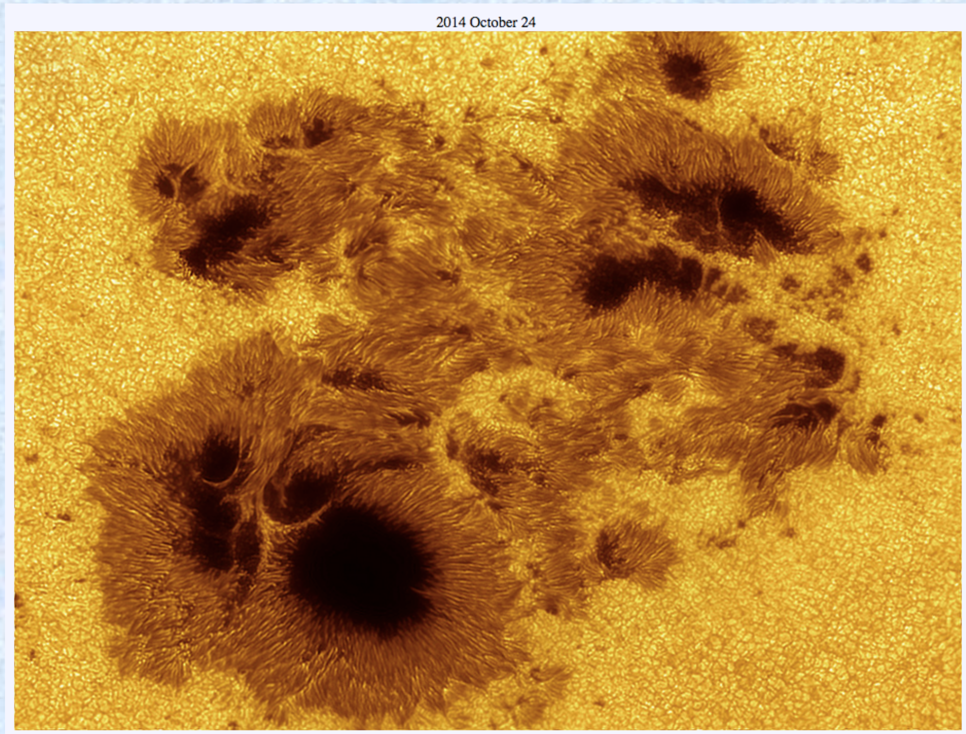
Astronomy 1 – Fall 2019



Reminder: Midterm Exam is Monday November 4th.

- Do you have your parscore form?
- Practice problems in Sections this week!

Lecture 8, October 28, 2019

Previously on Astro-1

- Properties of the Solar System.
- Properties of exoplanets and their planetary systems.
- How the Moon formed.
- How the Solar System formed.

Today on Astro-1

- The Sun: From its inner depths to the Earth
  - What holds the Sun up?
    - Internal structure
  - Why does the Sun shine?
    - How long will it shine?
    - What does it produce?
    - What are solar neutrinos?
  - Does the Sun have a surface?
    - Sunspots and the sun cycle
    - The corona
    - The solar wind

The Sun Rotates Slowly

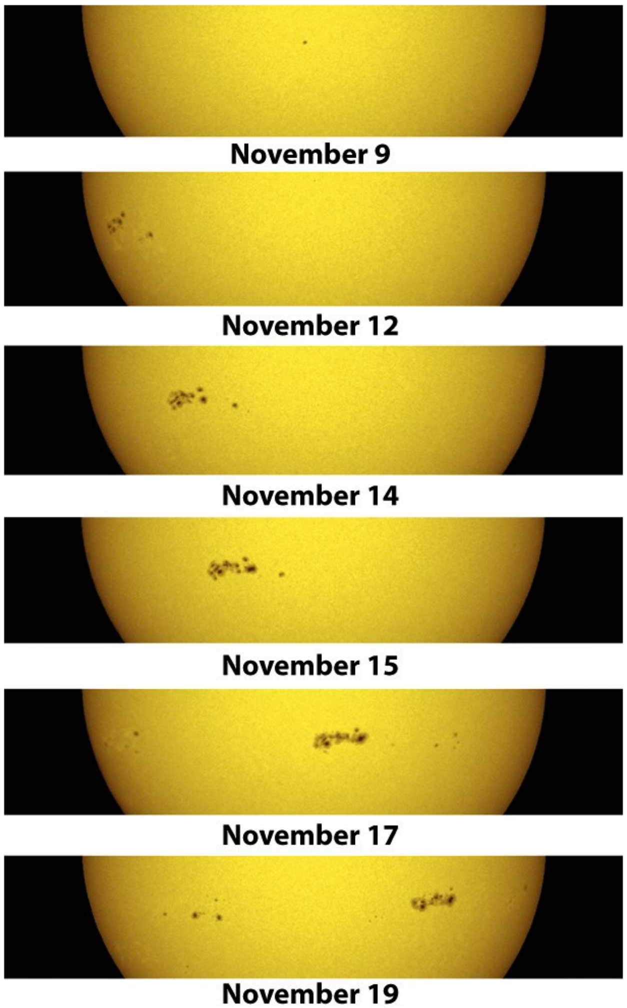


Figure 16-17
Universe, Eighth Edition

- This series of photographs taken in 1999 shows the rotation of the Sun.
- By observing the same group of sunspots from one day to the next, Galileo found that the Sun rotates once in about four weeks.
- The equatorial regions of the Sun actually rotate somewhat faster than the polar
- Regions..

The Sun is Heavy! Why Doesn't It Collapse?

TABLE 16-1 Sun Data

Distance from Earth:	Mean: 1 AU = 149,598,000 km Maximum: 152,000,000 km Minimum: 147,000,000 km
Light travel time to Earth:	8.32 min
Mean angular diameter:	32 arcmin
Radius:	696,000 km = 109 Earth radii
Mass:	1.9891×10^{30} kg = 3.33×10^{5} Earth masses
Composition (by mass):	74% hydrogen, 25% helium, 1% other elements
Composition (by number of atoms):	92.1% hydrogen, 7.8% helium, 0.1% other elements
Mean density:	1410 kg/m^3
Mean temperature:	Surface: 5800 K; Center: 1.55×10^{7} K
Luminosity:	3.9×10^{26} W
Distance from center of Galaxy:	8000 pc = 26,000 ly
Orbital period around center of Galaxy:	220 million years
Orbital speed around center of Galaxy:	220 km/s

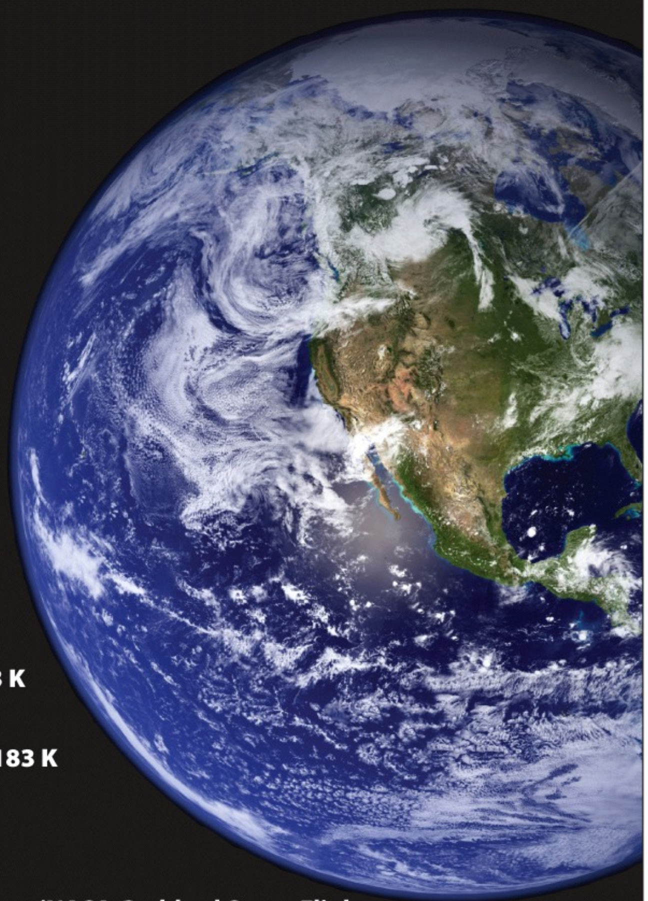
Table 16-1
Universe, Tenth Edition

The Earth is a Solid Made of Rock

It's Size is Set by the Physical Size of Atoms.

TABLE 9-1 EARTH DATA

Average distance from Sun:	1.000 AU = 1.496×10^8 km
Maximum distance from Sun:	1.017 AU = 1.521×10^8 km
Minimum distance from Sun:	0.983 AU = 1.471×10^8 km
Eccentricity of orbit:	0.017
Average orbital speed:	29.79 km/s
Orbital period:	365.256 days
Rotation period:	23.9345 hours
Inclination of equator to orbit:	23.45°
Diameter (equatorial):	12,756 km
Mass:	5.974×10^{24} kg
Average density:	5515 kg/m^3
Escape speed:	11.2 km/s
Albedo:	0.31
Surface temperature range:	Maximum: 60°C = 140°F = 333 K Mean: 14°C = 57°F ∇ 287 K Minimum: −90°C = −130°F ∇ 183 K
Atmospheric composition (by number of molecules):	78.08% nitrogen (N_2) 20.95% oxygen (O_2) 0.035% carbon dioxide (CO_2) about 1% water vapor



(NASA Goddard Space Flight Center Image by Reto Stöckli)

