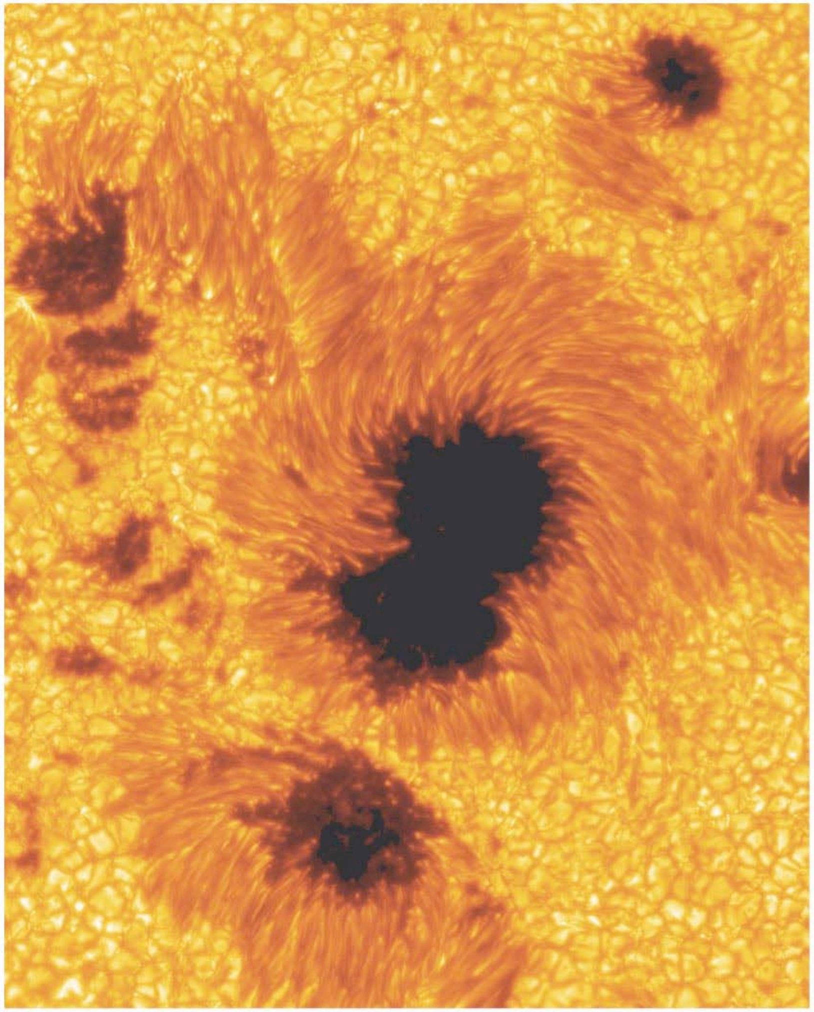
# Chapter 16
# The Sun



# Units of Chapter 16

# 16.1 Physical Properties of the Sun

Radius: 700,000 km

Mass: $2.0 \times 10^{30}$ kg = 300 Jupiters = 90,000 Earths

Density: not meaningful to give average because varies by orders of magnitude from surface to center.

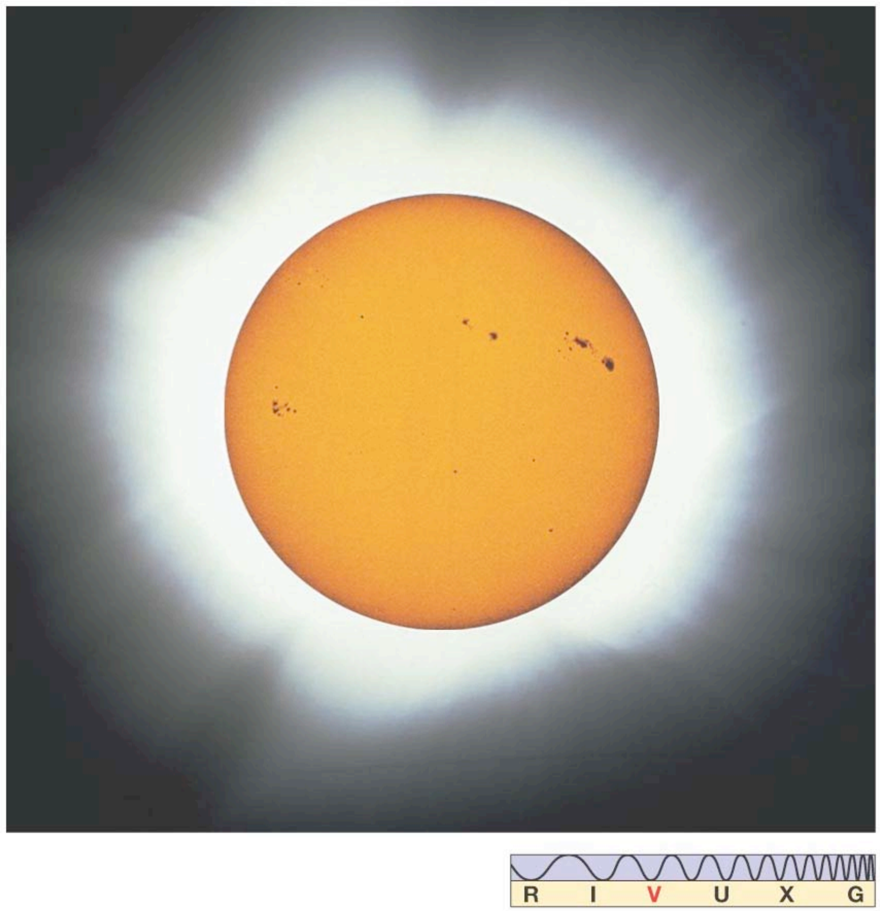
Rotation: Differential; period about a month

Surface temperature: 5800 K (a yellow star)

Apparent surface of Sun is "photosphere"

## The sun is the only star that we can *resolve* in detail, but most of what we want to know is in the deep interior

**This is a filtered image of the Sun showing sunspots, the sharp edge of the Sun due to the thin photosphere, and the corona:**



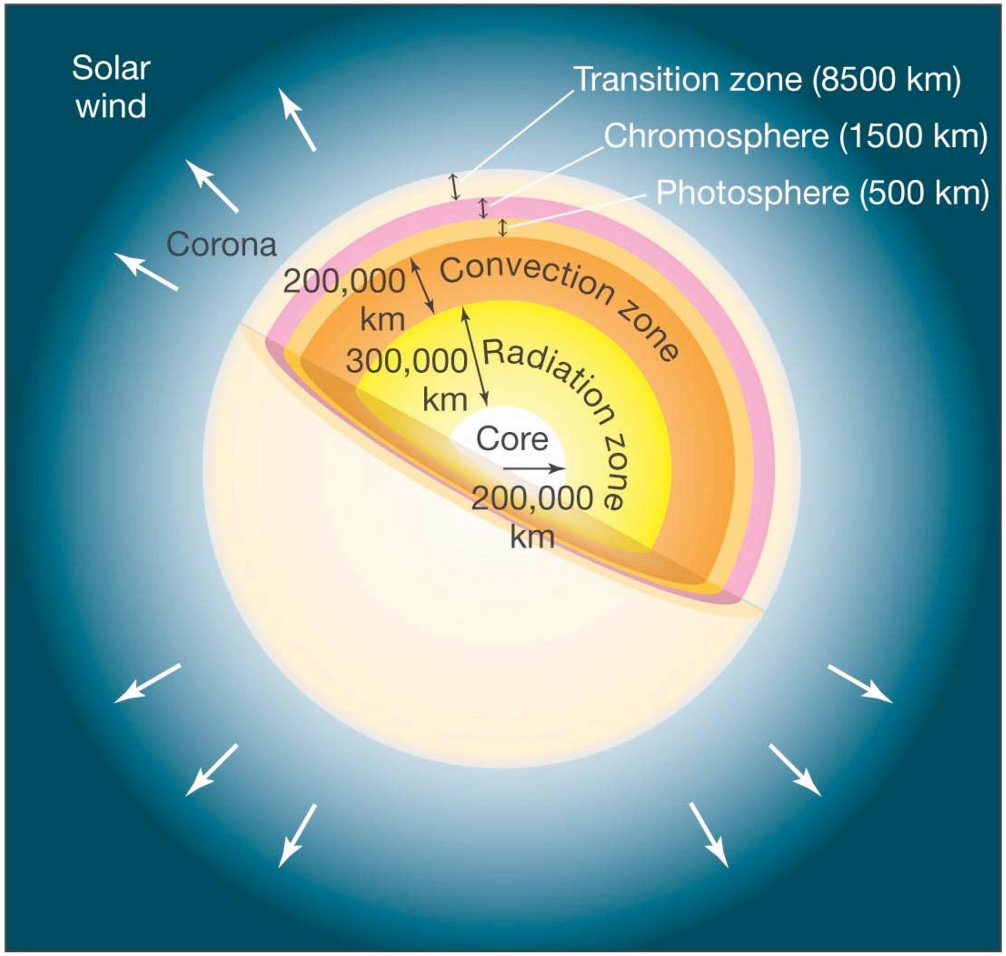
# The solar interior

Interior structure of the Sun:

Outer layers are not to scale

The core is where nuclear fusion takes place.

The energy emitted by the surface repesents energy transported from the core through the *radiative zone,* the *convection zone*, and finally the *photosphere*, which by definition is the thin atmospheric layer that is thin enough for the radiation to escape.

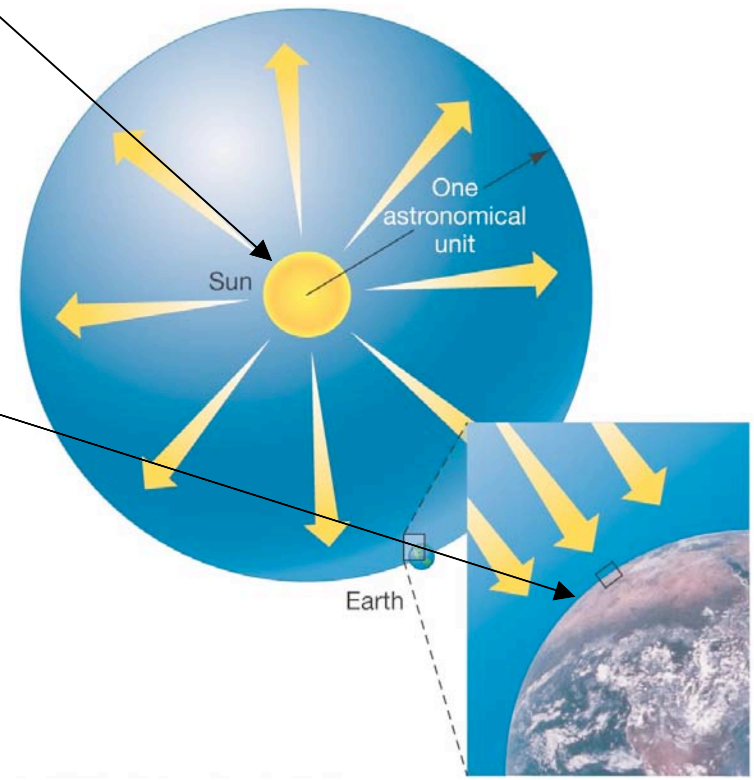


# 16.1 Physical Properties of the Sun

**Luminosity**— total energy radiated by the Sun— can be calculated from the fraction of that energy that reaches Earth, called the *solar constant.*

**Solar constant**— amount of Sun's energy incident on a square meter of the Earth per second—is 1400 W/$m^2$. That is not much more than a the glare from a very strong light bulb a foot or so away, but the Sun delivers that energy flux to *every* square meter of the Earth, and does it from 93 million miles (1AU) away.

