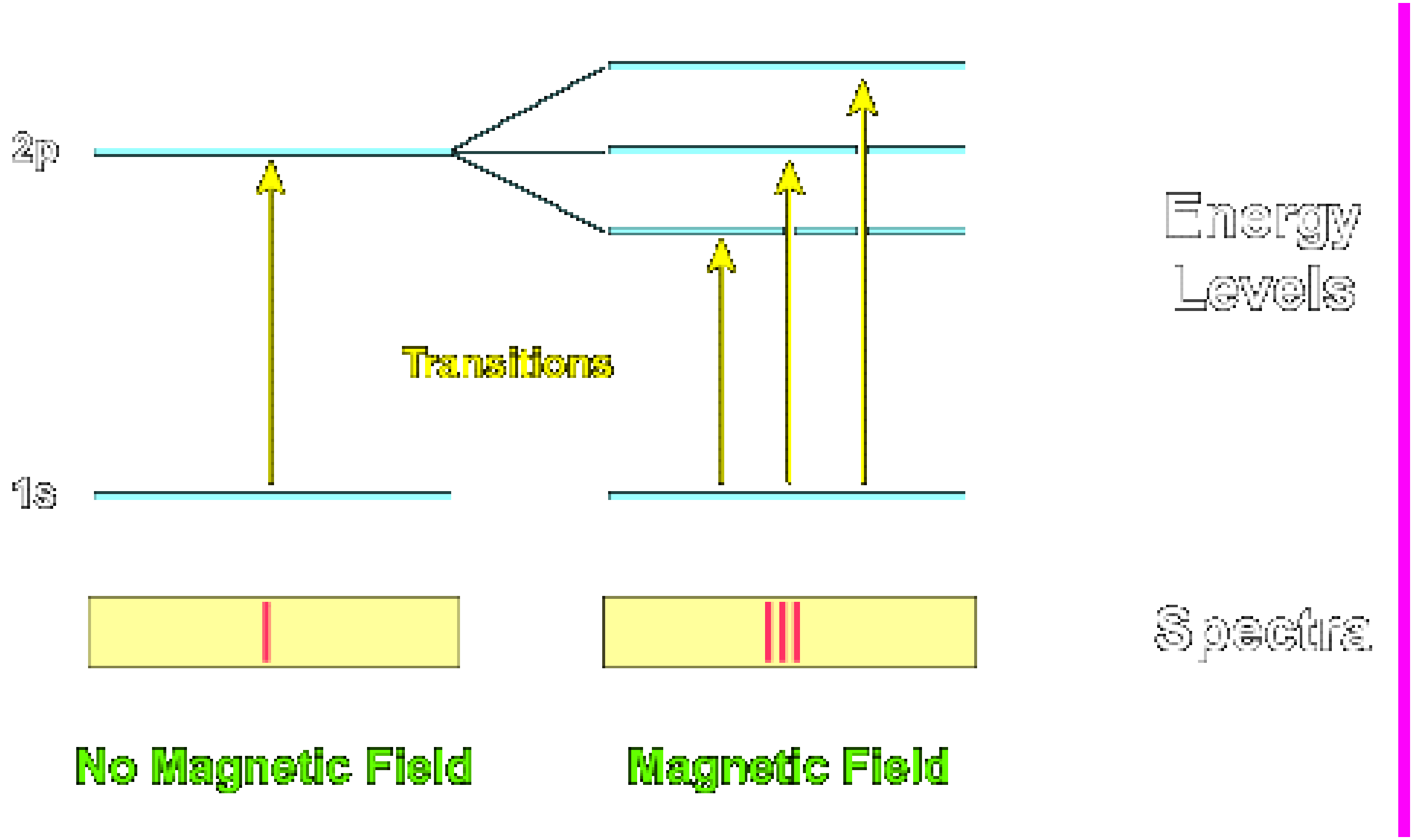
Confirmation of strong magnetic fields in sunspots ...
the Zeeman Effect!