Table 9-1
Universe, Tenth Edition

The Sun is Made of Gas

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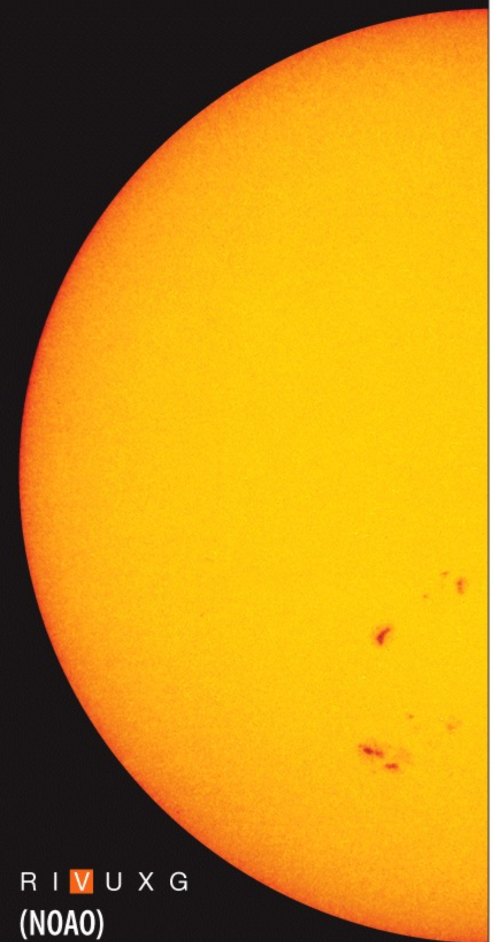
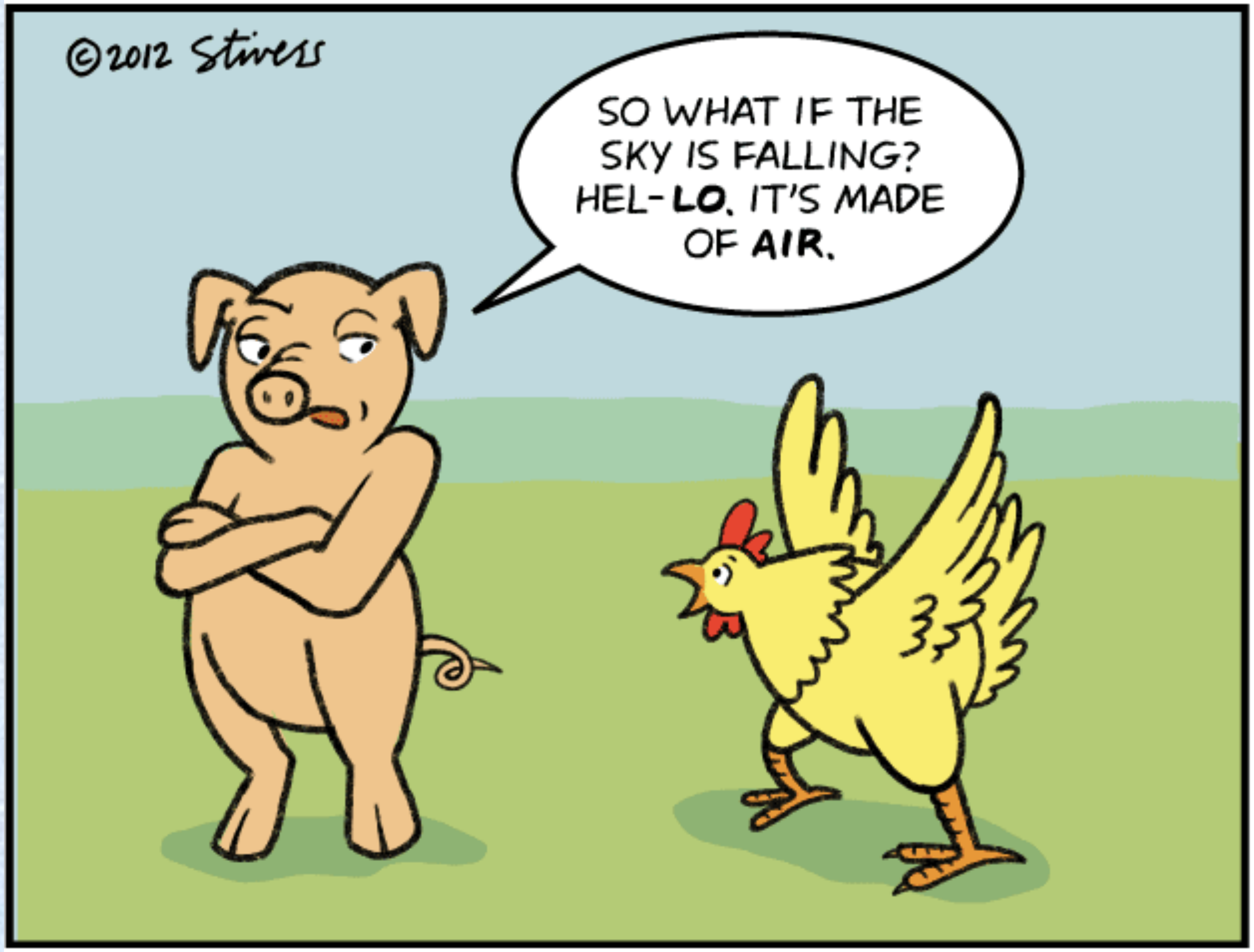
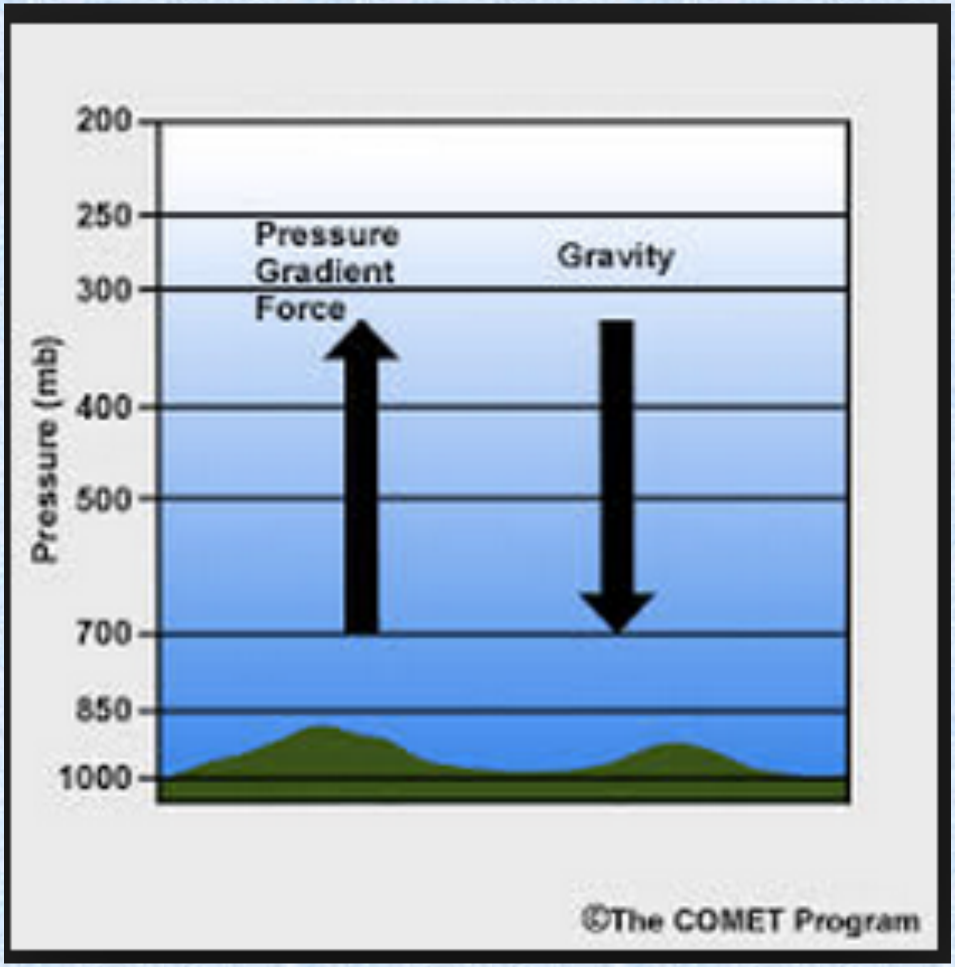


Table 16-1
Universe, Tenth Edition

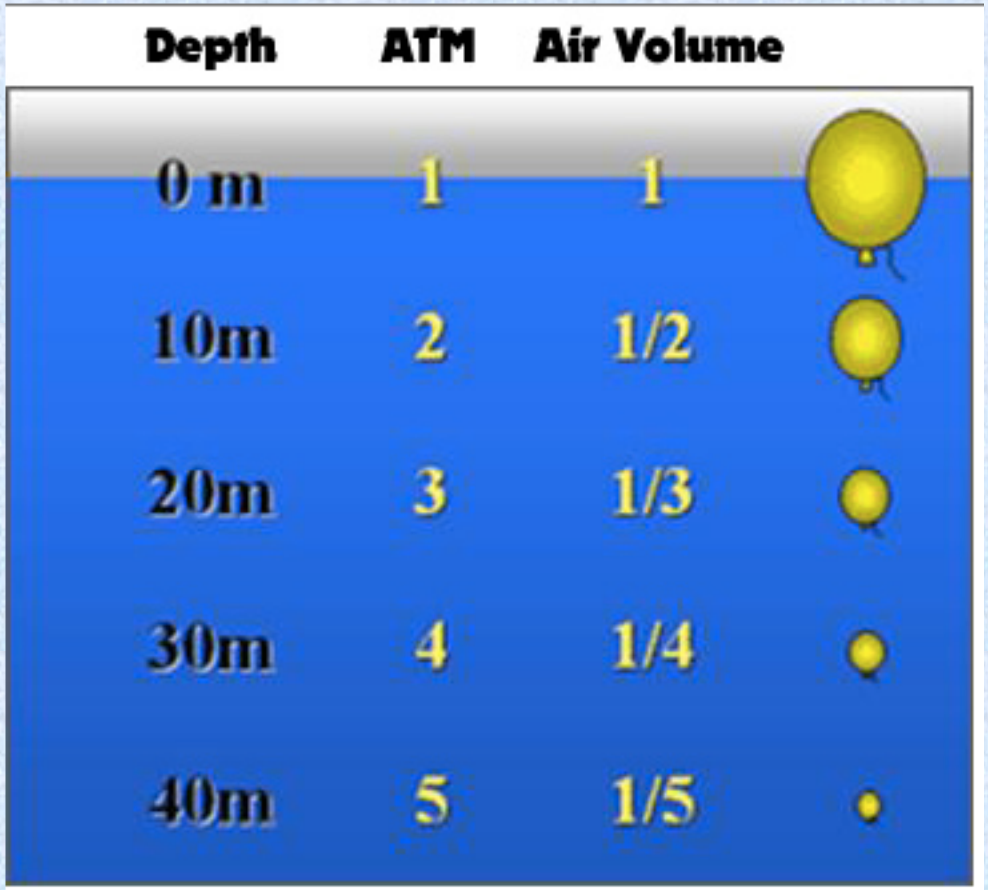
… And the Earth's Atmosphere Is Made of Gas



A Pressure Difference Holds Up the Atmosphere

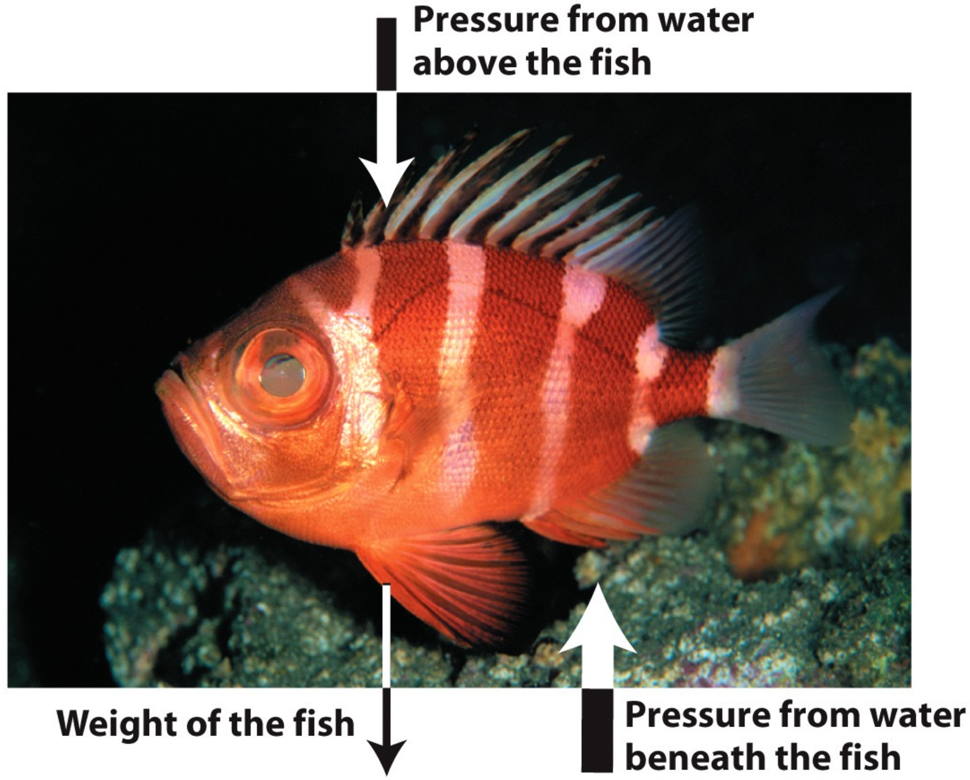


What Do You Feel When You Dive Under Water?



Pressure Difference Balances Gravity

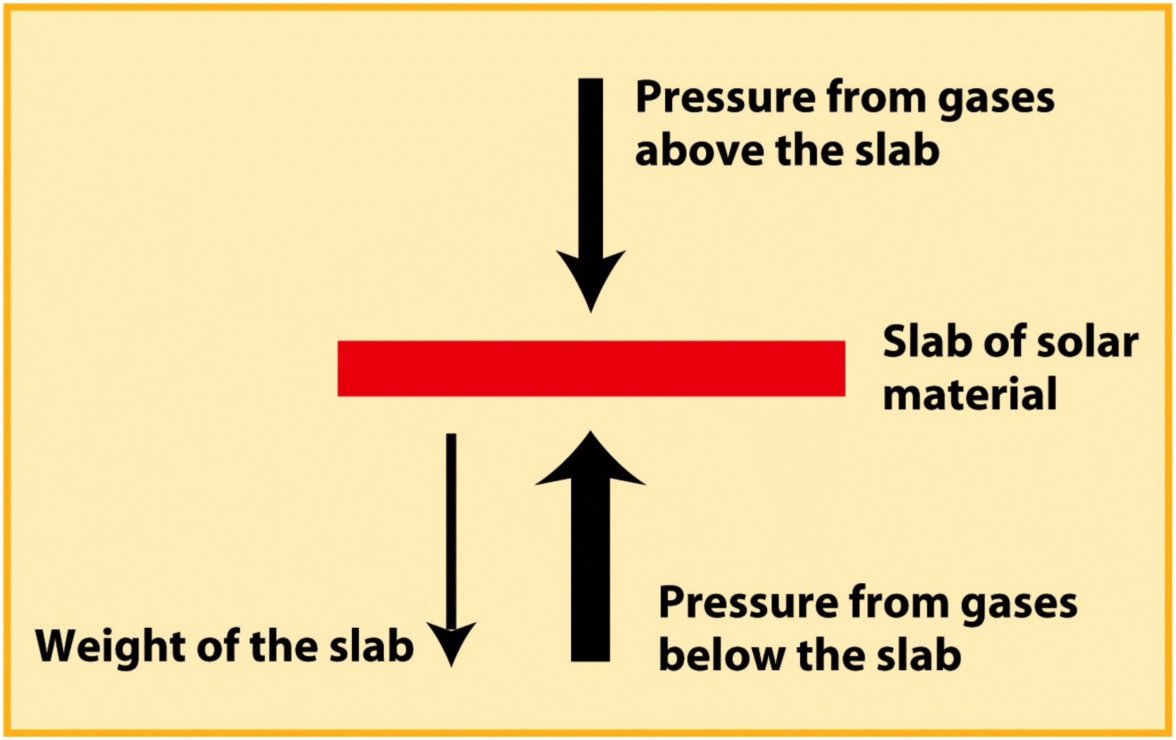
How Many Forces Act on the Fish?