**Total luminosity of the sun** is about $4 \times 10^{26}$ W—the equivalent of 10 billion 1-megaton nuclear bombs per second. We have no experience with such brightnesses, but just remember that if you moved the sun a parsec away, it would be a bright star in the sky.



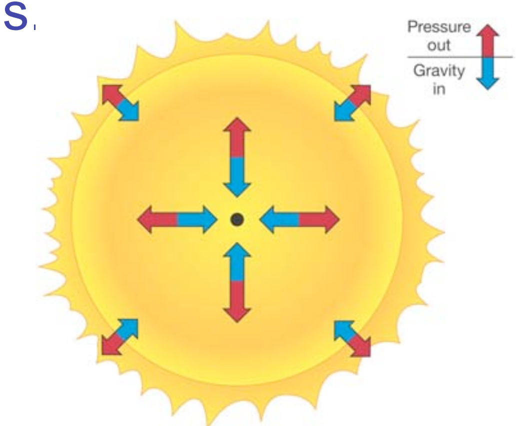

Since the sun will turn out to be a typical star, this is an extremely important bit of information: *What kind of fuel could generate that much energy for over 4 billion years?*

# 16.2 The Solar Interior: methods

1. Mathematical models, consistent with observation and physical principles, provide information about the Sun's interior.

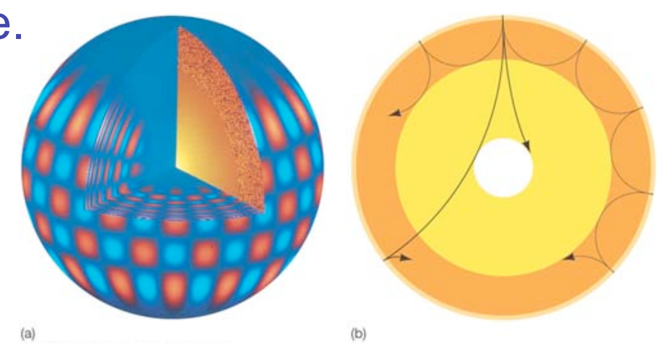
*Most* of what we know about the Sun's interior, and the interiors of other stars, comes entirely from these models.

Example: equation of hydrostatic equilibrium: In equilibrium, inward gravitational force must be balanced by outward pressure:



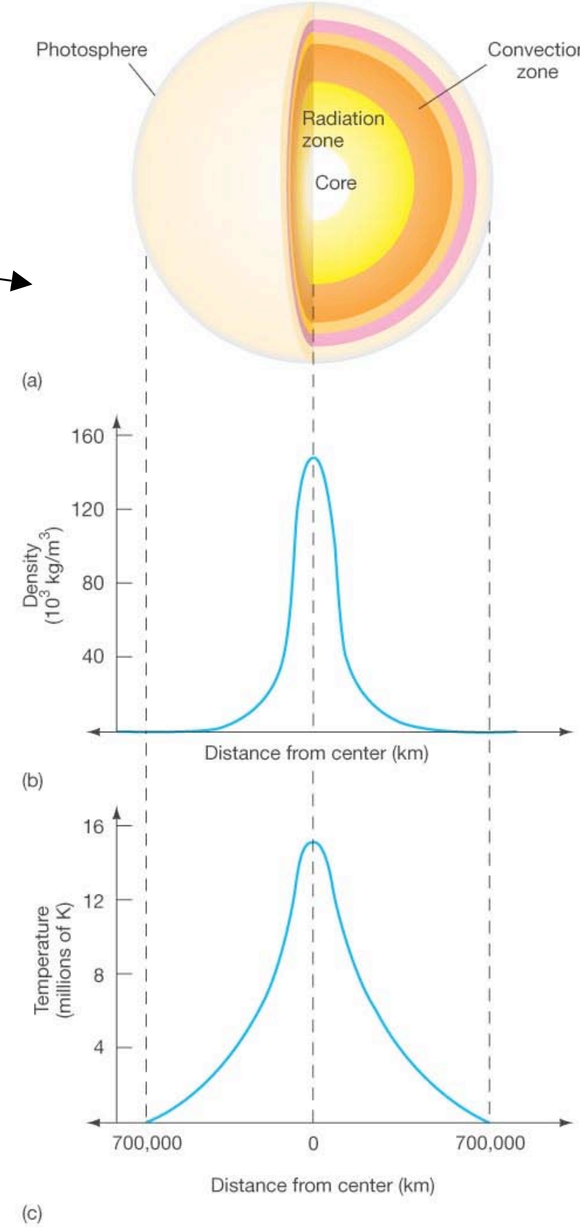

2. Another method for "looking into" the Sun: Doppler shifts of solar spectral lines indicate a complex pattern of vibrations near the surface. This area is called "solar siesmology."

This only probes the upper layers, and can't be used in as much detail for other stars. *Why do you think that is?*

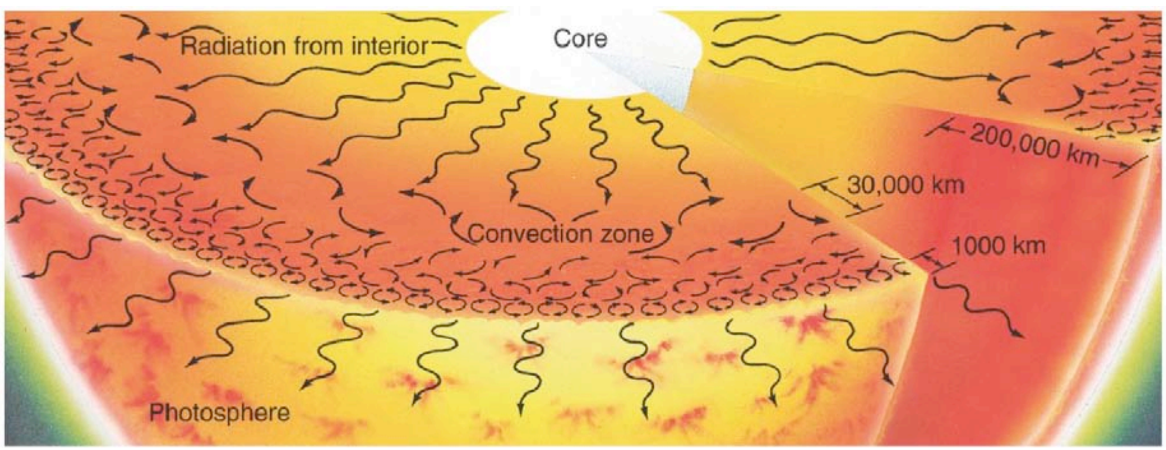


# What do we know about the solar interior?

Solar density and temperature, according to the standard solar model: sun gets denser and hotter as you move inwards.

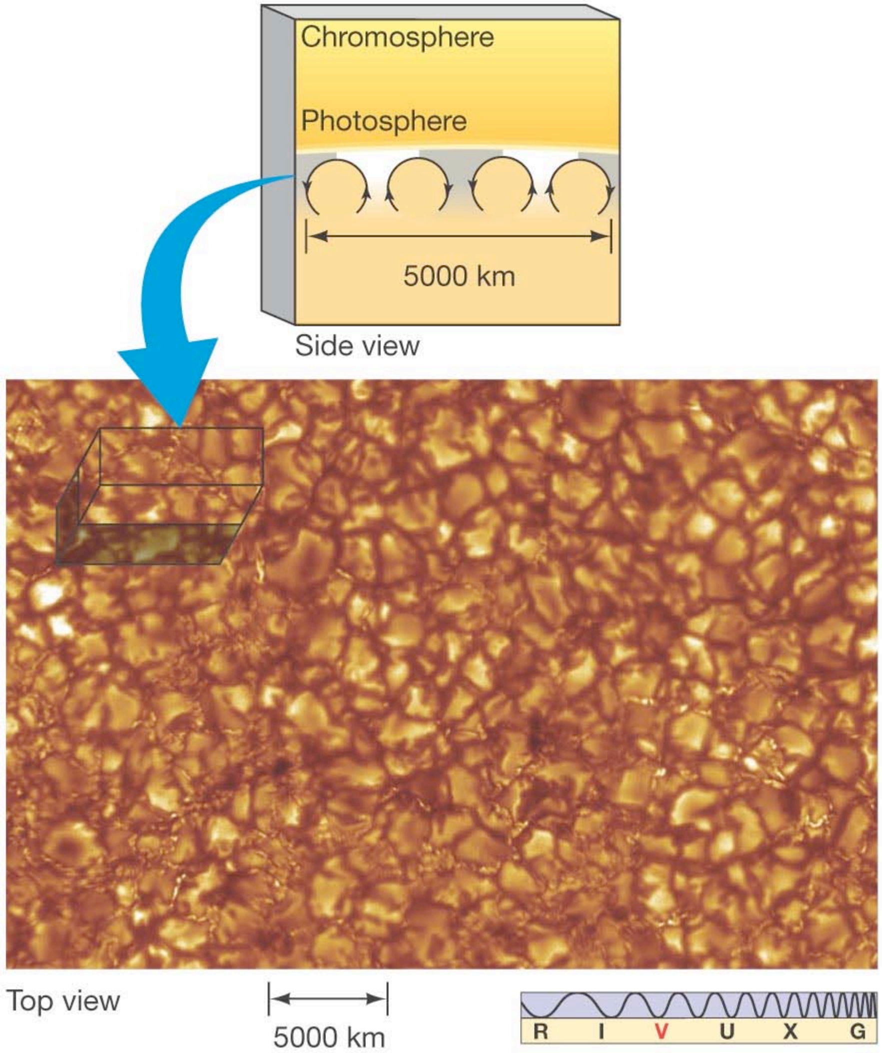



Energy transport: The heat generated in the sun's core is transported outward by photons in the *radiative zone*. Eventually radiation is not efficient enough to carry all the heat, and convection currents are set up in the *convection zone*. (Exactly like heating a room; will explain in class.



# The granulation: seeing the “top” of the convection zone

The visible top layer of the convection zone is granulated, with areas of upwelling material surrounded by areas of sinking material. We can see these rising and falling convection currents through the photosphere.