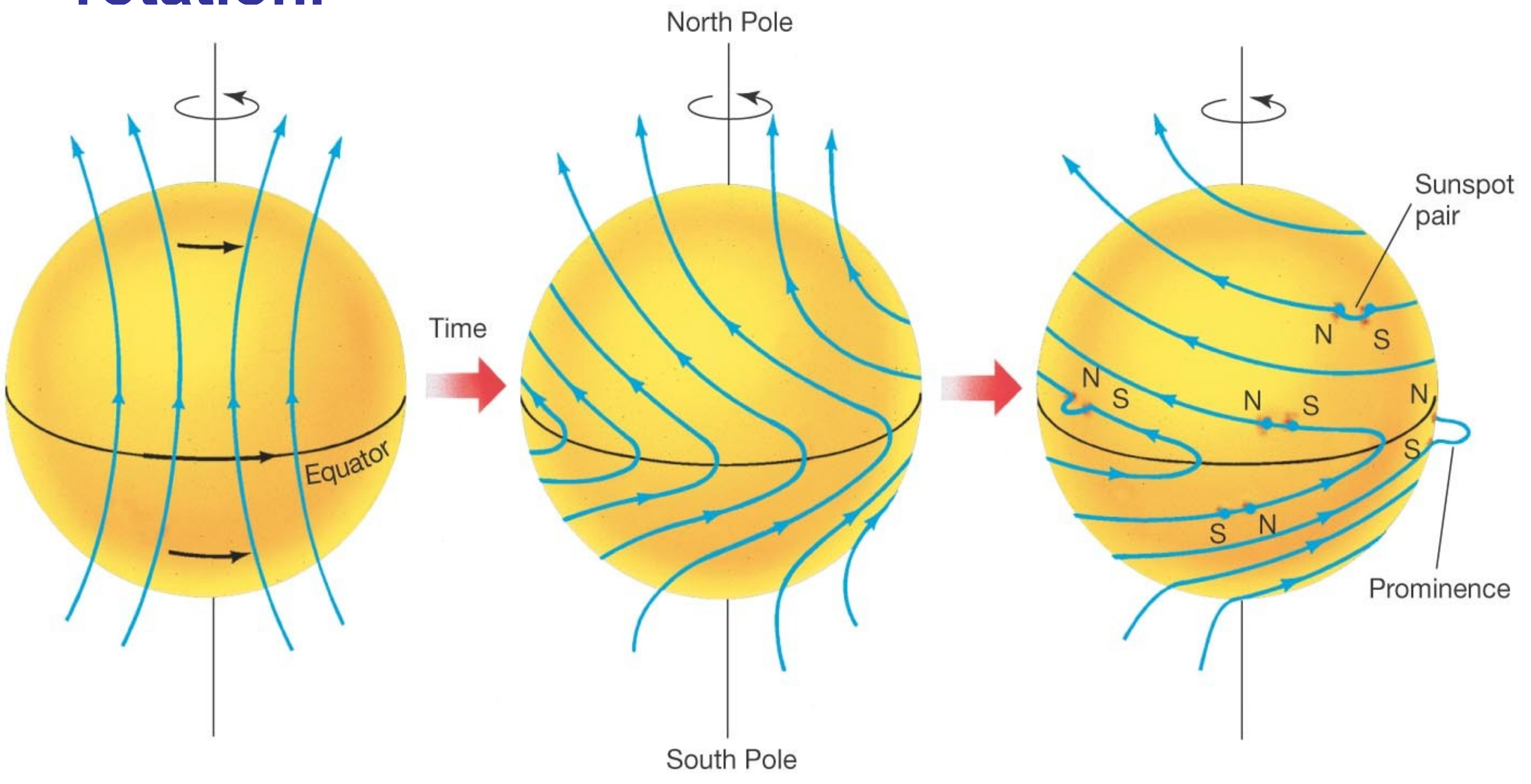
16.4 Solar Magnetism

The Zeeman Effect Is explained in terms of splitting energy levels in atoms.



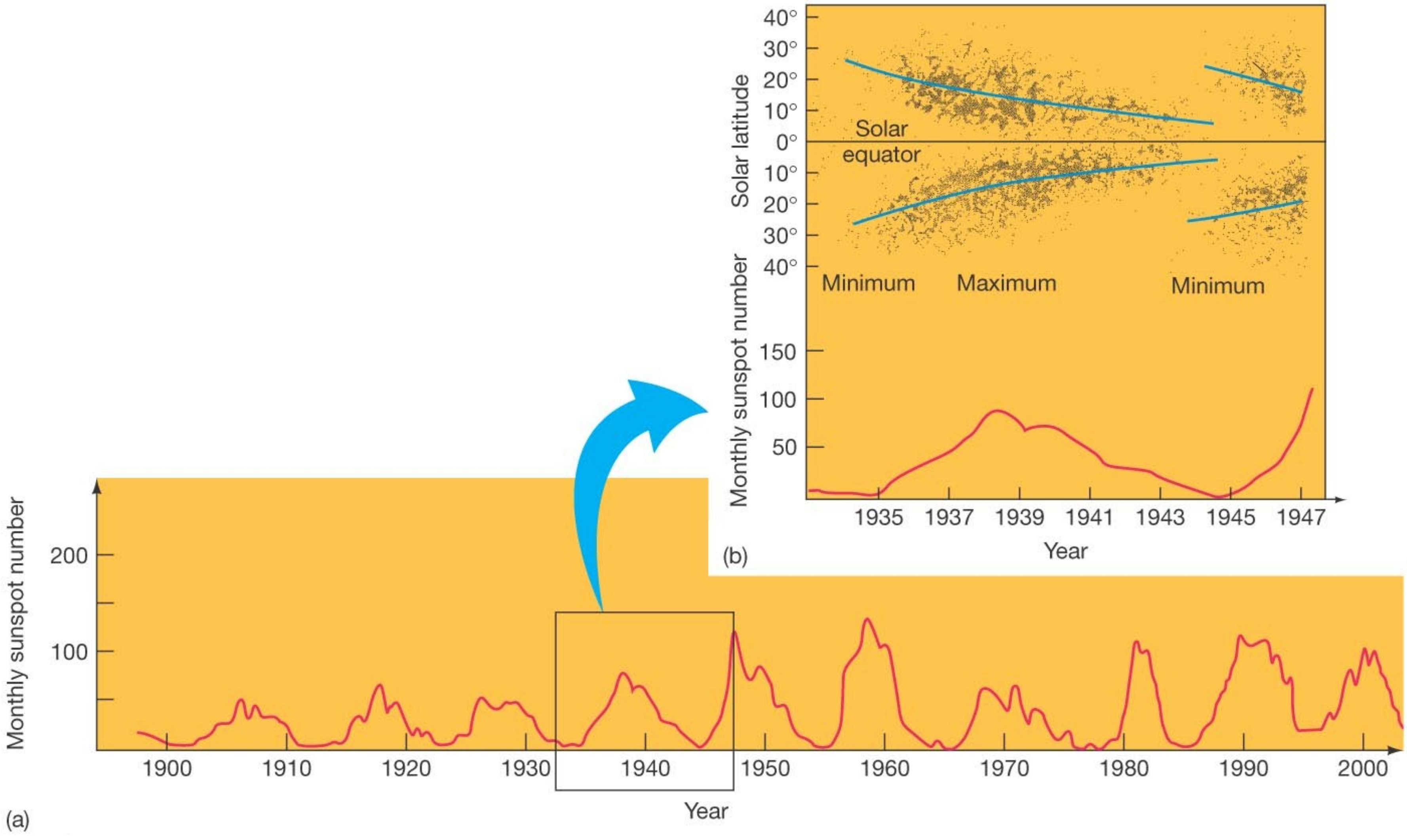
16.4 Solar Magnetism

Sunspots originate when magnetic field lines are distorted by Sun's differential rotation.