A fish floating in water is in hydrostatic equilibrium, so forces balance

Figure 16-2b
Universe, Tenth Edition
Ken Usami/PhotoDisc

A Pressure Gradient Holds the Sun in Hydrostatic Equilibrium



Material inside the sun is in hydrostatic equilibrium, so forces balance

Figure 16-2a
Universe, Eighth Edition

Why is the Sun Hot?

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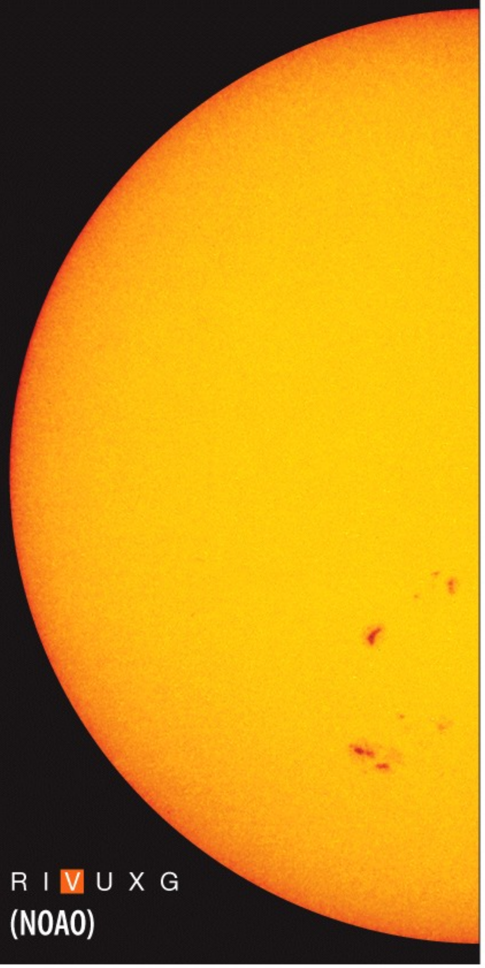


Table 16-1
Universe, Tenth Edition

Model of the Sun

Note: We've said nothing about nuclear reactions!

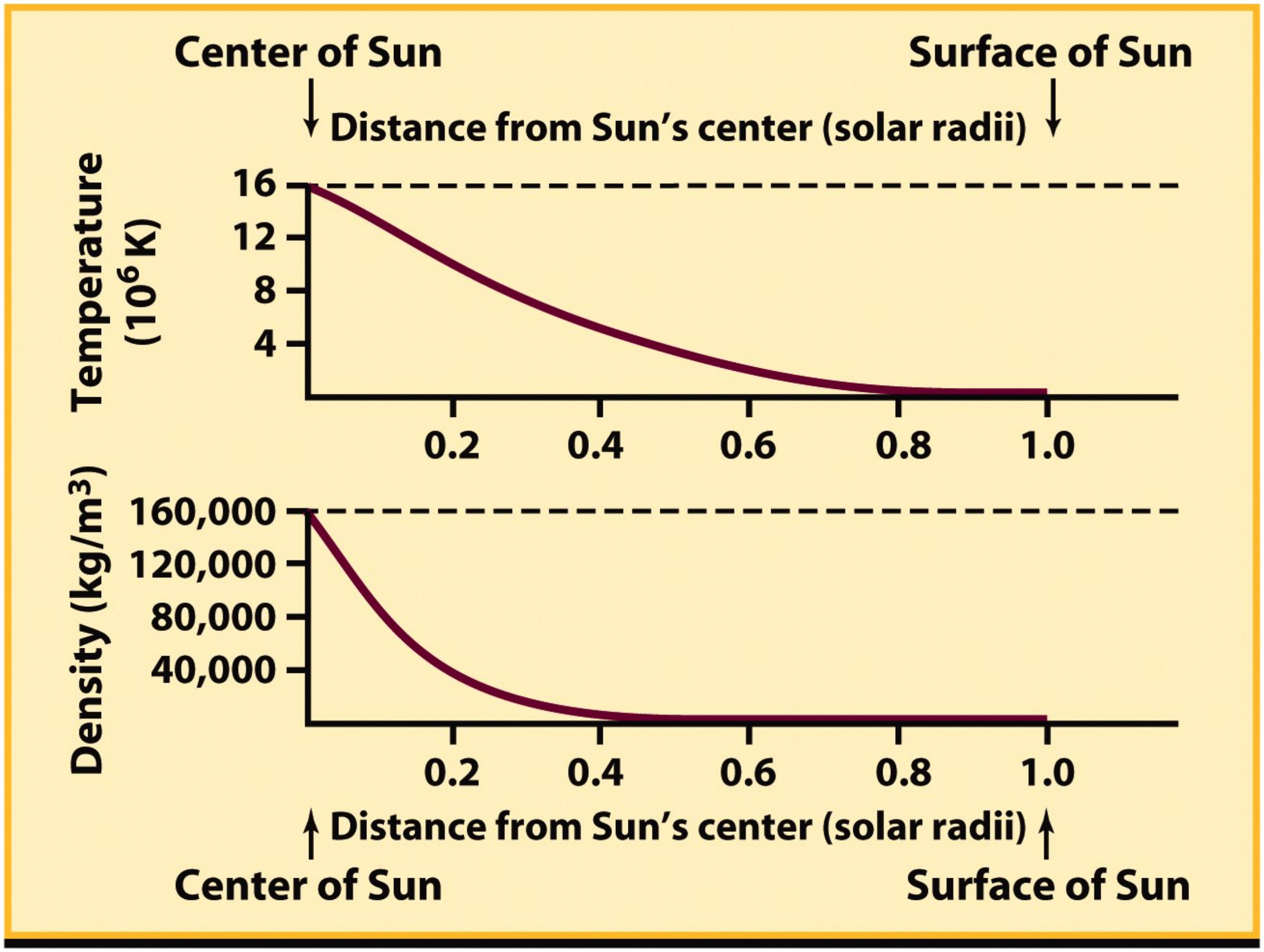


Figure 16-3 part 2
Universe, Eighth Edition

Structure of the Sun

TABLE 16-2 A Theoretical Model of the Sun

Distance from the Sun's center (solar radii)	Fraction of luminosity	Fraction of mass	Temperature ($\times 10^6$ K)	Density (kg/m^3)	Pressure relative to pressure at center
0.0	0.00	0.00	15.5	160,000	1.00
0.1	0.42	0.07	13.0	90,000	0.46
0.2	0.94	0.35	9.5	40,000	0.15
0.3	1.00	0.64	6.7	13,000	0.04
0.4	1.00	0.85	4.8	4,000	0.007
0.5	1.00	0.94	3.4	1,000	0.001
0.6	1.00	0.98	2.2	400	0.0003
0.7	1.00	0.99	1.2	80	4×10^{-5}
0.8	1.00	1.00	0.7	20	5×10^{-6}
0.9	1.00	1.00	0.3	2	3×10^{-7}
1.0	1.00	1.00	0.006	0.00030	4×10^{-13}

Note: The distance from the Sun's center is expressed as a fraction of the Sun's radius ($R_\odot$). Thus, 0.0 is at the center of the Sun and 1.0 is at the surface. The fraction of luminosity is that portion of the Sun's total luminosity produced within each distance from the center; this is equal to 1.00 for distances of 0.25 $R_\odot$ or more, which means that all of the Sun's nuclear reactions occur within 0.25 solar radius from the Sun's center. The fraction of mass is that portion of the Sun's total mass lying within each distance from the Sun's center. The pressure is expressed as a fraction of the pressure at the center of the Sun.

Table 16-2
Universe, Tenth Edition

- The Sun's structure changes slowly over time.

Contraction Generates Heat

- If we push on a gas to compress it, it will heat up because we've done work on it.
- A gas must do work on its surroundings in order to expand, so it will cool down.

- Contraction of a protostellar cloud heats it up.
- Contraction stops when hydrostatic equilibrium is reached.

- The Sun shines because it's surface is hot and opaque.
  - *Note that the Sun would shine regardless of whether there were nuclear reactions in the Sun.*
  - *Consider 'failed stars' without nuclear reactions.*

Failed Stars Shine

They Just Don't Fuse H into He

- A gas cloud less massive than the Solar Nebula collapses until the density becomes so high that the particles are touching. Then the particles hold up the object in a manner similar to a solid, and no further collapse occurs.
- The resulting object is hot. Its surface radiates like a blackbody at 8000 to 1800 K.
- The central temperature can be as high as a million degrees. Hot, but not hot enough to burn H by the proton – proton chain.
- We call these objects Brown Dwarfs. They would have become stars if they'd been slightly more massive.

Why Do We Think the Sun is Powered by Nuclear Fusion Then?

- In the mid-1800s, Lord Kelvin and Hermann von Helmholtz calculated how long it would take the Sun to lose the heat generated from its contraction.
- The Sun loses its heat through radiation at its surface.
  - Time = (Work done by gravity) / (Solar Luminosity)
  - Time = 25 million years
  - Great mystery of the 19^{th} century.
- Why is this timescale a problem?
  - Sun must be roughly 4.5 billion years old.
    - Moon rocks form most heavily cratered regions are 4.5 billion years old.
    - Most meteorites are 4.54 billion years old.
    - Oldest rocks on earth are also close to 4.5 Gyr.

Hydrogen Fusion Keeps the Sun Hot Over Billions of Years

In the early 20th century, ideas from relativity and nuclear physics led to an understanding of how fusion releases energy.

Where does the energy in this equation come from?

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

Einstein says that a mass 'm' is converted to an energy E according to

$$E = m\,c^2.$$

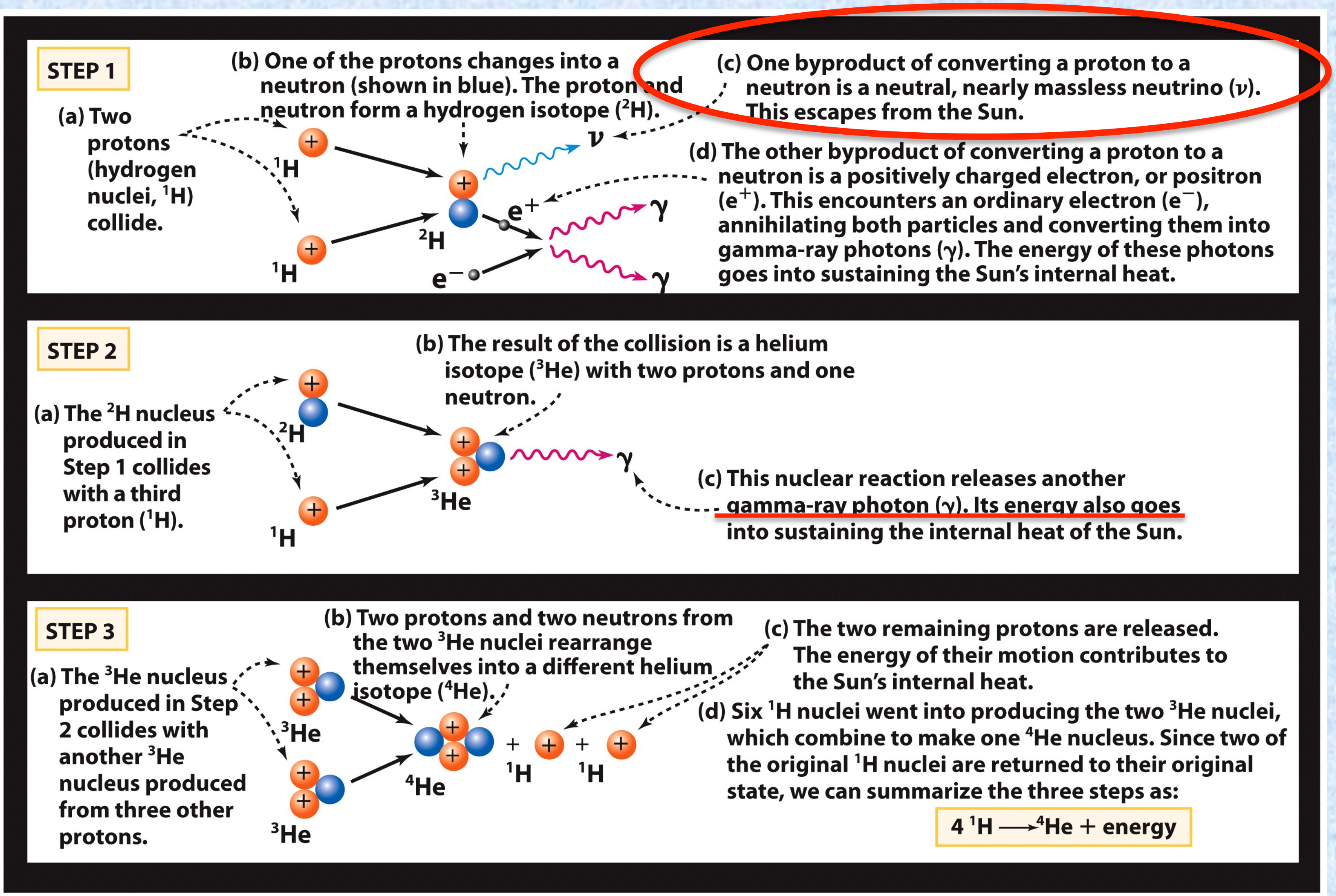
Evaluate the mass difference

$$m = 4\ m_H - m_{He} = 0.048 \times 10^{-27}\ \text{kg}$$

and find the energy released

$$E = (0.048 \times 10^{-27}\ \text{kg})\ c^2 = 4.3 \times 10^{-12}\ \text{joule.}$$