# Discovery 16-1:
# SOHO: Eavesdropping on the Sun

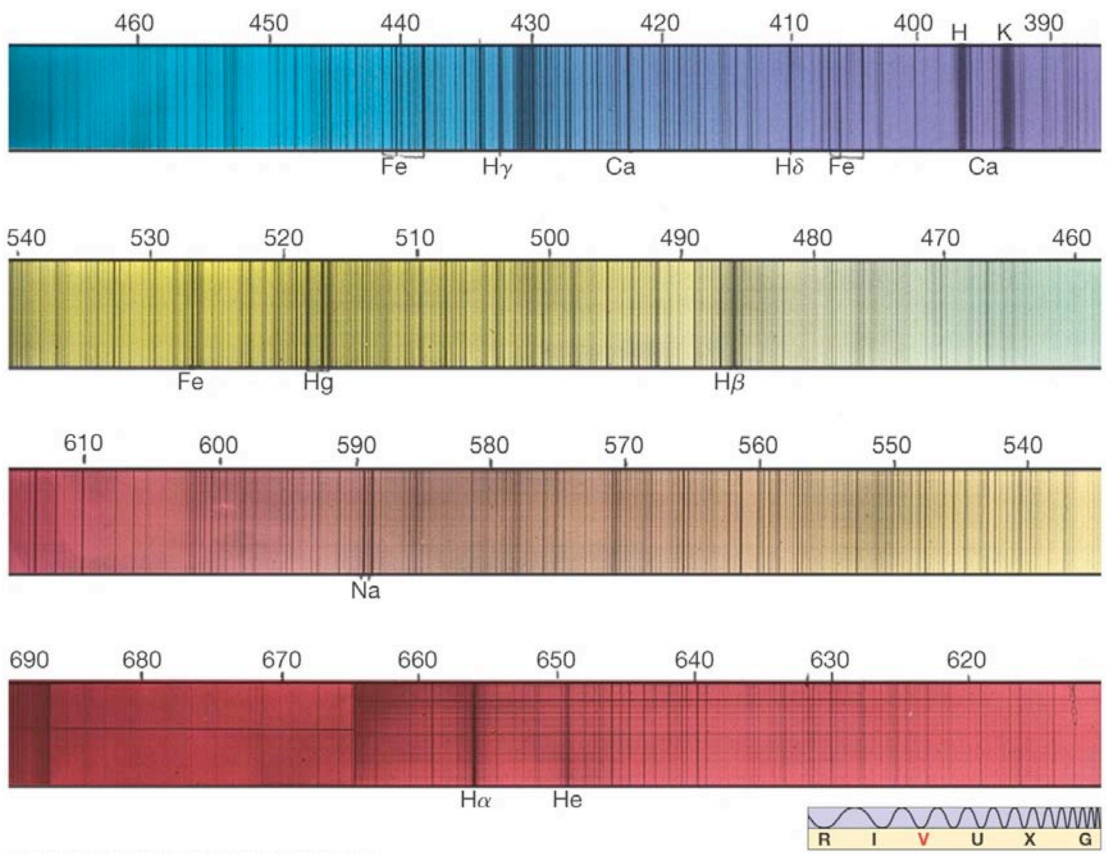
SOHO: Solar and Heliospheric Observatory

Orbits at Earth's L1 point, outside the magnetosphere

Multiple instruments measure magnetic field, corona, vibrations, and ultraviolet emissions

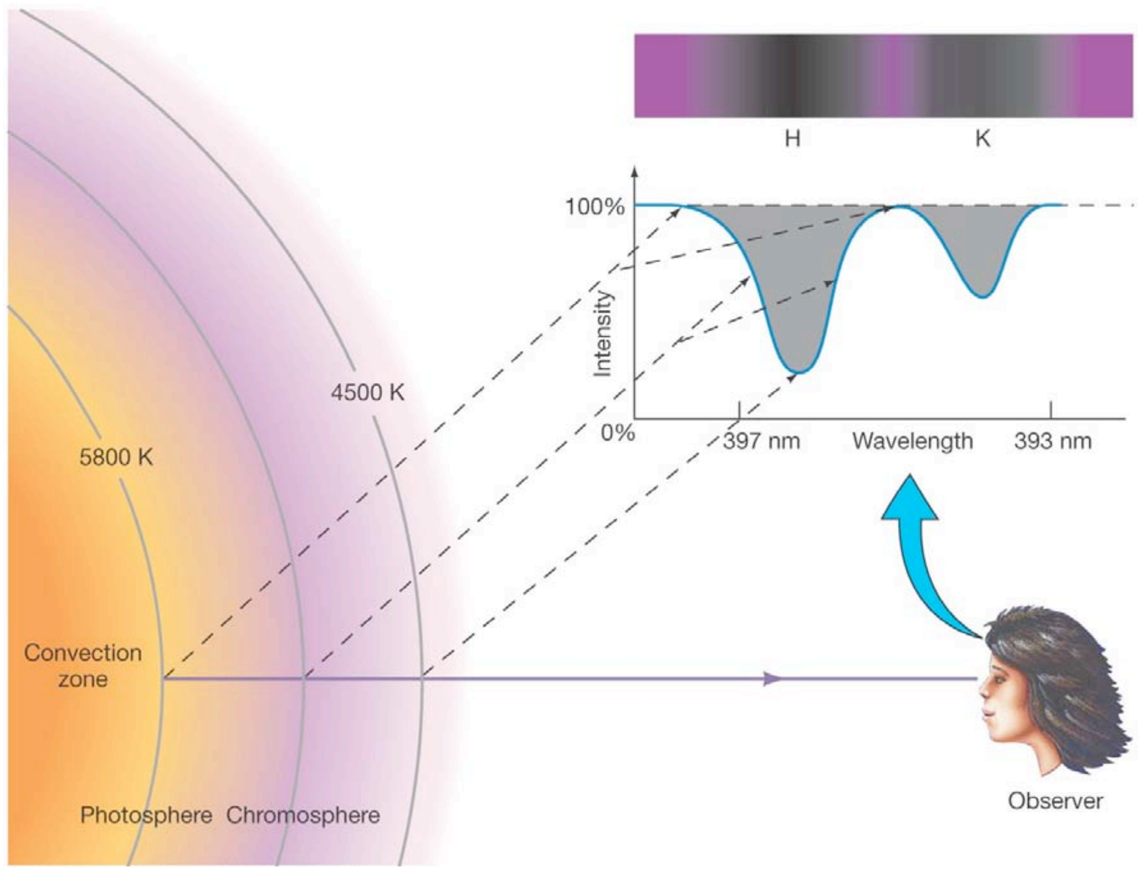
# 16.3 The Sun's Atmosphere

**Spectral analysis** can tell us what elements are present, but only in the chromosphere and (mainly) photosphere of the Sun. This spectrum has lines from 67 different elements:



# 16.3 The Sun’s Atmosphere

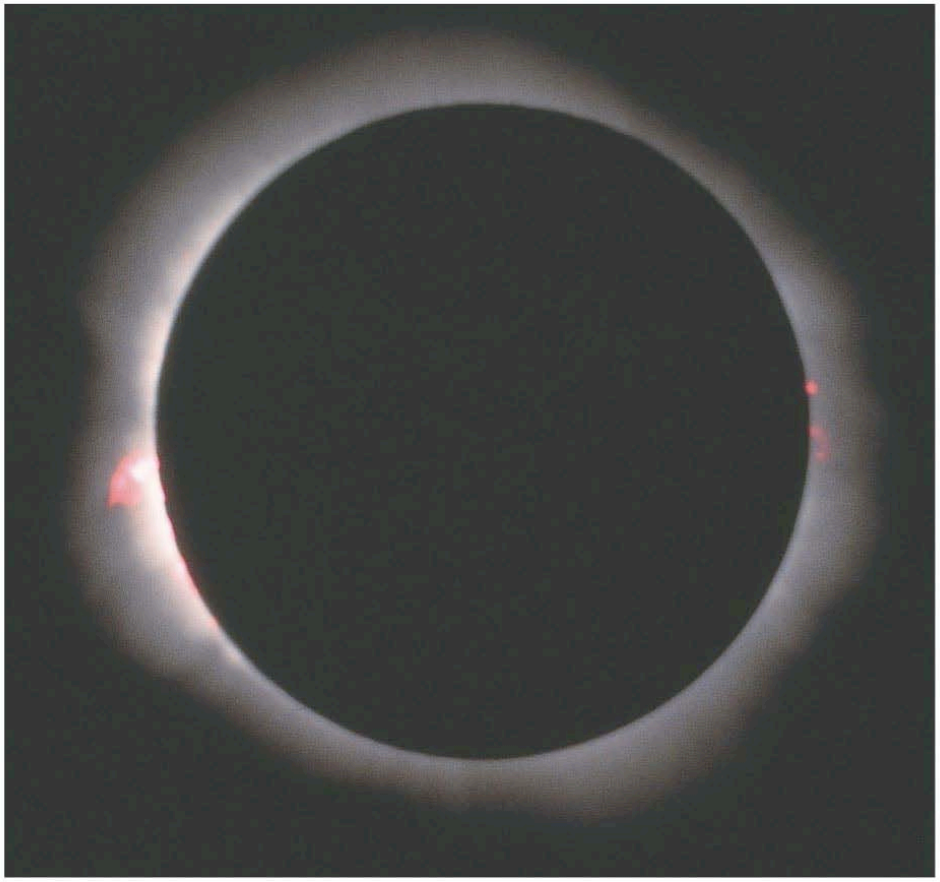
Spectral lines are formed when light is absorbed before escaping from the Sun; this happens when its energy (frequency, wavelength) is close to an atomic transition, so it is **absorbed**.