16.4 Solar Magnetism

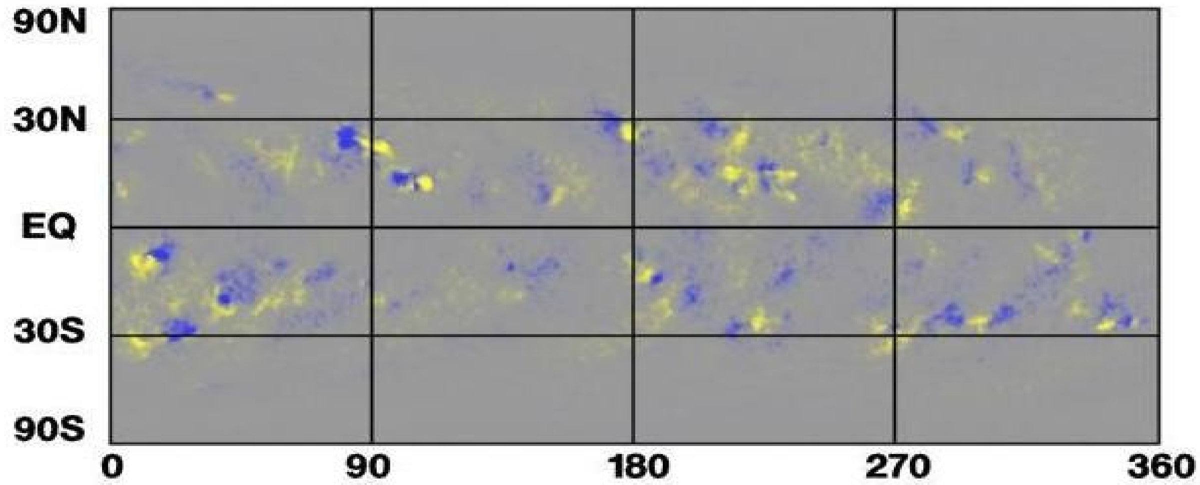
The Sun has an 11-year **sunspot cycle**.



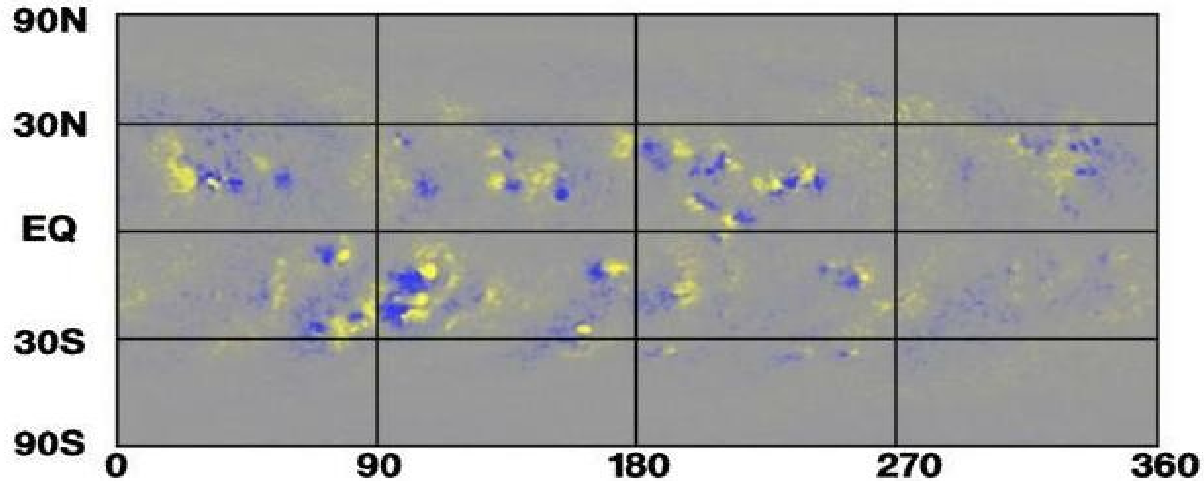
16.4 Solar Magnetism

This is really a 22-year cycle, because the spots switch polarities every 11 years.

Cycle 21



Cycle 22



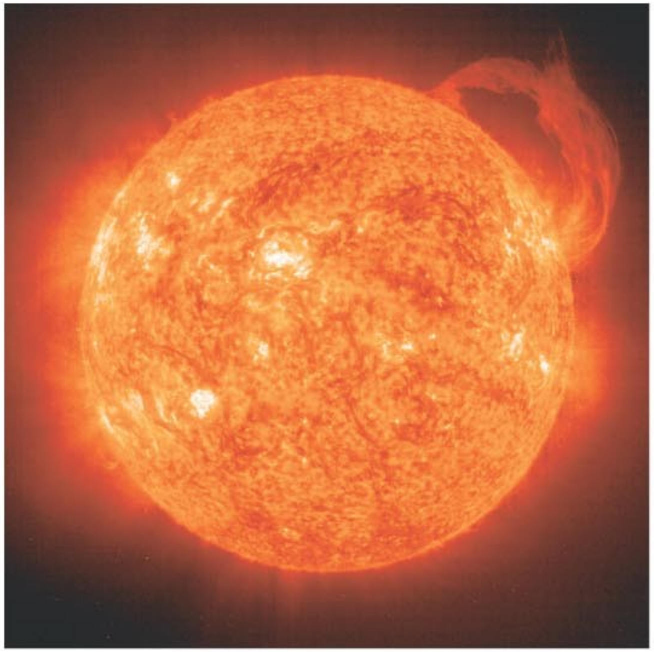
16.5 The Active Sun

Areas around sunspots are active.