The Proton-Proton Chain



Cosmic Connections 16b
Universe, Tenth Edition

Prediction: Solar Neutrinos

About 10^{14} neutrinos must pass through every square meter of Earth each second

.

Detect the flashes of light they make when they interact with a big tank of water deep underground.

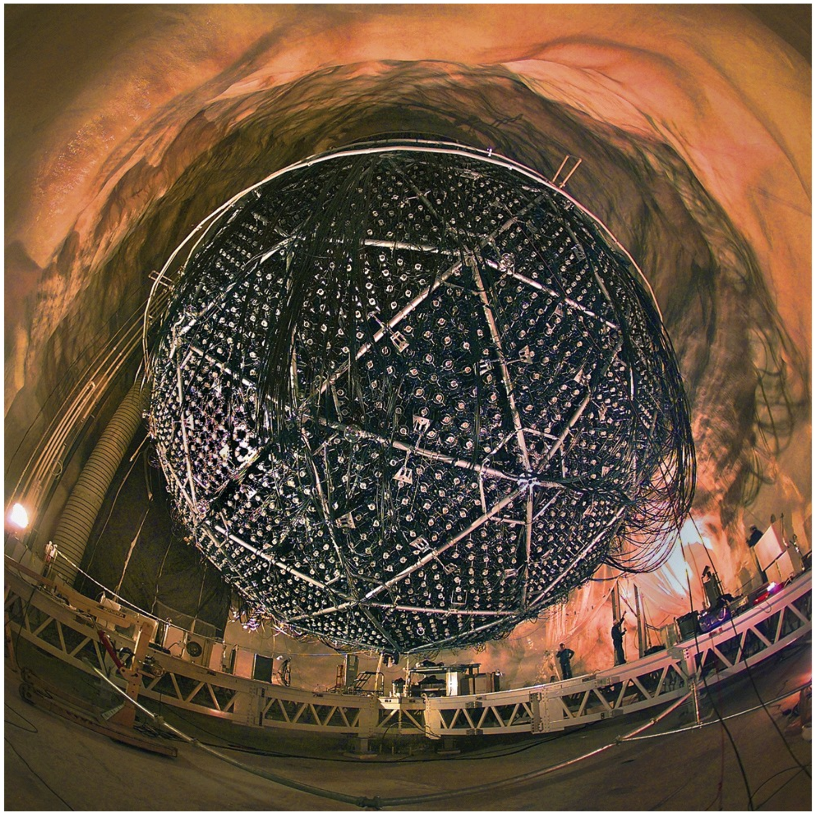


Figure 16-6
Universe, Tenth Edition
Science Source

Energy Production in the Sun

Thermonuclear reactions can only occur in the Sun's core — that's the only place where pressures and temperatures are high enough

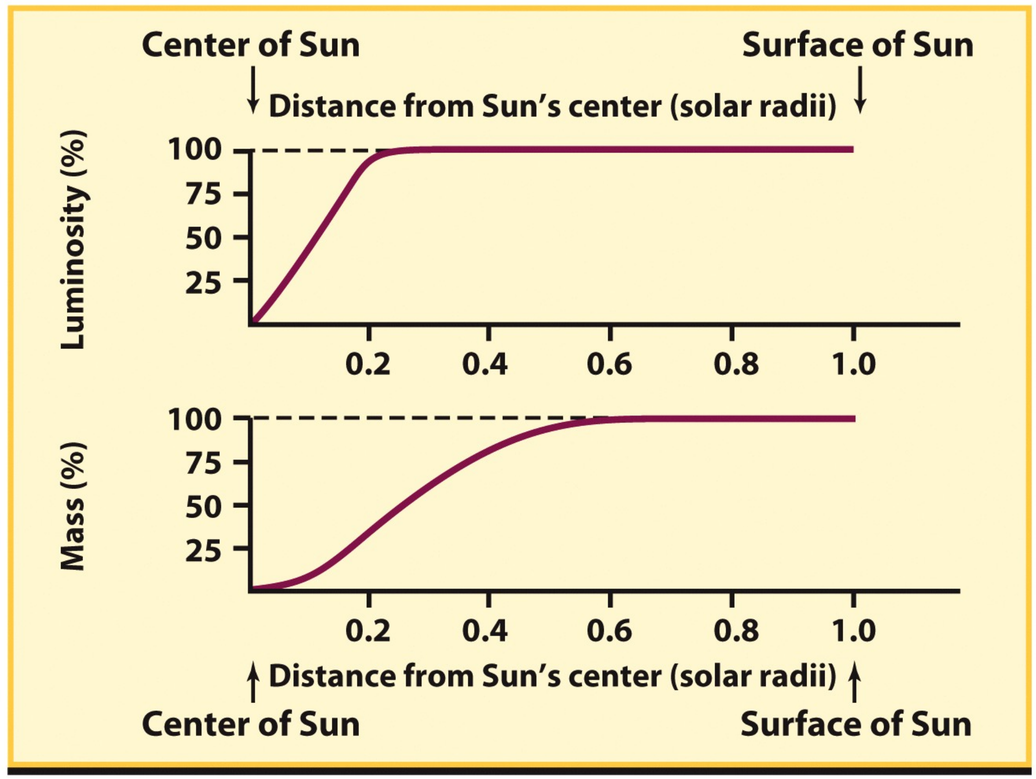
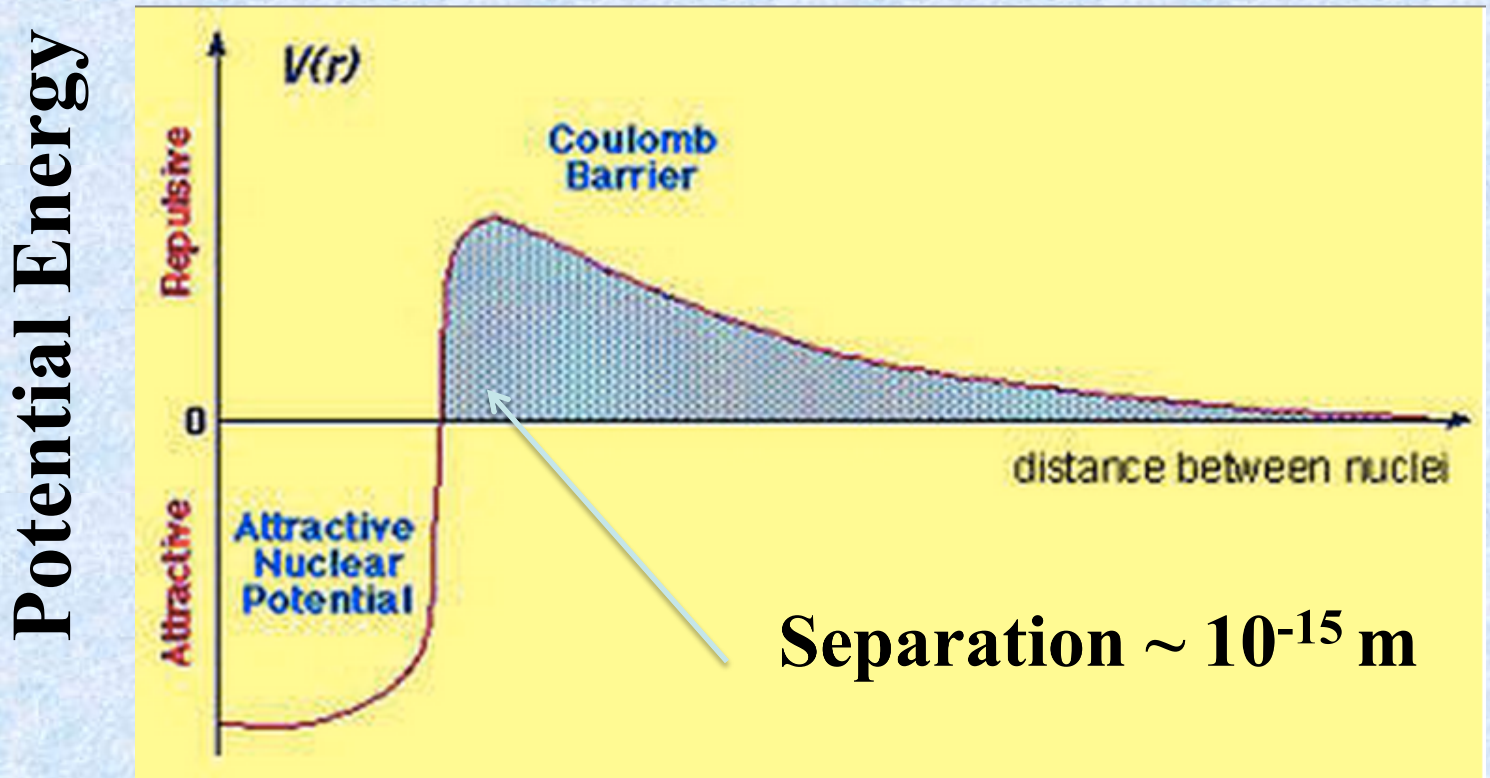


Figure 16-3 part 1
Universe, Tenth Edition

Hydrogen Fusion Requires High Temperature

High Temperatures are Required to Overcome the Repulsion of Two Positively Charged Particles.



Where Does the Sun's Energy Come From? (iClicker Question)

A. Nuclear fusion in the center of the Sun creates new energy. Energy is not conserved.

B. Nuclear fusion converts mass into energy in the center of the Sun. A ^{4}He nucleus is a bit less massive than four H nuclei.

C. Nuclear fusion converts energy into mass in the center of the Sun. A ^{4}He nucleus is a bit more massive than four H nuclei.

D. Nuclear fission in the center of the Sun

E. Nuclear fission near the surface of the Sun.

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E. Nuclear fission near the surface of the Sun.

The Sun is hot because …
(iClicker Question)

A. It is made of fire.
B. Nuclear reactions make it hot.
C. The average density is low, so the average temperature must be high to produce enough pressure to hold up its weight.
D. It is hot due to the contraction of the pre-solar nebula.
E. Both C & D.

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D. It is hot due to the contraction of the pre-solar nebula.
E. Both C & D.

How do the electron and the neutrino differ?

A. There is no difference between them.
B. The neutrino has no charge, a much smaller mass than the electron, and interacts weakly with matter.
C. The neutrino has no charge, a mass the same as the electron, and interacts weakly with matter.
D. The neutrino has the same charge and mass as an electron, and interacts weakly with matter.
E. The neutrino has no charge, a much smaller mass than the electron, and interacts strongly with matter.

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The Interior of the Sun Emits Gamma Rays
Why does the photosphere emit optical light?