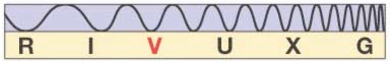


# 16.3 The Sun's Atmosphere

## The cooler chromosphere is above the photosphere.

Difficult to see directly, as photosphere is too bright, unless Moon covers photosphere and not chromosphere during eclipse:



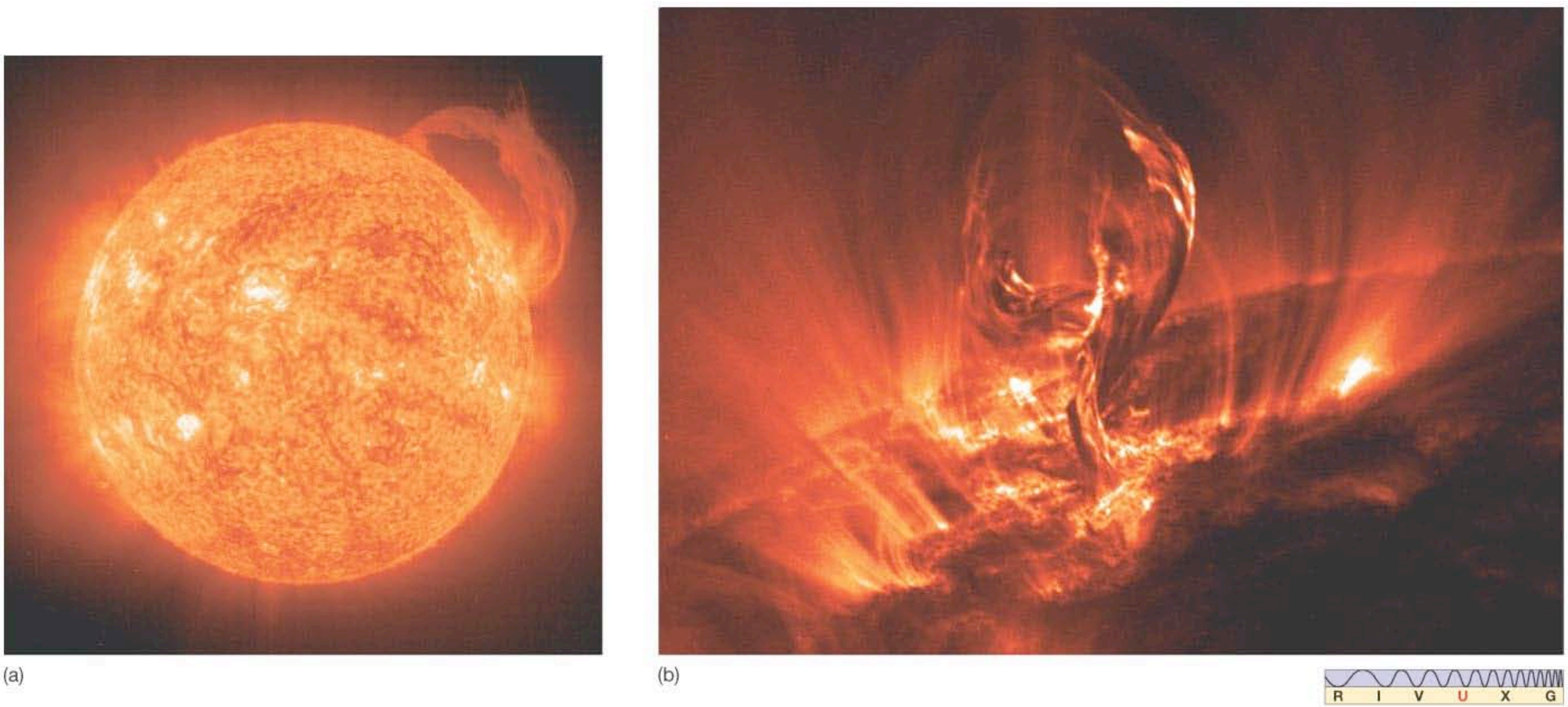


# 16.5 The Active Sun: *we are skipping all the material in 16.4 and 16.5*

But look at the pictures!

Areas around sunspots are active; large **eruptions** may occur in photosphere

**Solar prominence** is large sheet of ejected gas:




(a) (b)

# Discovery 16-2: Solar–Terrestrial Relations

Does Earth feel effects of 22-year solar cycle directly?

Possible correlations seen; cause not understood, as energy output doesn't vary much

Solar flares and coronal mass ejections ionize atmosphere, disrupting electronics and endangering astronauts

# 16.6 The Core of the Sun

Given the Sun's mass and energy production, we find that, on the average, every kilogram of the sun produces about 0.2 milliwatts of energy

This is not much—gerbils could do better— but it continues through the 10-billion-year lifetime of the Sun

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

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

# Nuclear fusion: Energy source for the sun

Why do we believe this? *Because nothing else comes close to working.* This was in fact the earliest suggestion that there must be something like quantum mechanics in order to allow to nuclei to fuse at very high temperatures.

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; if you add up the masses of the initial nuclei, you will find that it is more than the mass of the final nucleus.

# Nuclear fusion converts mass into energy

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

$$E = mc^2$$

In this equation, $c$ is the speed of light, which is a very large number.

What this equation is telling us is that a small amount of mass is the equivalent of a large amount of energy—tapping into that energy is how the Sun keeps shining so long.

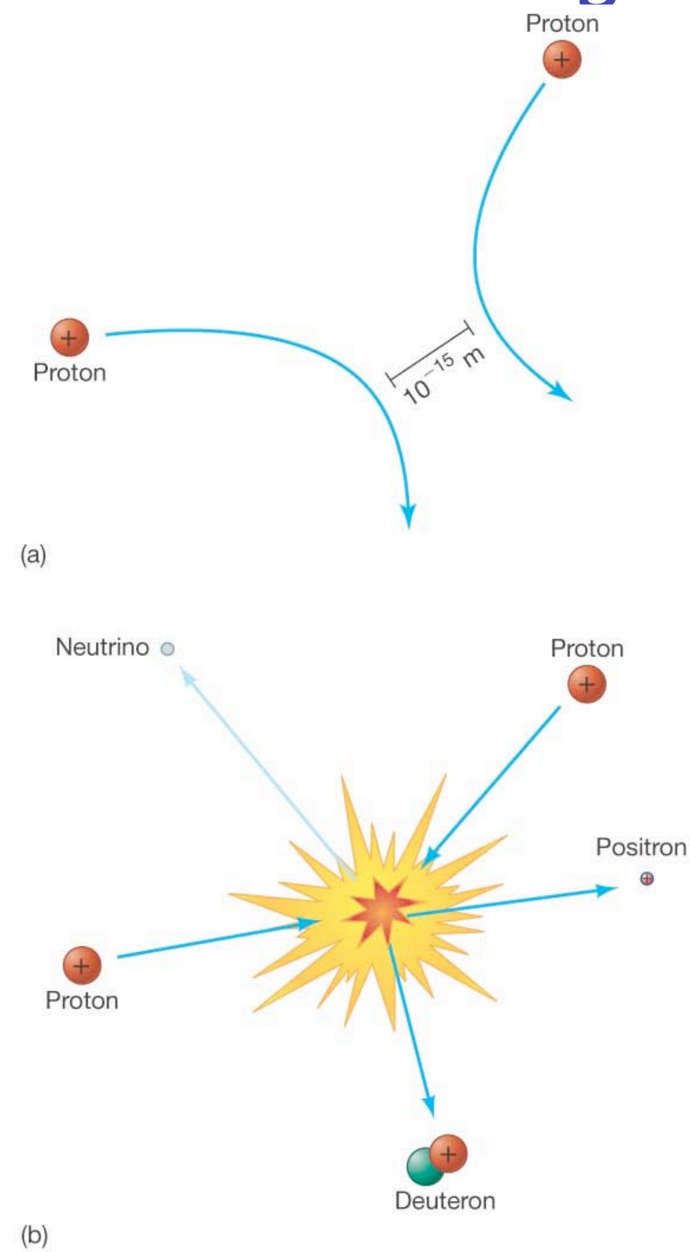
# What nuclear reactions could be occurring?

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.

But even then, only the **lightest** elements (the ones with the smallest electric charge barriers to be overcome) can undergo fusion.

The lightest elements are also the most abundant: hydrogen and helium.



# The proton-proton reaction

The previous image depicts **proton–proton** fusion. In this reaction:

proton + proton → deuteron + positron + neutrino

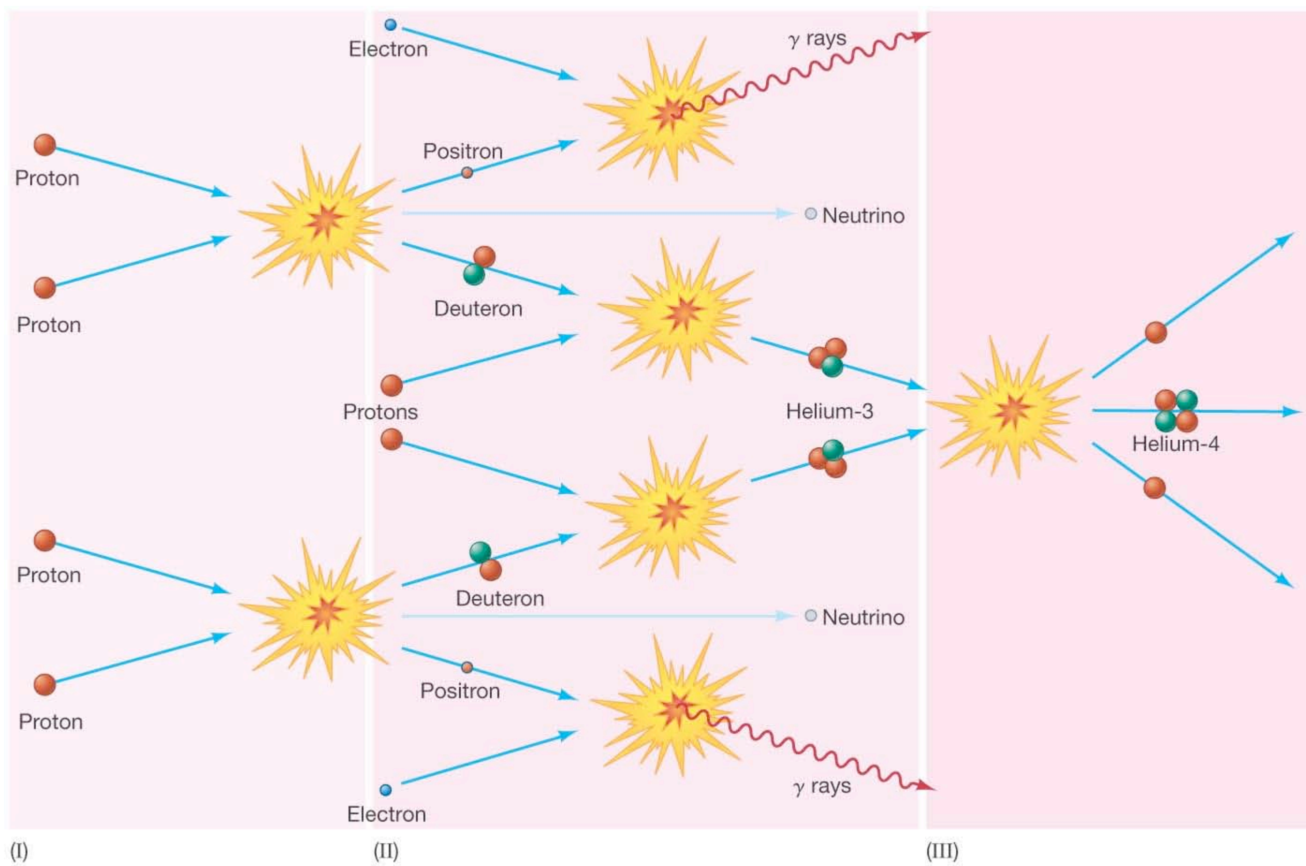
The **positron** is just like the electron except positively charged; the **neutrino** is also related to the electron but has no charge and very little, if any, mass.

In more conventional notation:

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

# Proton-proton cycle: More detail

This is the first step in a three-step fusion process that powers most stars. Study diagram to get a feel for the stages involved, but don't worry about memorizing the different reactions.