Solar prominence : gas loop on limb

Solar Filament: gas loop viewed "head on"

Coronal mass ejection: loop breaks, gas ejected



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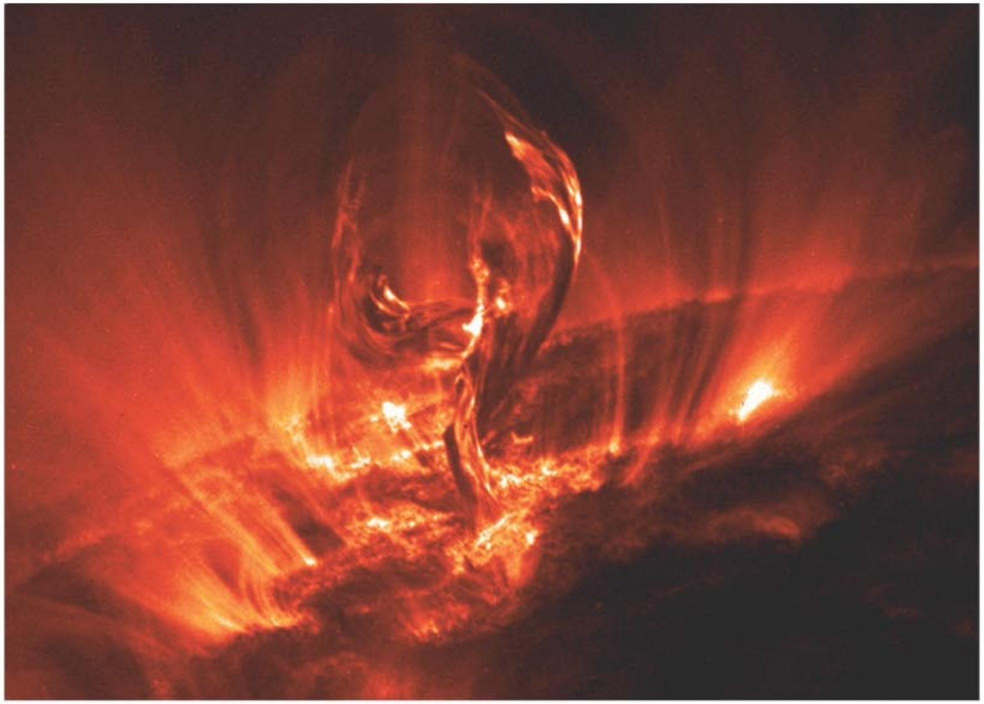

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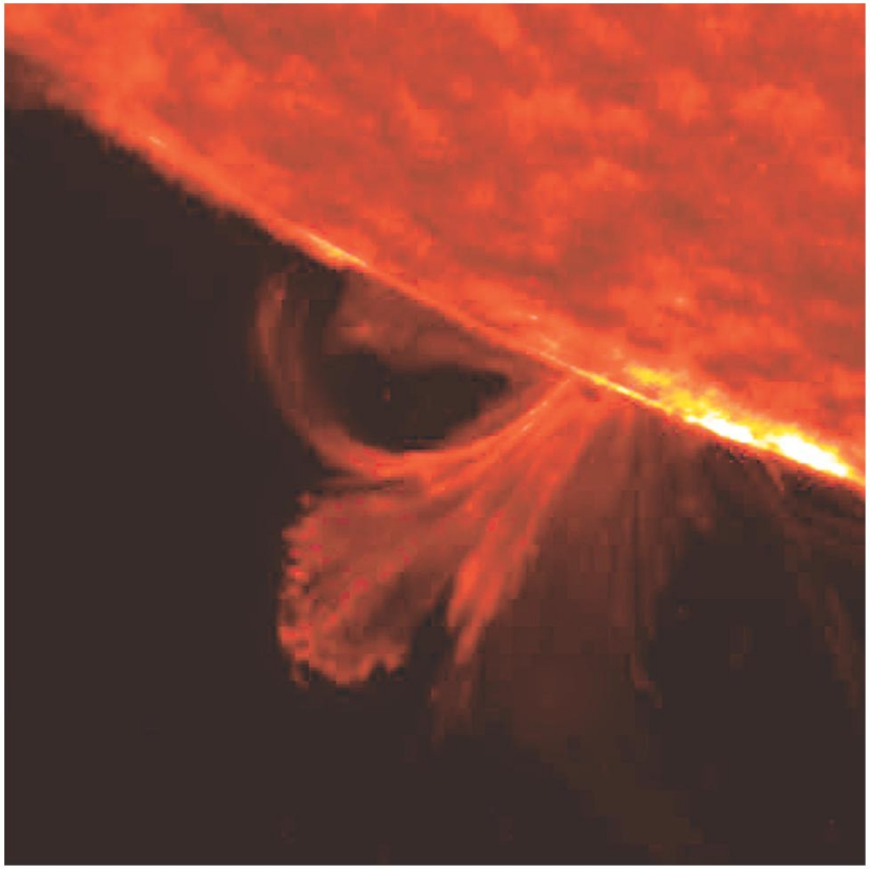
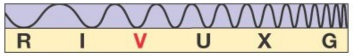
Solar Flare:

16.5 The Active Sun

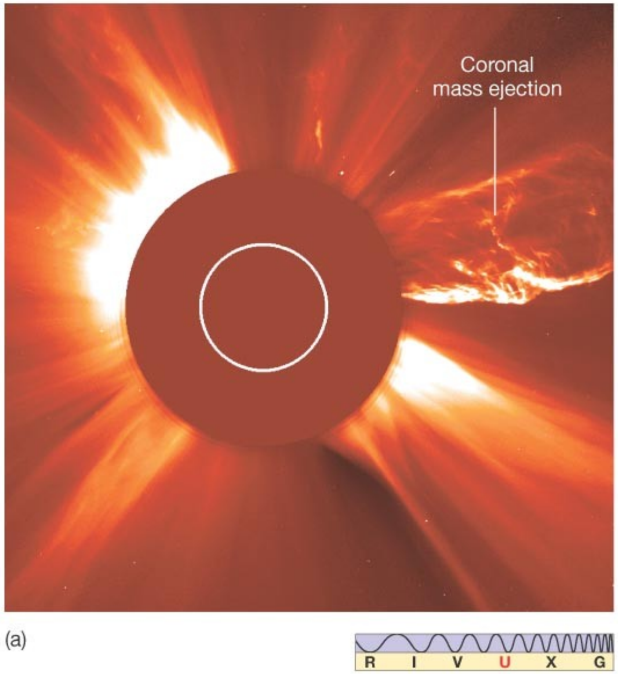
Solar flare is a large **explosion** on Sun's surface, emitting a similar amount of energy to a prominence, but in seconds or minutes rather than days or weeks:





16.5 The Active Sun

Coronal mass ejection occurs when a large "bubble" detaches from the Sun and escapes into space.