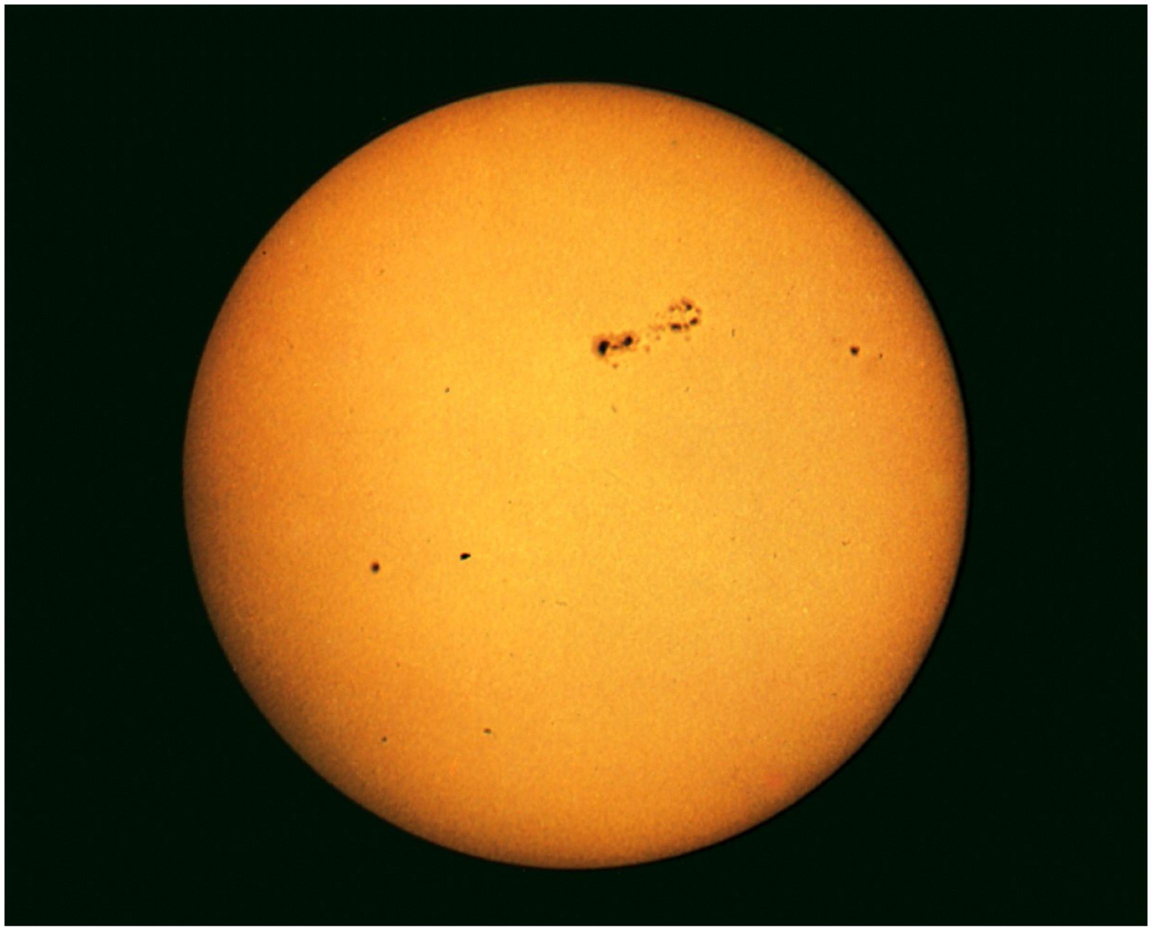

Figure 16-7
Universe, Eighth Edition

The energy produced in the central core of the Sun is transported to the surface

A. by radiation in the layers just outside the central core and by convection in the outer layers.

B. by convection in the layers just outside the central core and by radiation in the outer layers.

C. by convection from just outside the central core all the way to the surface.

D. by radiation from just outside the central core all the way to the surface.

E. only by convection.

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C. by convection from just outside the central core all the way to the surface.

D. by radiation from just outside the central core all the way to the surface.

E. only by convection.

How Does the Heat Get Out of the Sun?

- The Sun is very massive. It's a really good blanket.
- It takes light about 200,000 years to get from the core to the surface.
- Photon leaving the photosphere then take 8 minutes to get to us!

General Principles of Heat Diffusion

energy transported per unit area =
energy per particle per unit area × *particle velocity*

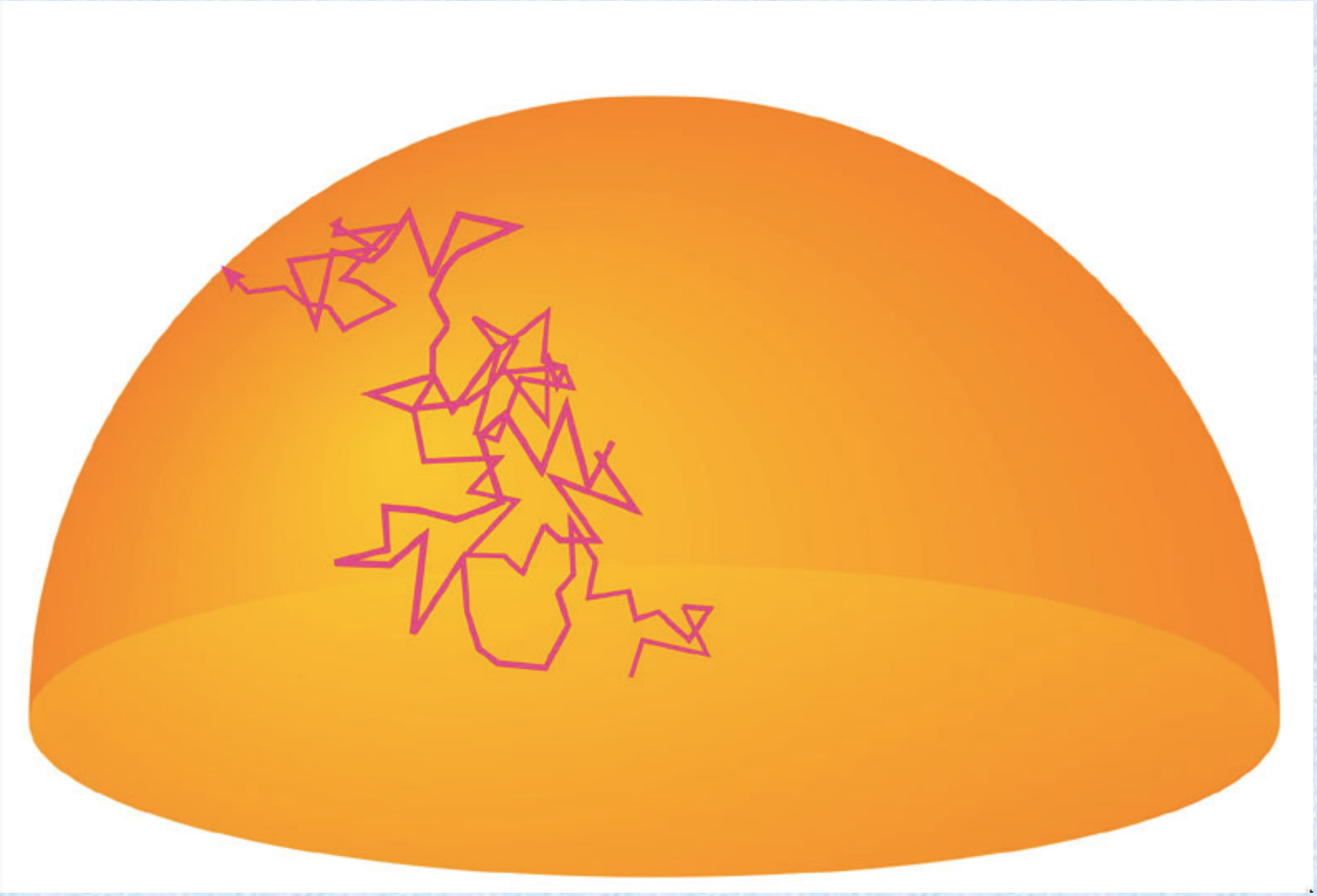
Examples if include:

1. Conduction (electrons)

2. Radiative Diffusion (photons)

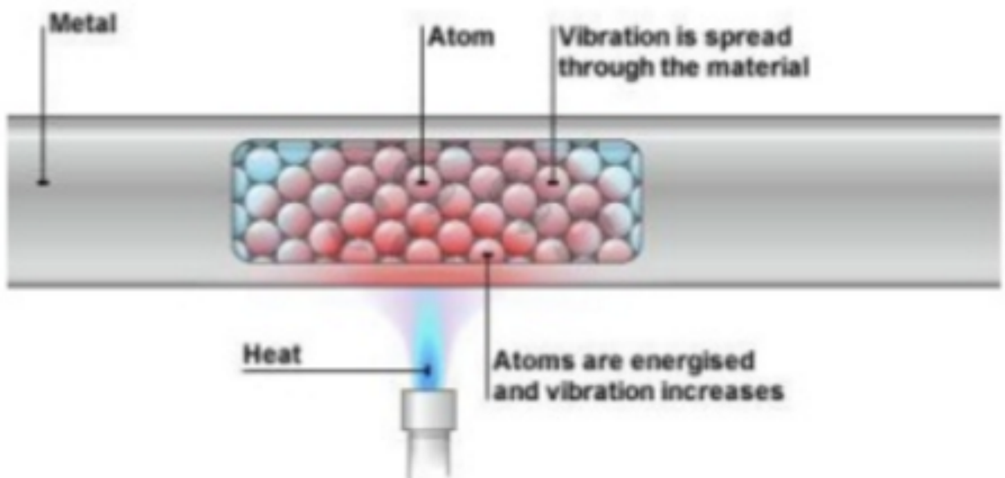
3. Convection (fluid elements, macrosopic)