# 16.6 The Core of the Sun

The **second step** is the formation of an isotope of **helium**:

$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \text{energy}$$

The final step takes two of the **helium-3** isotopes and forms **helium-4** plus two protons:

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + {}^{1}H + {}^{1}H + \text{energy}$$

# 16.6 The Core 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 Core of the Sun

The **energy** created in the whole reaction can be calculated by the difference in mass between the initial particles and the final ones—for each interaction it turns out to be **$4.3 \times 10^{-12}$ J**.

This translates to **$6.4 \times 10^{14}$ J** per kg of hydrogen, so the 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**.

# More Precisely 16-1: Fundamental Forces

Physicists recognize four fundamental forces in nature:

1. Gravity: Very weak, but always attractive and infinite in range
2. Electromagnetic: Much stronger, but either attractive or repulsive; infinite in range
3. Weak nuclear force: Responsible for beta decay; short range (1-2 proton diameters); weak
4. Strong nuclear force: Keeps nucleus together; short range; very strong

# 16.7 Observations of Solar Neutrinos

Neutrinos are emitted directly from the core of the Sun and escape, interacting with virtually nothing. Being able to observe these neutrinos would give us a direct picture of what is happening in the core.

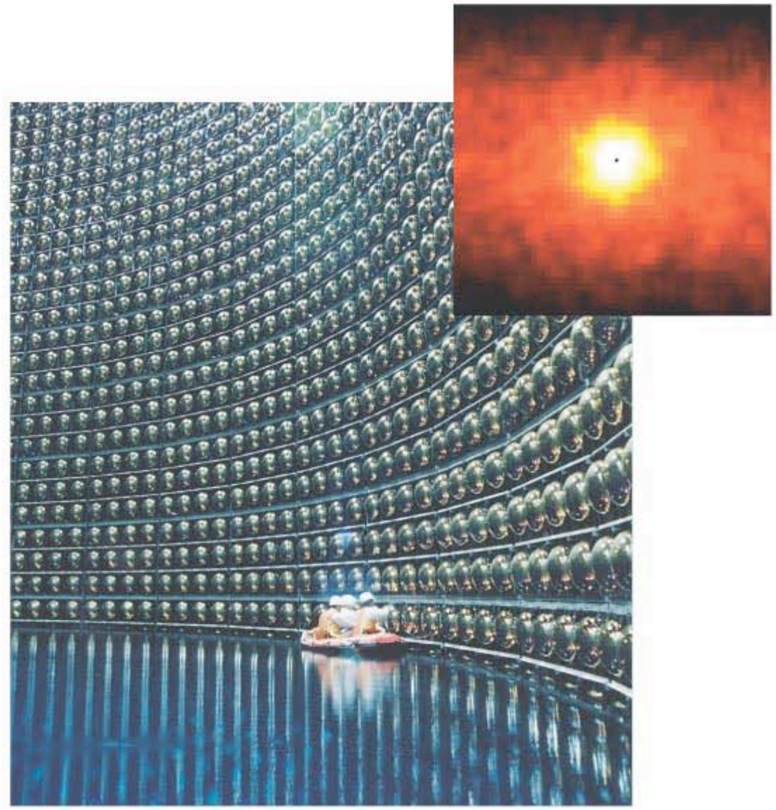
Unfortunately, they are no more likely to interact with Earth-based detectors than they are with the Sun; the only way to spot them is to have a huge detector volume and to be able to observe single interaction events.

This is the basis for the huge “neutrino observatories”, the first of which was the Ray Davies Homestead Mine. Complex “observing” procedure,no detections for many years. Either problem with experiment, or the Sun has ”turned off” its nuclear reactions in the core.

Or something else…

# 16.7 Observations of Solar Neutrinos

**Typical solar neutrino detectors; resolution is very poor**



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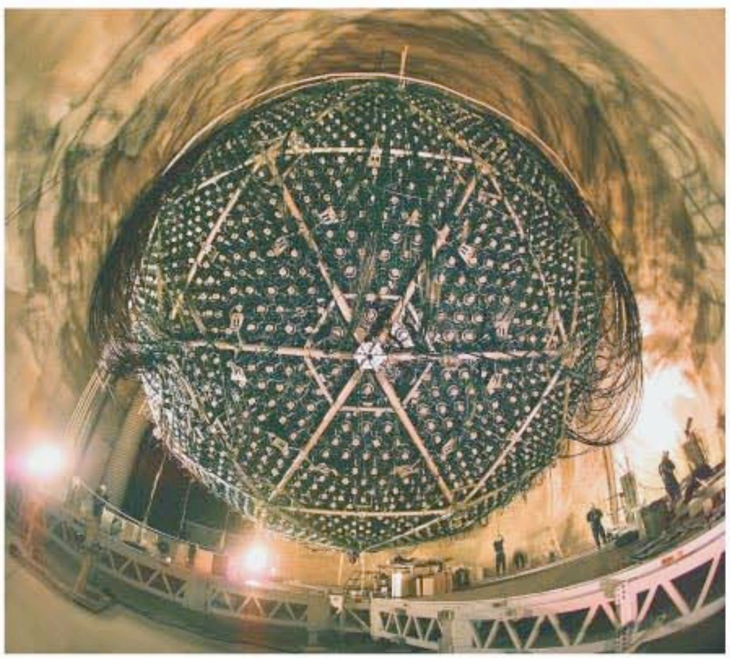

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# 16.7 Observations of Solar Neutrinos

**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

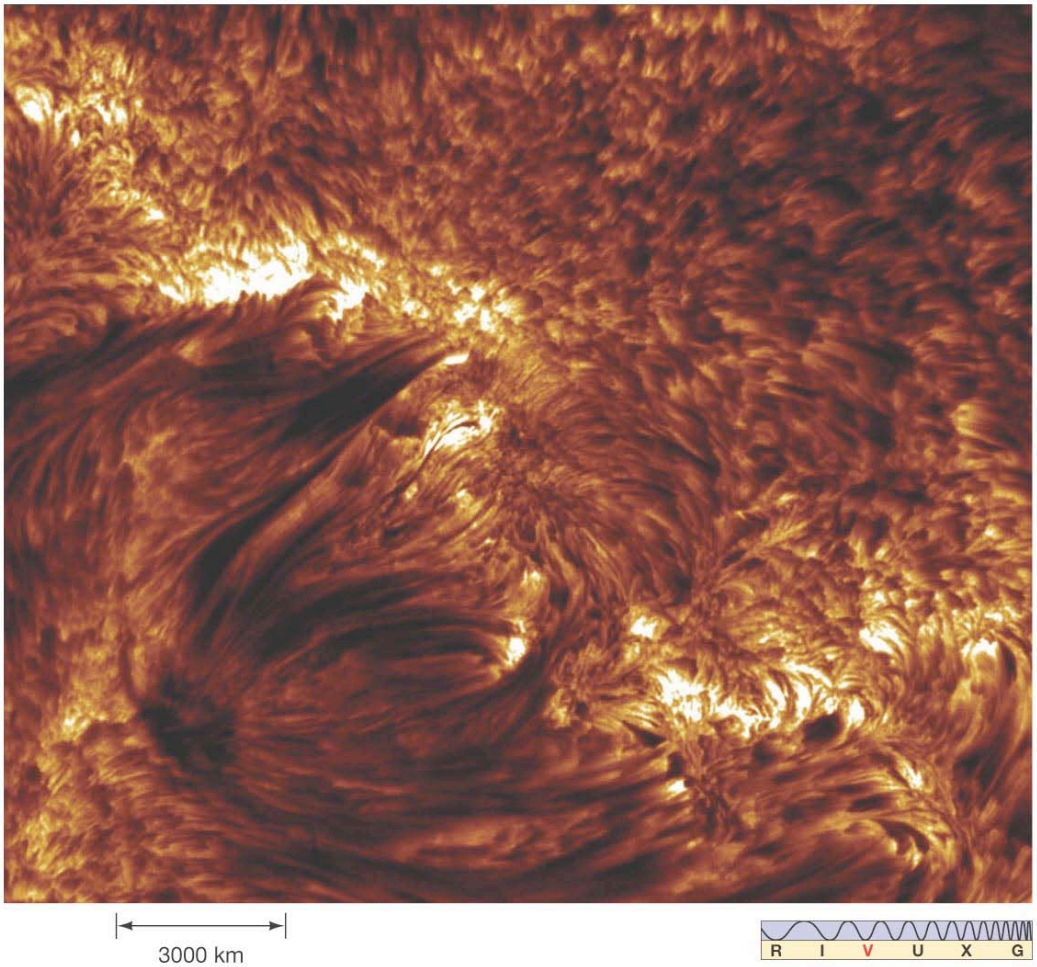
**(Items in grey are sections not covered on exam)**

- Main interior regions of Sun: core, radiation zone, convection zone, photosphere, chromosphere, transition region, corona, solar wind. (Class: We are only covering from the photosphere inward)
- Energy comes from nuclear fusion; produces neutrinos along with energy (class: *explain in words what happens in the proton-proton cycle)*
- Standard solar model is based on hydrostatic equilibrium of Sun
- Study of solar oscillations leads to information about interior
- 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 (class: *explain what that behavior is*)

**Remaining slides are from sections not covered on exam. They are included only in case you like pictures, or haven't looked through this part of the book. You ought to at least see the only star we will ever see "close up"**

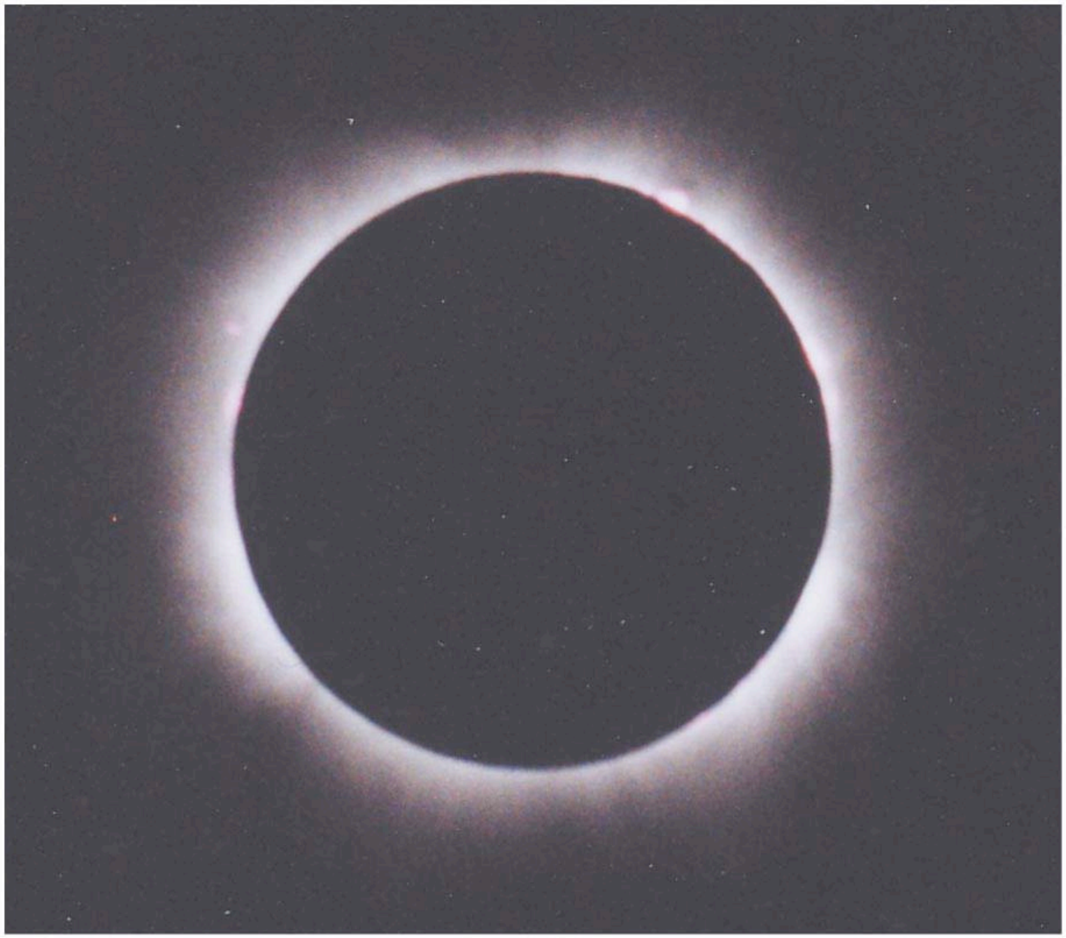
# 16.3 The Sun's Atmosphere

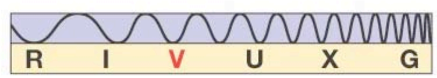
## Small solar storms in chromosphere emit **spicules**:



# 16.3 The Sun's Atmosphere

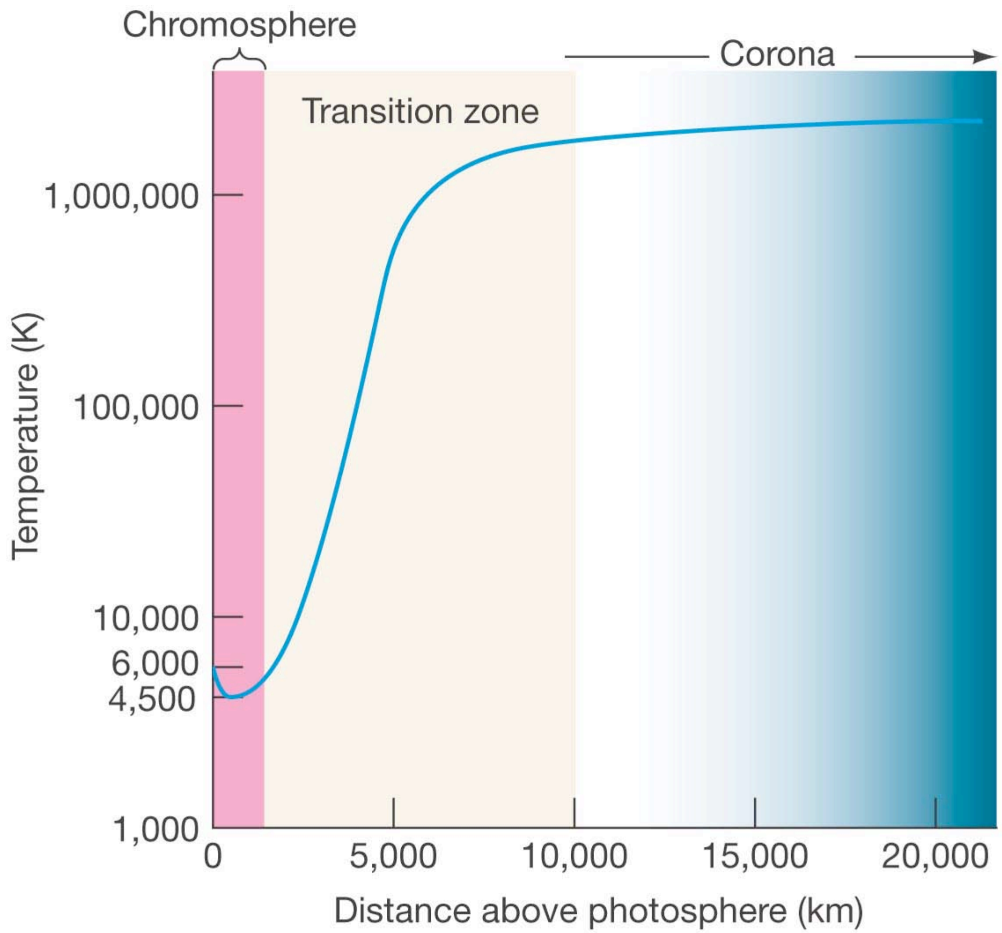
**Solar corona** can be seen during eclipse if both photosphere and chromosphere are blocked:





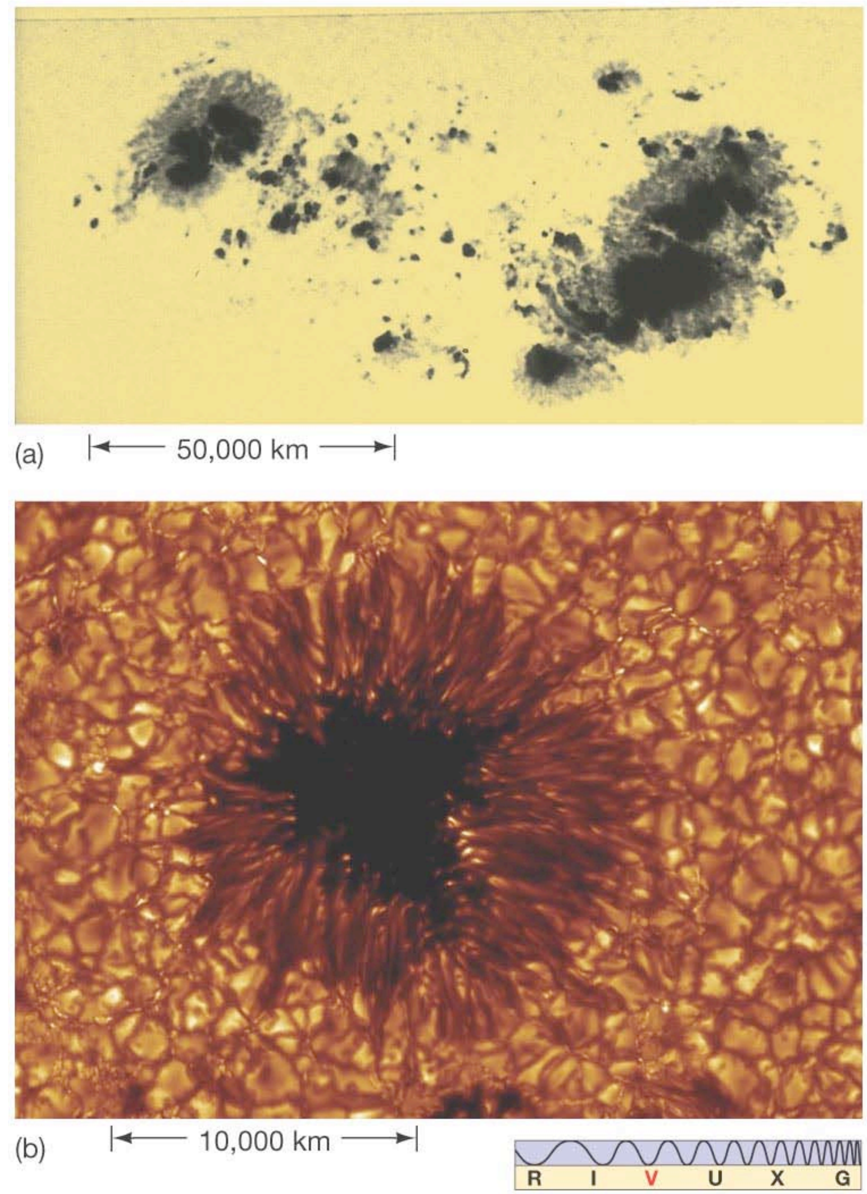
# 16.3 The Sun's Atmosphere

**Corona is much hotter than layers below it—must have a heat source, probably electromagnetic interactions**



# 16.4 Solar Magnetism

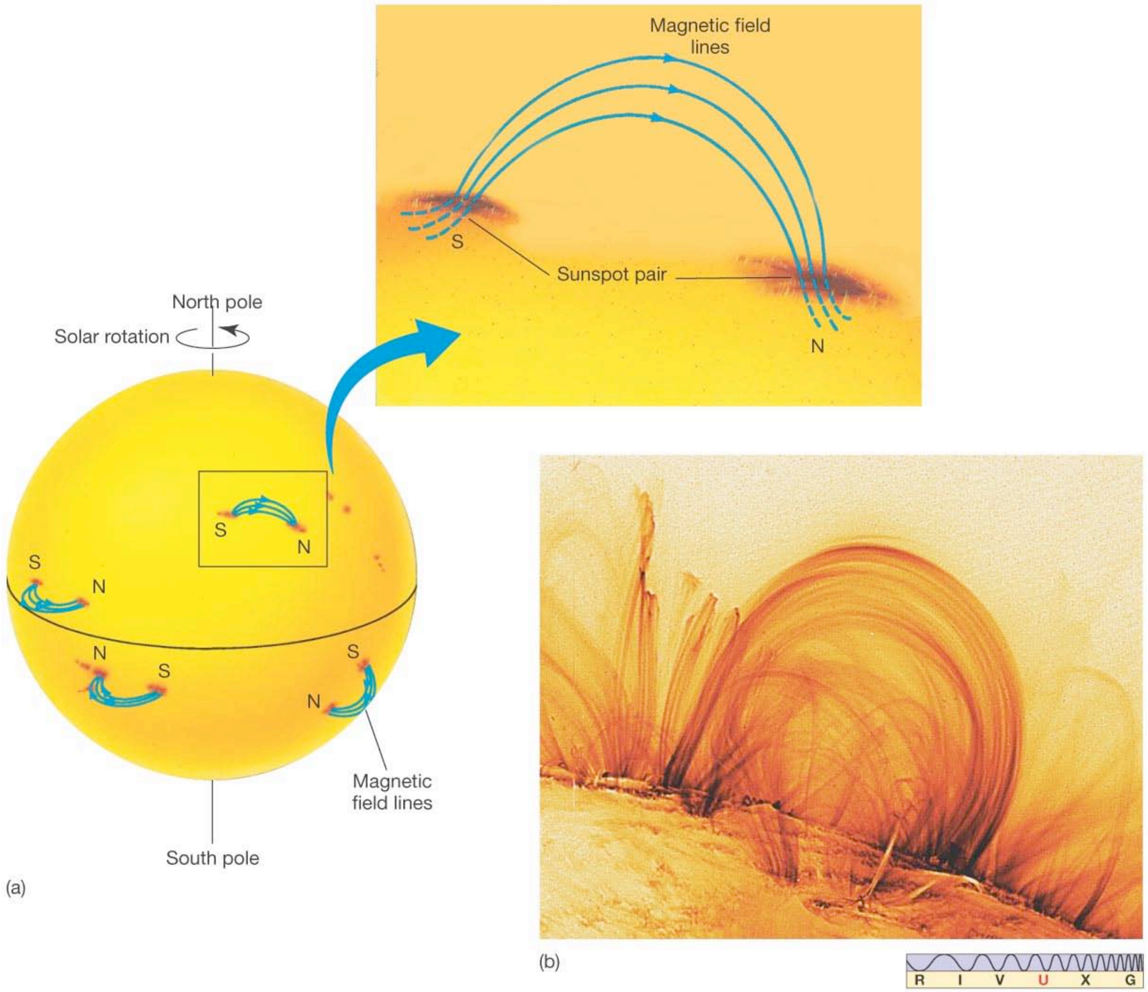
**Sunspots**: Appear dark because slightly cooler than surroundings