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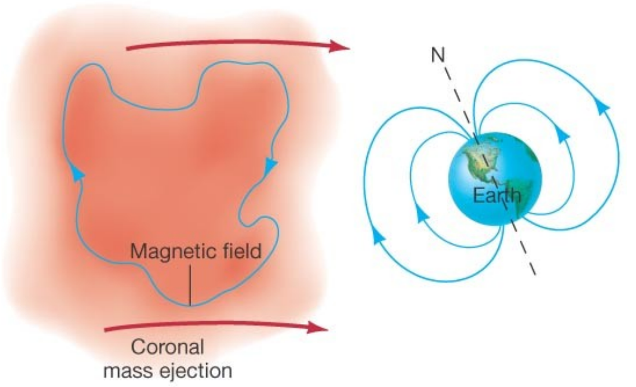

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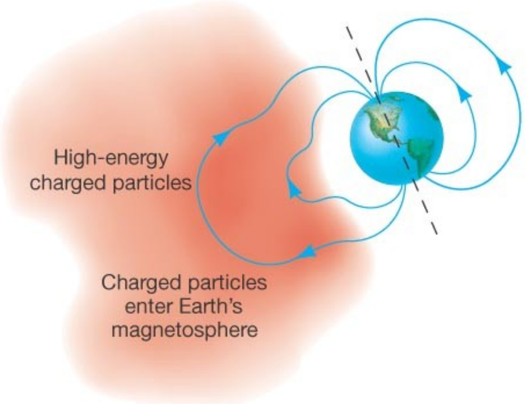

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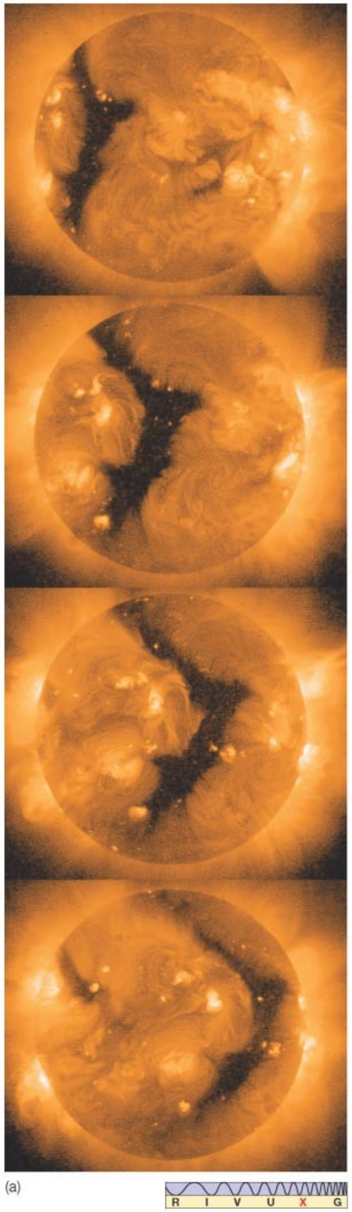
16.5 The Active Sun