Heat Transport 1. : Radiative Diffusion



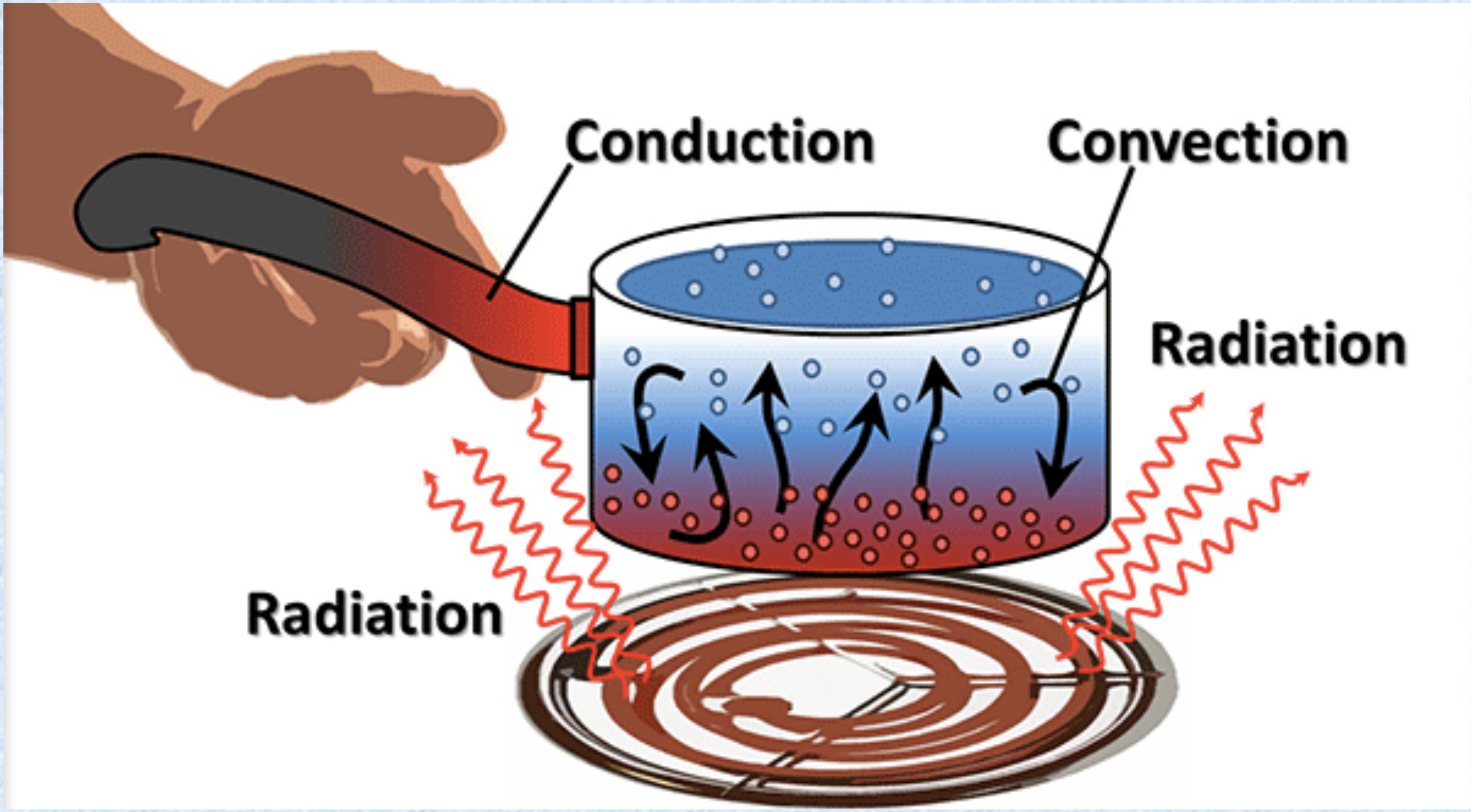
Heat Transport: Conduction

Conduction

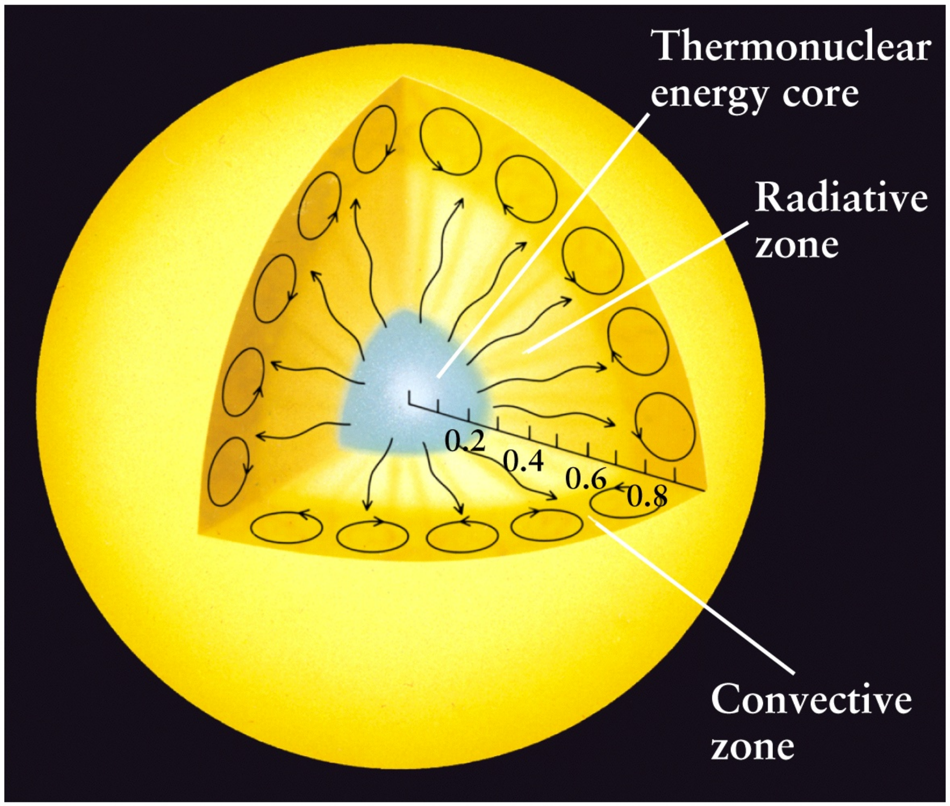


Heat energy is conducted through the solid in this way. As the atoms of the solid gain kinetic energy the temperature of the solid increases.

Heat Transport: Convection

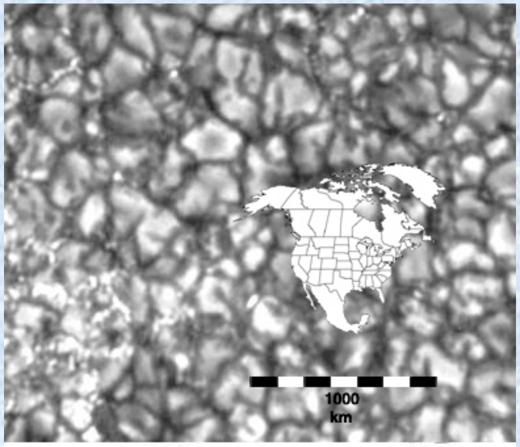


Heat Transport in the Sun



- Radiative diffusion transport heat out to roughly 0.7 solar radii.
- Convection transports heat in the outer layers of the Sun.
- We can see the affect of convection on the photosphere.

Photosphere ('Surface') of the Sun



Photospheric granulation, G. Scharmer
Swedish Vacuum Solar Telescope
10 July 1997

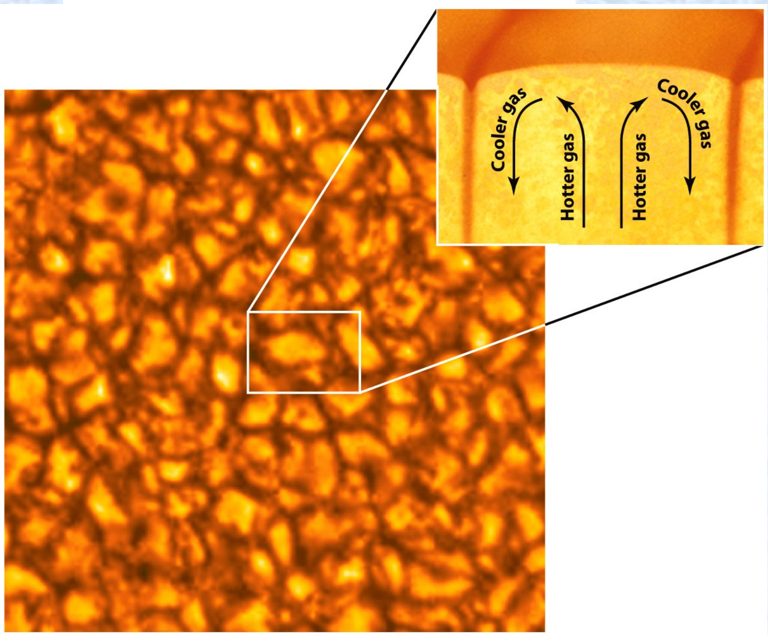


Figure 16-9
Universe, Eighth Edition

- Granules are convection cells about 1000 km (600 mi) wide in the Sun's photosphere.
- Rising hot gas produces bright granules.
- Cooler gas sinks downward along the boundaries between granules; this gas glows less brightly, giving the boundaries their dark appearance.
- The surface of the Sun is in constant motion. It's boiling!
  - HW5 – Problem 2 – Calculate the Doppler shift created by the motion.

Doppler Image of Solar Surface

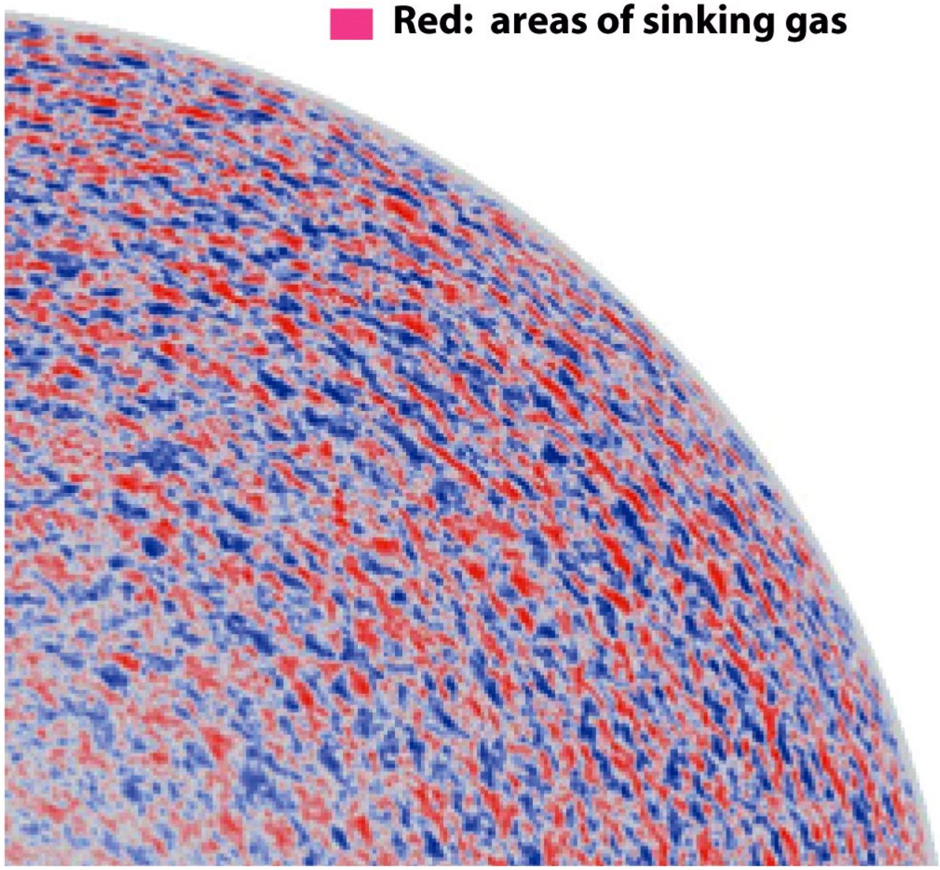
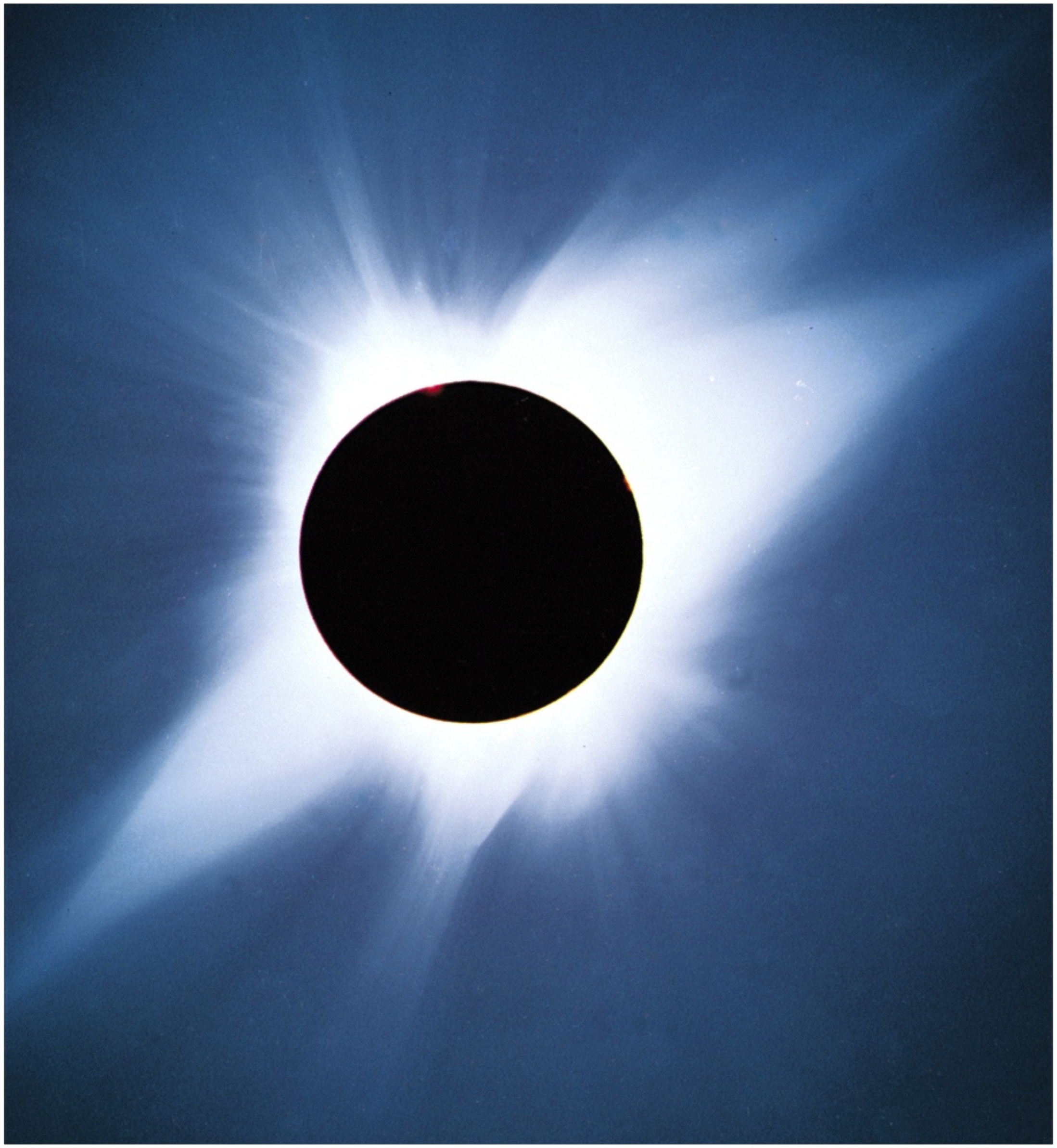


Figure 16-10
Universe, Eighth Edition

- Granules are arranged in supergranules (35,000 km in diameter).
- Supergranules display relatively little contrast between their center and edges, so they are hard to observe in ordinary images.
- But they can be seen in a false-color Doppler image like this one.