# 16.4 Solar Magnetism

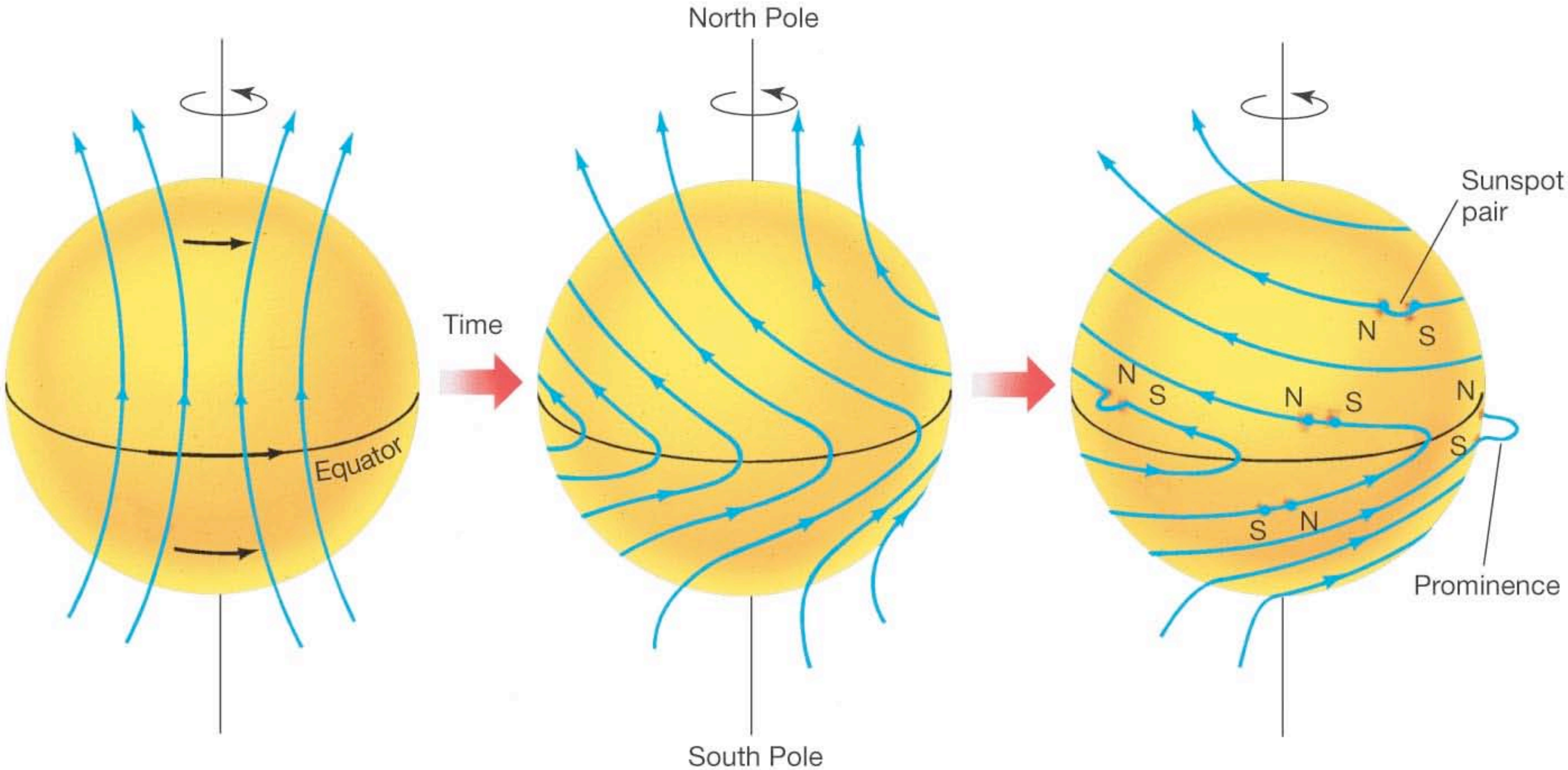
**Sunspots come and go, typically in a few days.**

**Sunspots are linked by pairs of magnetic field lines:**



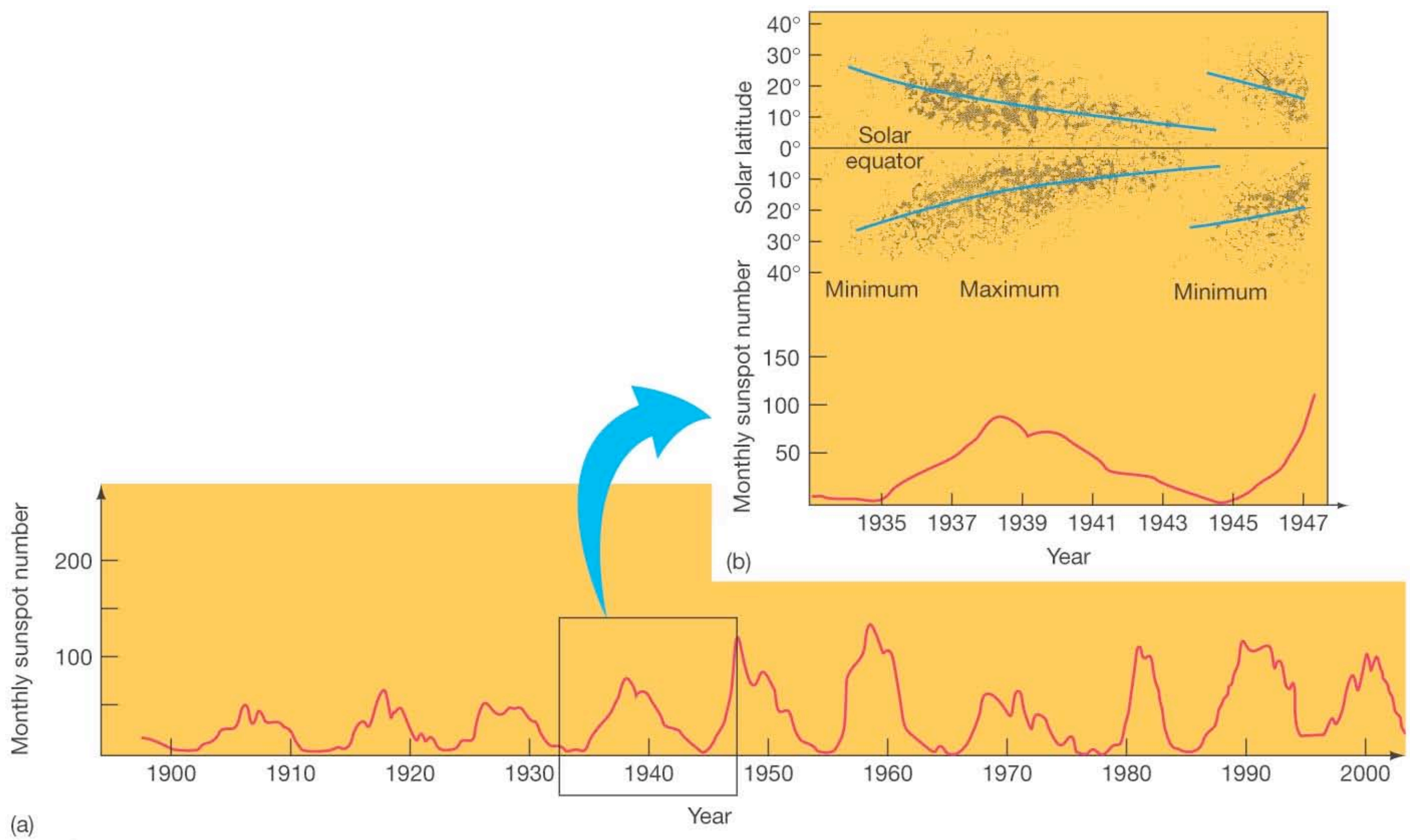
# 16.4 Solar Magnetism

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



# 16.4 Solar Magnetism

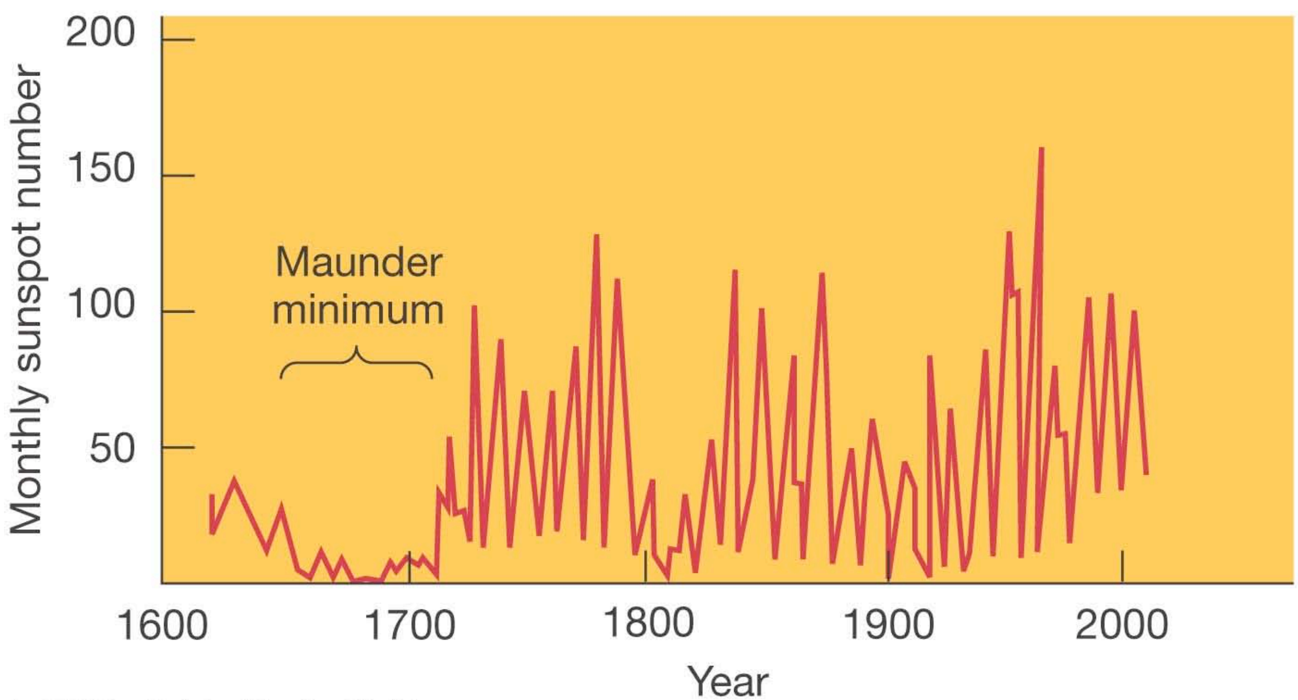
**The Sun has an 11-year sunspot cycle, during which sunspot numbers rise, fall, and then rise again.**