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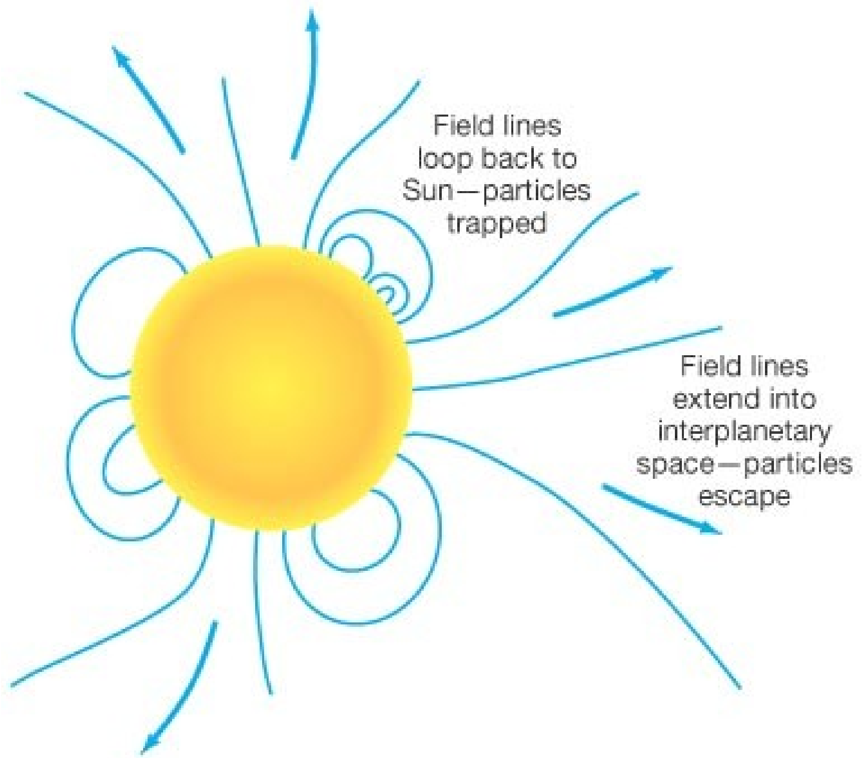
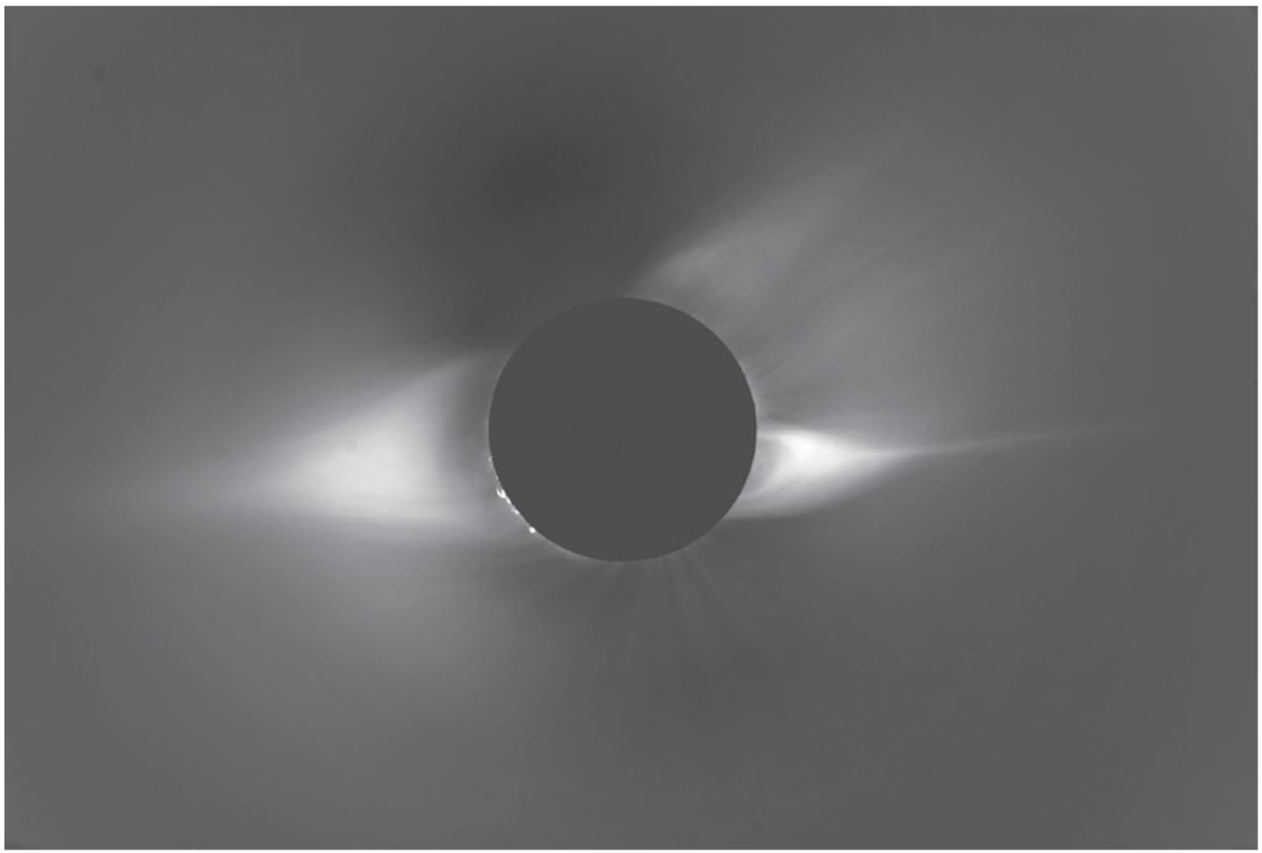


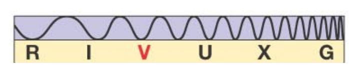
(b)

Solar wind escapes the Sun mostly through **coronal holes**, which can be seen in X-ray images as dark regions.

16.5 The Active Sun

Solar corona changes along with sunspot cycle; it is much larger and more irregular at sunspot peak.





16.5 The Active Sun

See YouTube video "Sun Montage – SOHO" for video of all of the preceding phenomena.

https://www.youtube.com/watch?v=QdwGb-iJOeI&ab_channel=TahitiPetey

16.6 The Heart of the Sun

What powers the Sun??

It emits energy at the rate of $4X10^{26}$ W.

It continues emitting for 10 billion years.

We find that the total lifetime energy output is about 3×10^{13} J/kg

This is a lot, and it is produced steadily, not explosively. How?

16.6 The Heart of the Sun

Gravitational contraction? no

Combustion? no

Nuclear fusion yes!

In general, nuclear fusion works like this:

$$\text{nucleus 1} + \text{nucleus 2} \rightarrow \text{nucleus 3} + \text{energy}$$

But where does the energy come from?

- **It comes from the mass loss:**

The initial mass is greater than the final mass.

The total mass-energy must stay constant.

16.6 The Heart of the Sun

The conversion between mass and energy comes from Einstein's famous equation:

$$E = mc^2$$

E **= energy**

c **is the speed of light**

m**=difference between final and initial mass**

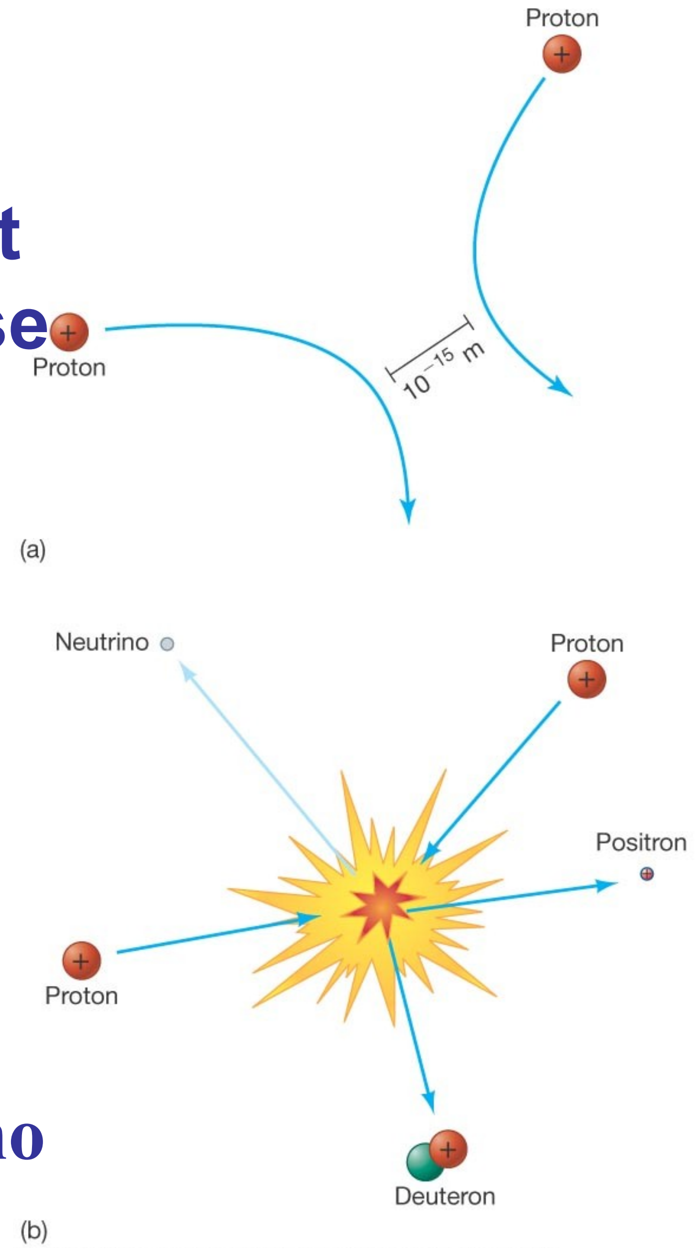
→ a small amount of mass becomes a large amount of energy

16.6 The Heart of the Sun

Nuclear fusion requires that like-charged nuclei get close enough to each other to fuse.

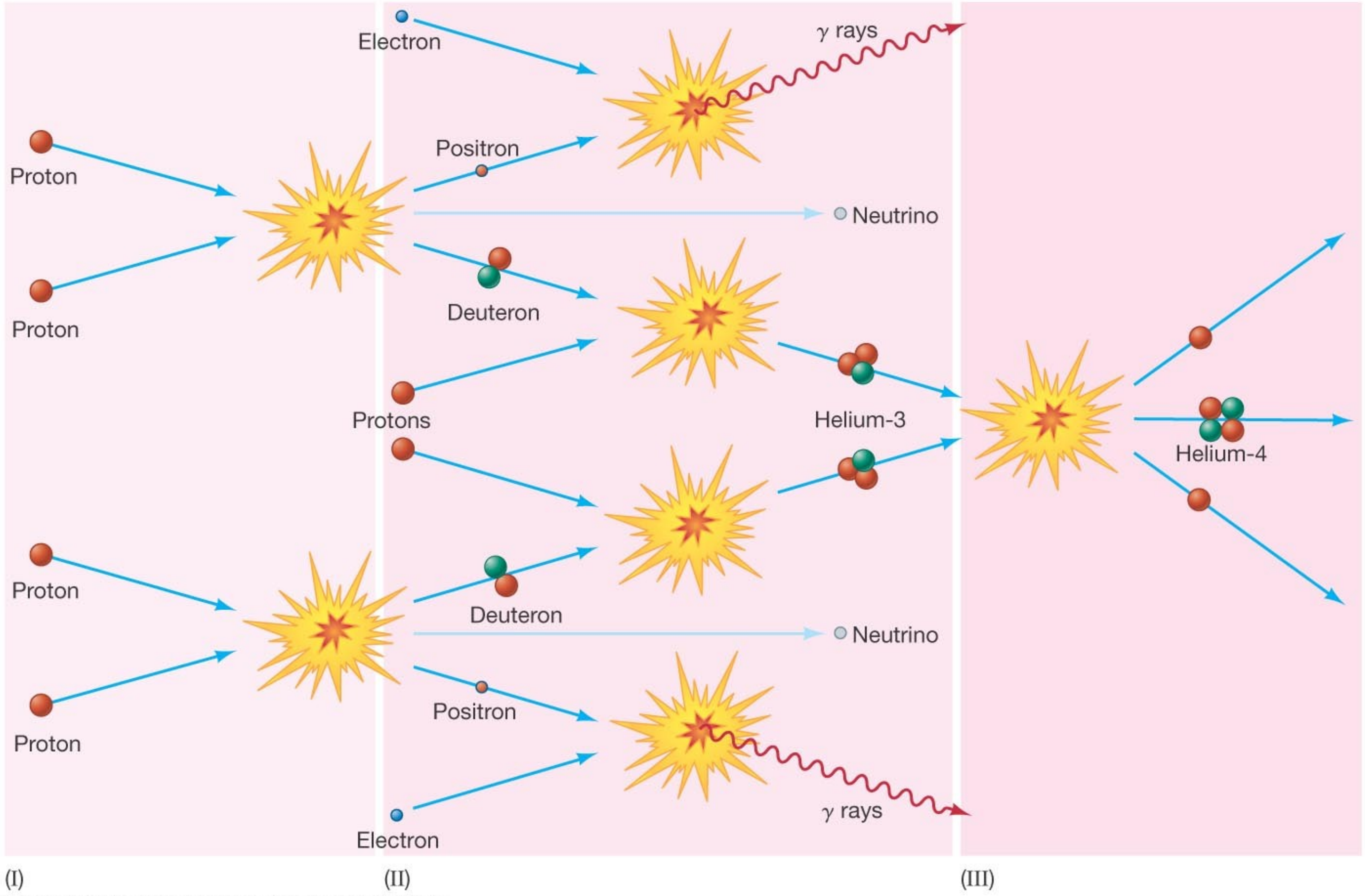
This can happen only if the **temperature** is extremely high—over 10 million K.