Variations in the Sun's magnetic field drive the activity on and above the solar surface



The solar corona lies above the photosphere and is about a million degrees.

It is transparent because it is so tenuous (very low density).

The Solar Cycle

Quiet → **Active** → Quiet

22 year cycle

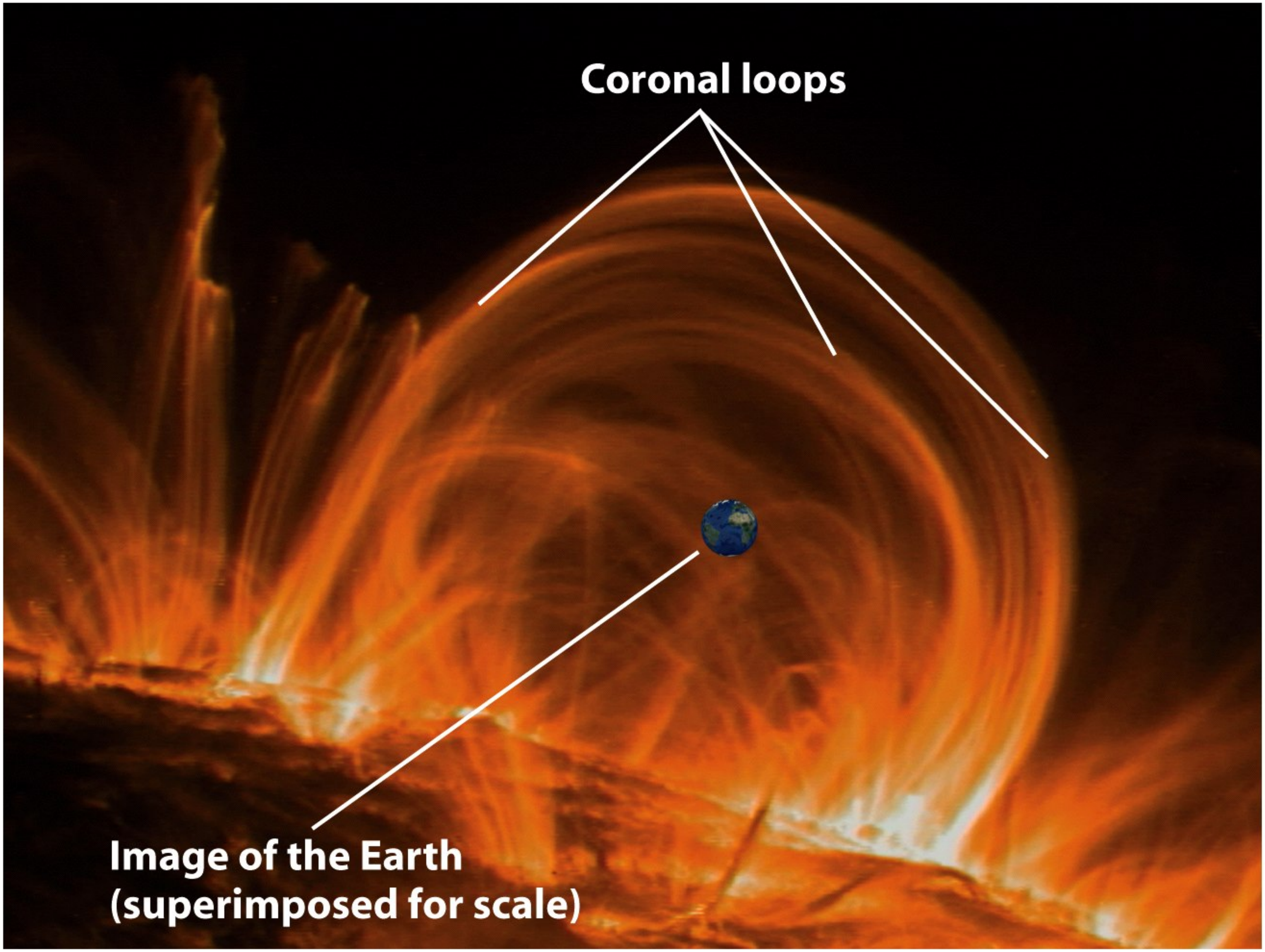


Figure 16-25a
Universe, Eighth Edition

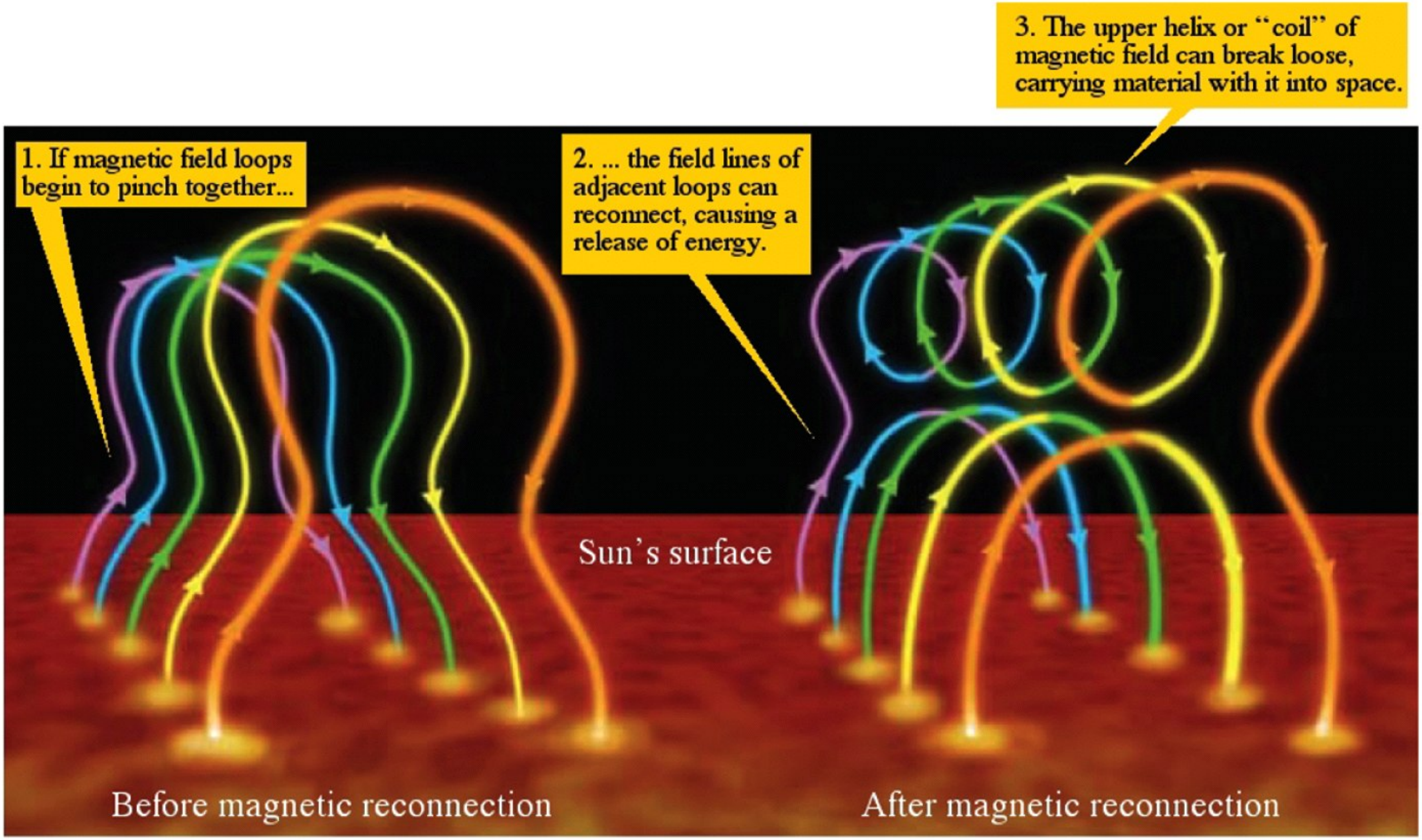
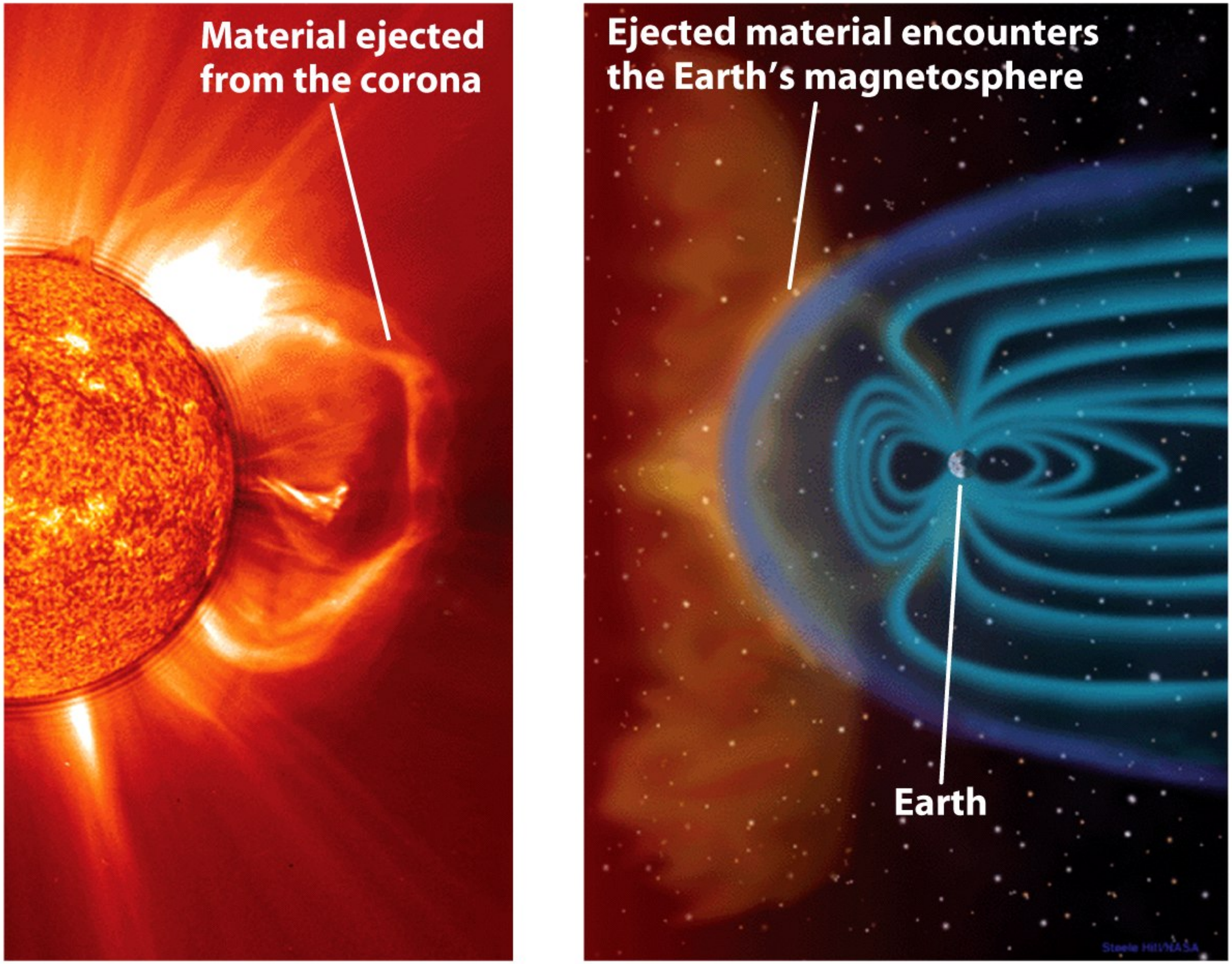