# 16.4 Solar Magnetism

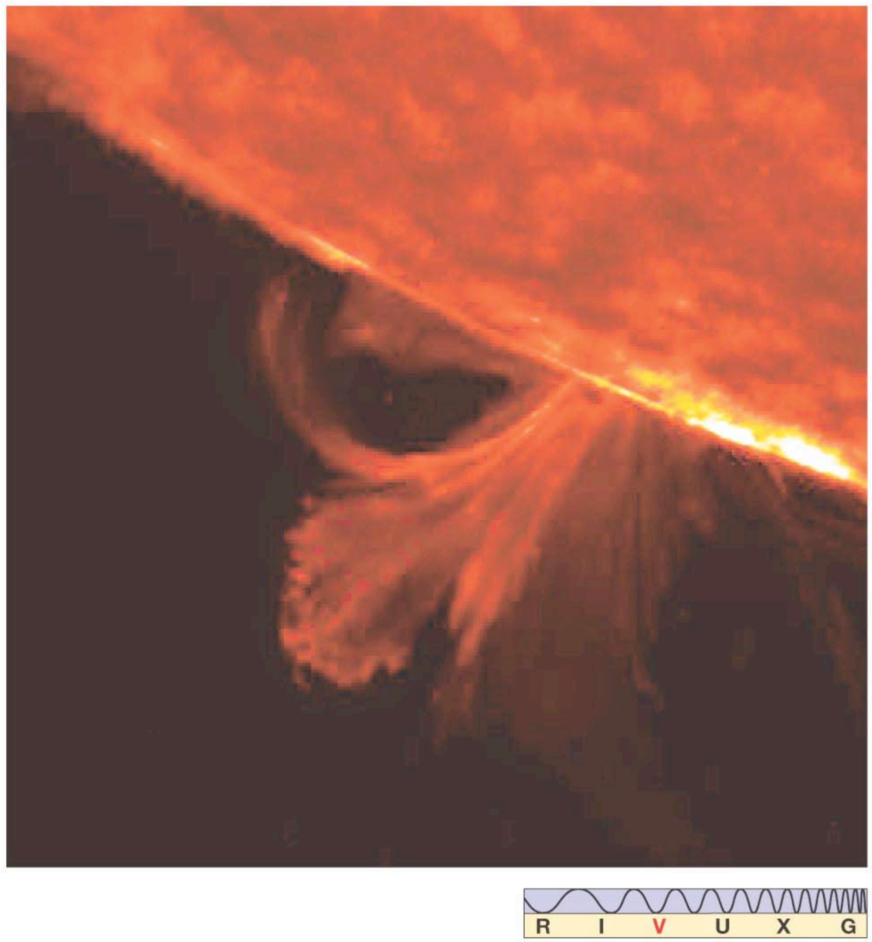
**This is really a 22-year cycle, because the spots switch polarities between the northern and southern hemispheres every 11 years.**

**Maunder minimum: Few, if any, sunspots**



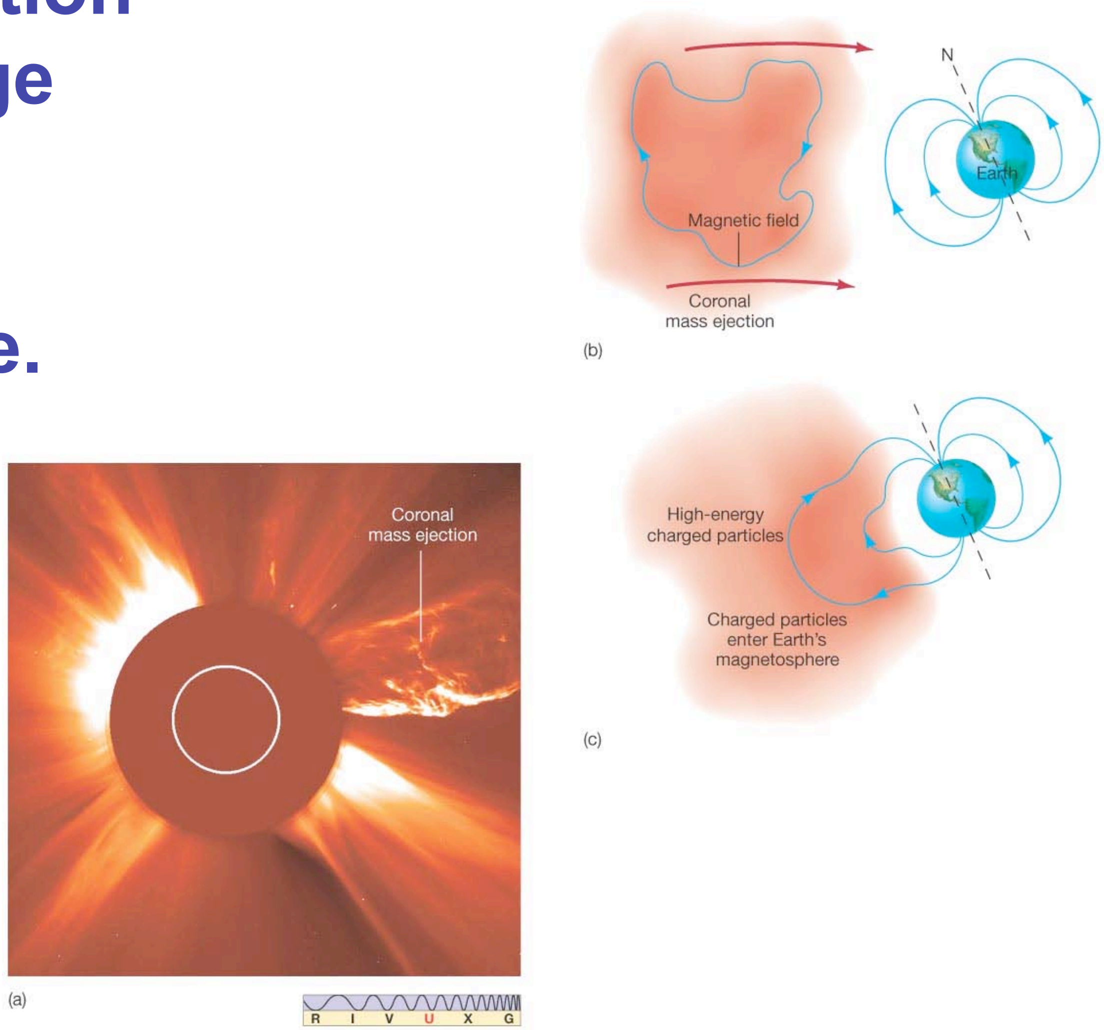
# 16.5 The Active Sun

**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:

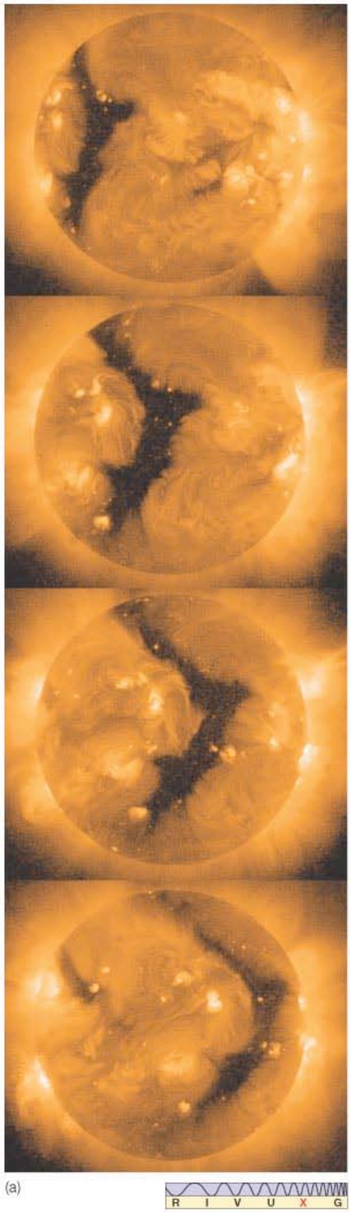


# 16.5 The Active Sun

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



# 16.5 The Active Sun

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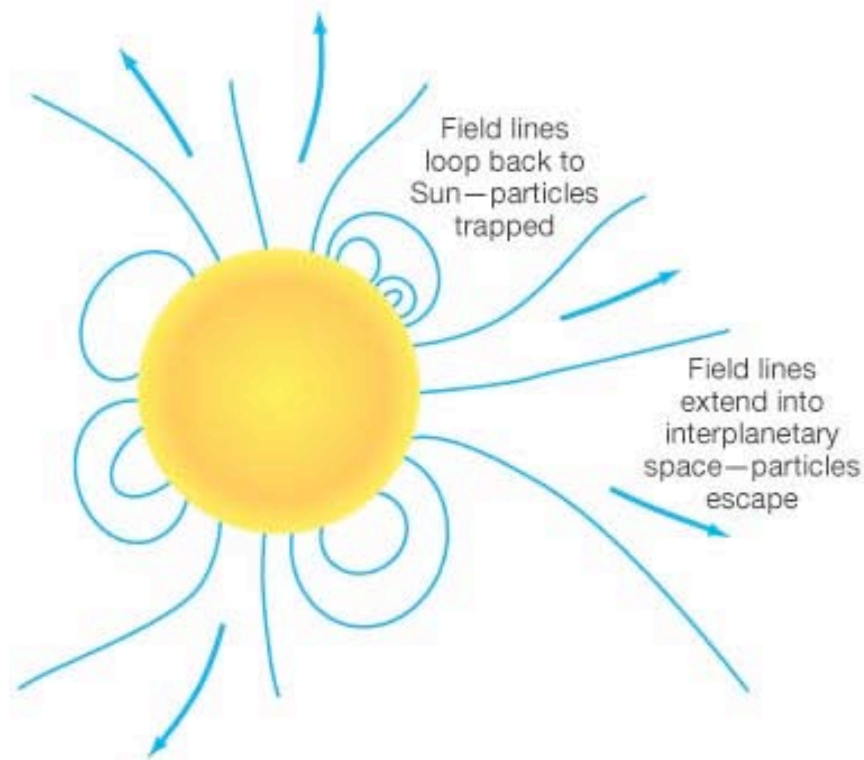


(b)

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

# 16.5 The Active Sun

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