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + \text{positron} + \text{neutrino}$$



16.6 The Heart of the Sun

This is the first step in a three-step fusion process that powers most stars:



16.6 The Heart of the Sun

The **ultimate result** of the process:

$$4(^{1}H) \rightarrow {}^{4}He + \text{energy} + 2 \text{ neutrinos}$$

The **helium** stays in the core.

The energy is in the form of **gamma rays**, which gradually lose their energy as they travel out from the core, emerging as visible light.

The **neutrinos** escape without interacting.

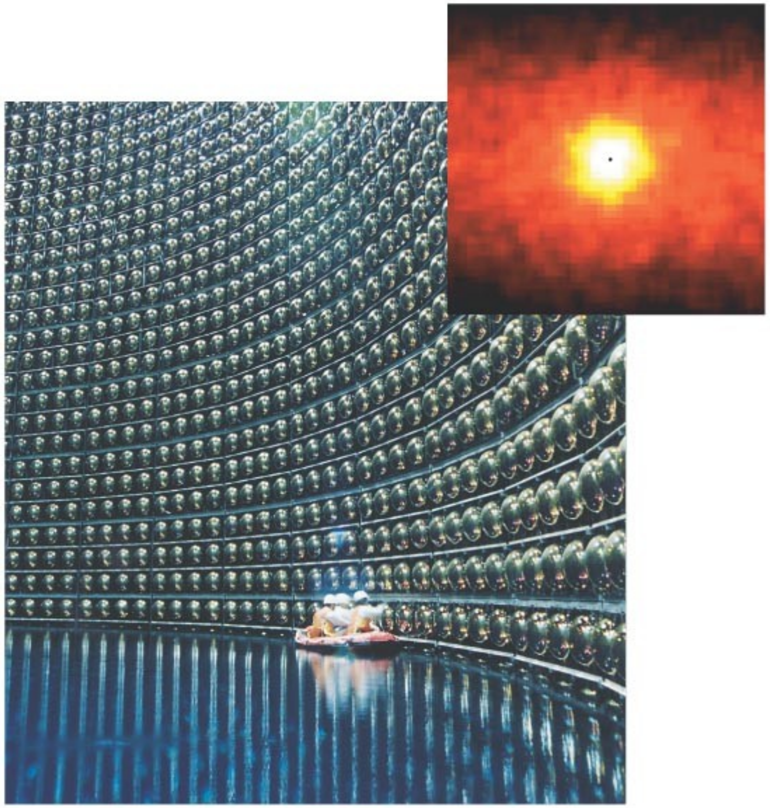
16.6 The Heart of the Sun

Sun must convert 4.3 million tons of matter into energy every second.

The Sun has enough hydrogen left to continue fusion for about another 5 billion years.

16.7 Observations of Solar Neutrinos

Typical solar neutrino detectors; resolution is very poor



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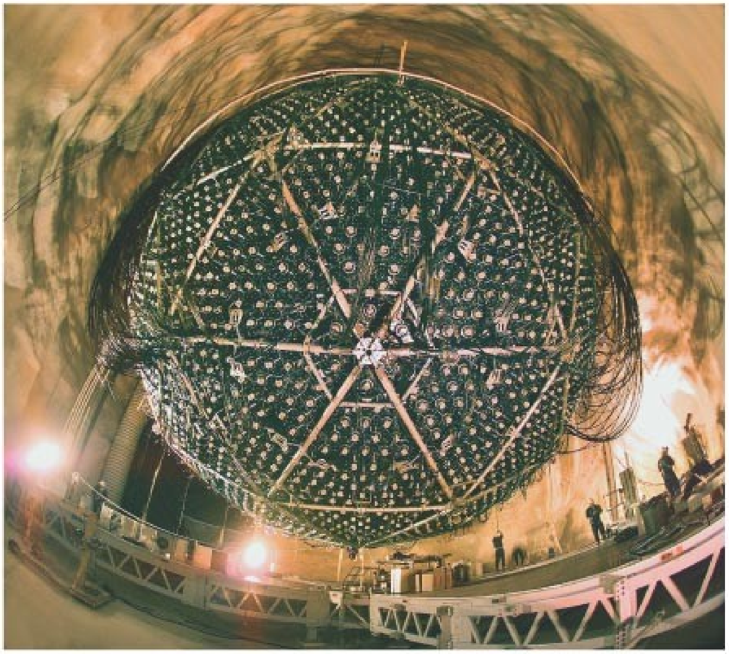

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16.7 Observations of Solar Neutrinos

Detection of solar neutrinos has been going on for more than 30 years now; there has always been a deficit in the type of neutrinos expected to be emitted by the Sun.

Recent research proves that the Sun is emitting about as many neutrinos as the standard solar model predicts, but the neutrinos change into other types of neutrinos between the Sun and the Earth, causing the apparent deficit.

Summary of Chapter 16

- Main interior regions of Sun: core, radiation zone, convection zone, photosphere, chromosphere, transition region, corona, solar wind
- Energy comes from nuclear fusion; produces neutrinos along with energy
- Standard solar model is based on hydrostatic equilibrium of Sun
- Study of solar oscillations leads to information about interior

Summary of Chapter 16 (cont.)

- Absorption lines in spectrum tell composition and temperature
- Sunspots associated with intense magnetism
- Number of sunspots varies in an 11-year cycle
- Large solar ejection events: prominences, flares, and coronal ejections
- Observations of solar neutrinos show deficit, due to peculiar neutrino behavior