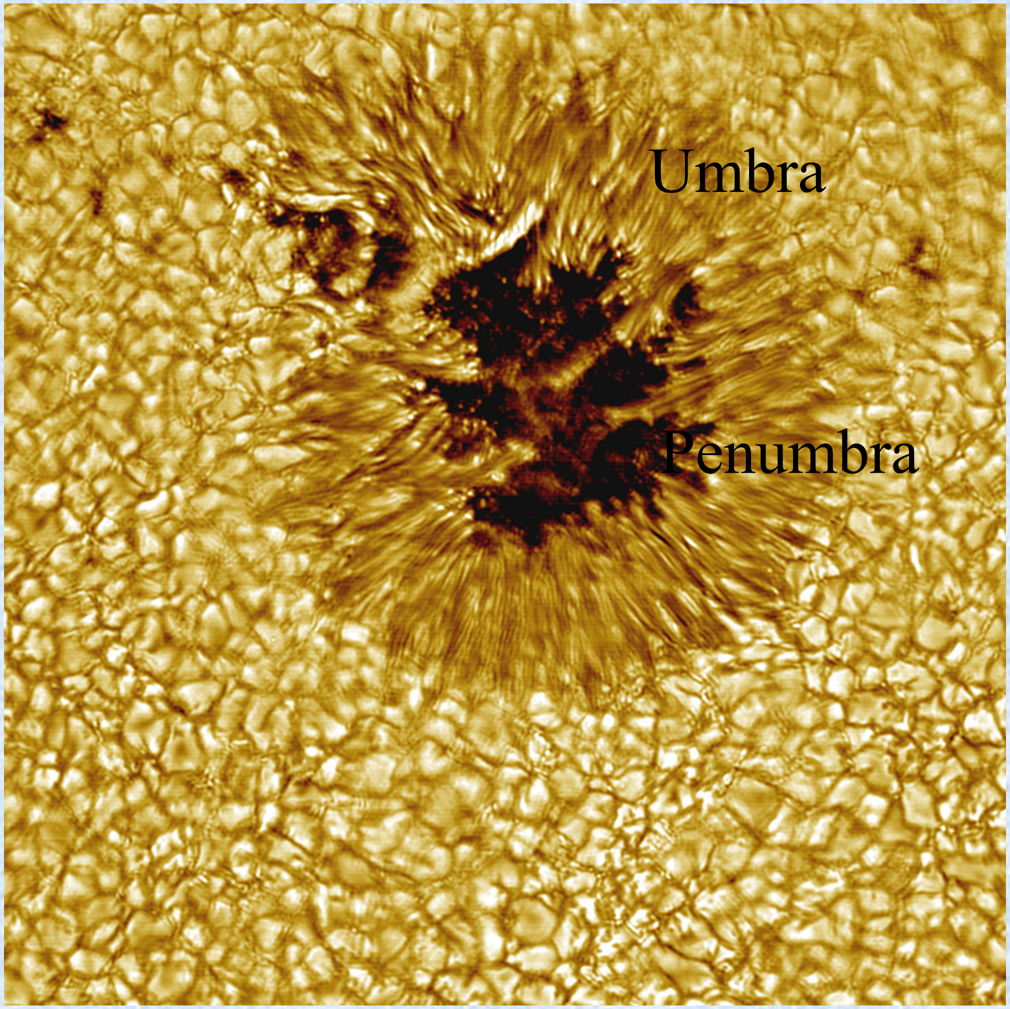
Figure 16-25b
Universe, Eighth Edition



(a) **A coronal mass ejection** **(b)** **Two to four days later**

Figure 16-28
Universe, Eighth Edition

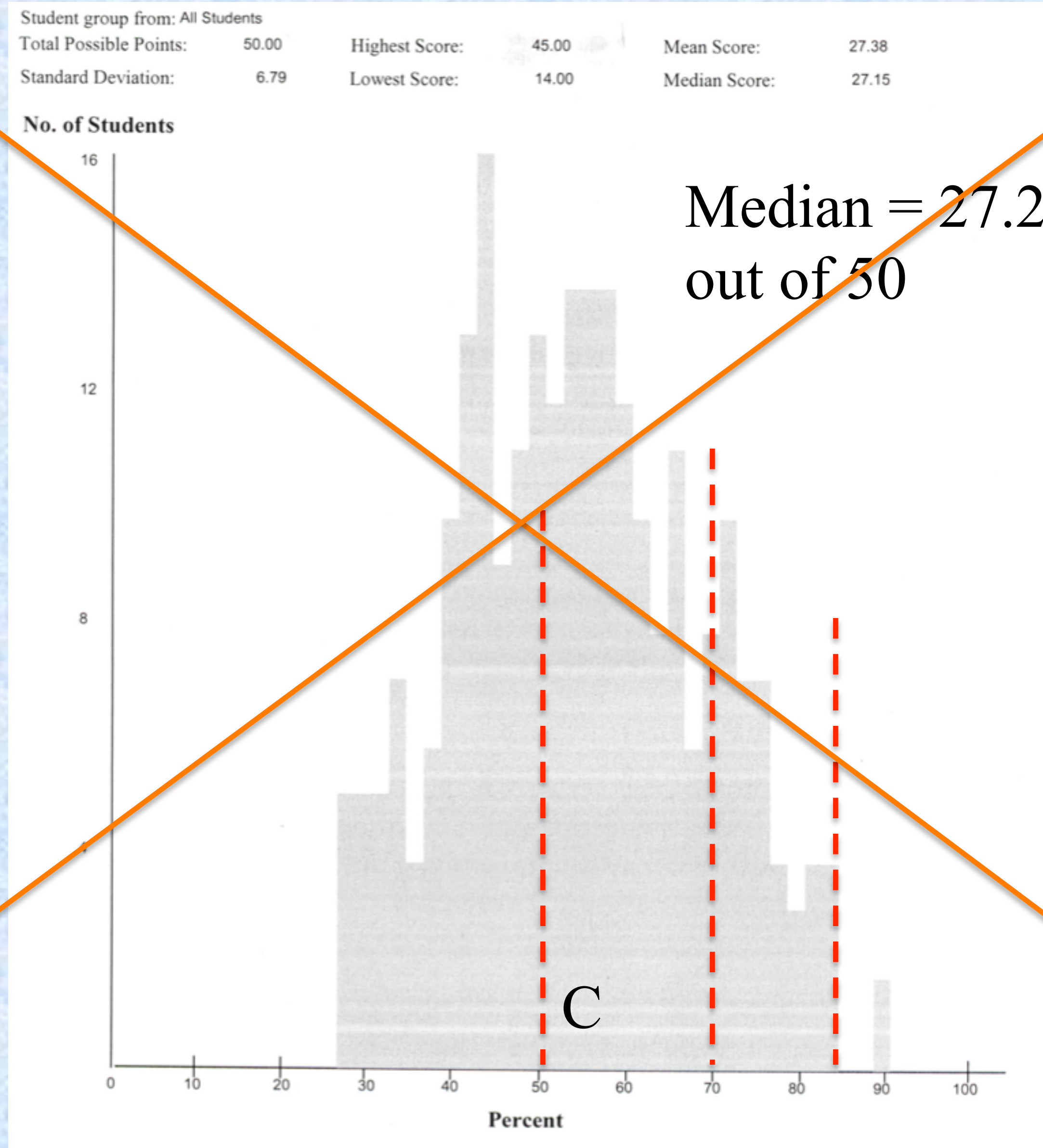
Blackbody Radiation (ch 5): Application on HW5 (ch 16) − Problem 3



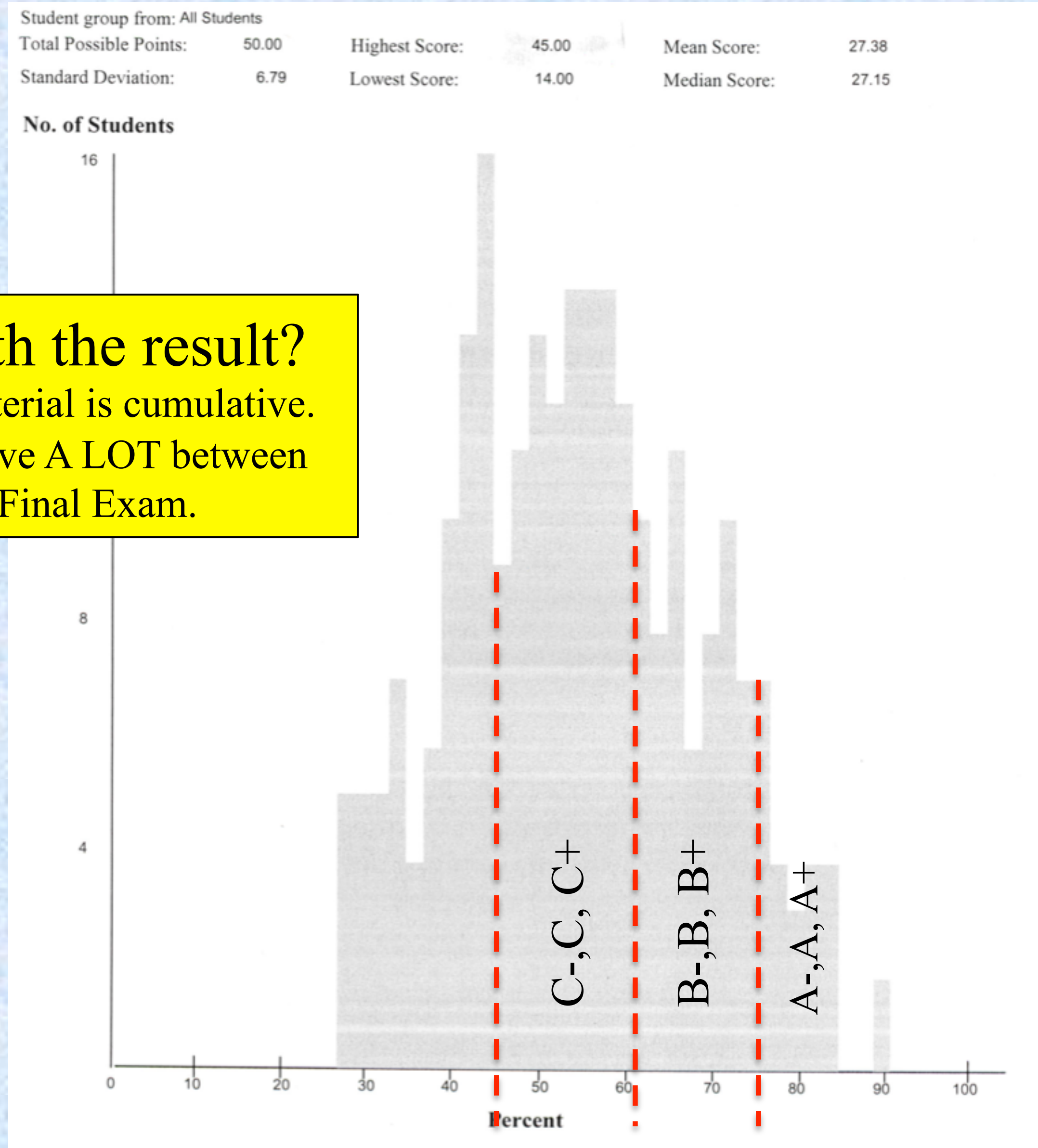
How To Prepare for the Midterm

- Read chapters 1-8, 10, 16-17.
- Complete HW 1, 2, 3, 4, 5.
- Study for about 3 hours for every hour in the classroom.
- Then *(perhaps with the equation sheet in front of you – see webpage)*
  - Go through the Concept Check Questions (and Answers) for each chapter.
  - Go through the Homework Solutions and check your answers.
  - Review the iClicker questions and answers in the Lecture Notes
- At anytime that you are feeling confused, go to office hours and ask questions.
- Get a good night's rest prior to the exam.
- Bring your parscore form, calculator (optional), and several #2 pencils.

Midterm #1 Results (Straight Scale)



Midterm #1 Results (Curved Scale)



Not happy with the result?

Don't panic. The material is cumulative. Students often improve A LOT between the Midterm and the Final Exam.

Summary

- The Sun is very massive, and it would collapse under its own weight in about 30 minutes if there weren't forces holding it up.
- A pressure gradient holds the Sun up against the pull of gravity.
- The Sun would shine even without any nuclear reactions.
  - But it would 'burn out' too quickly. Nuclear reactions lengthen the lifetime of stars.
- Hydrogen fusion ($E=mc^2$) occurs at 10^7 K in the core of the Sun.
  - And produces neutrinos that are observed on Earth.
  - Today, we define a 'star' as a gravitationally bound sphere of gas powered by nuclear reactions.
  - Objects that shine without nuclear reactions include brown dwarfs and large planets.
- The Sun acts like a big blanket around its core.
  - Radiative diffusion transport energy out to about 0.71 solar radii.
  - Convection moves the energy to the outermost layers.