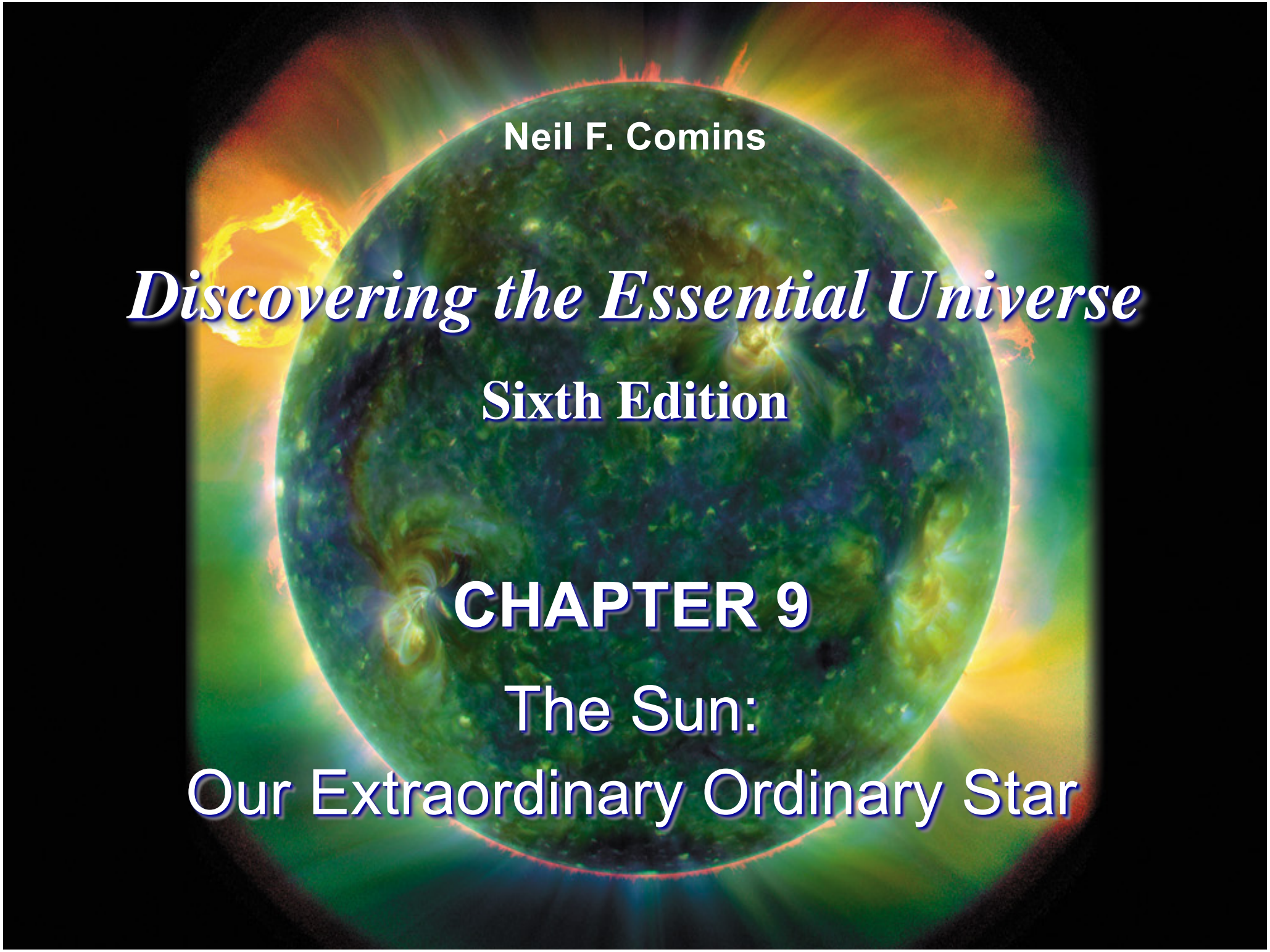

Neil F. Comins
Discovering the Essential Universe
Sixth Edition
CHAPTER 9
The Sun:
Our Extraordinary Ordinary Star

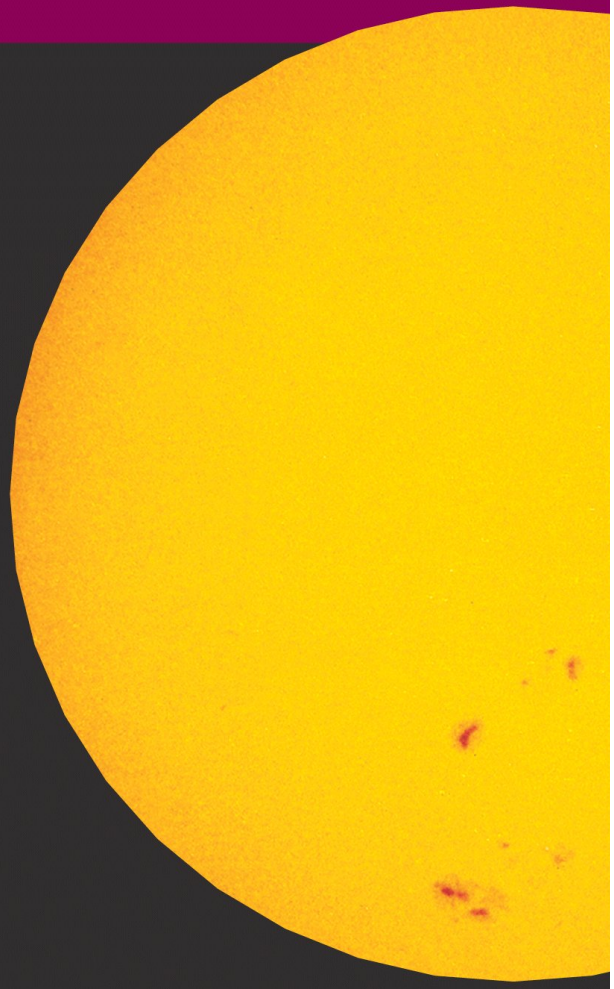
# Our Star, the Sun

# In this chapter you will discover…

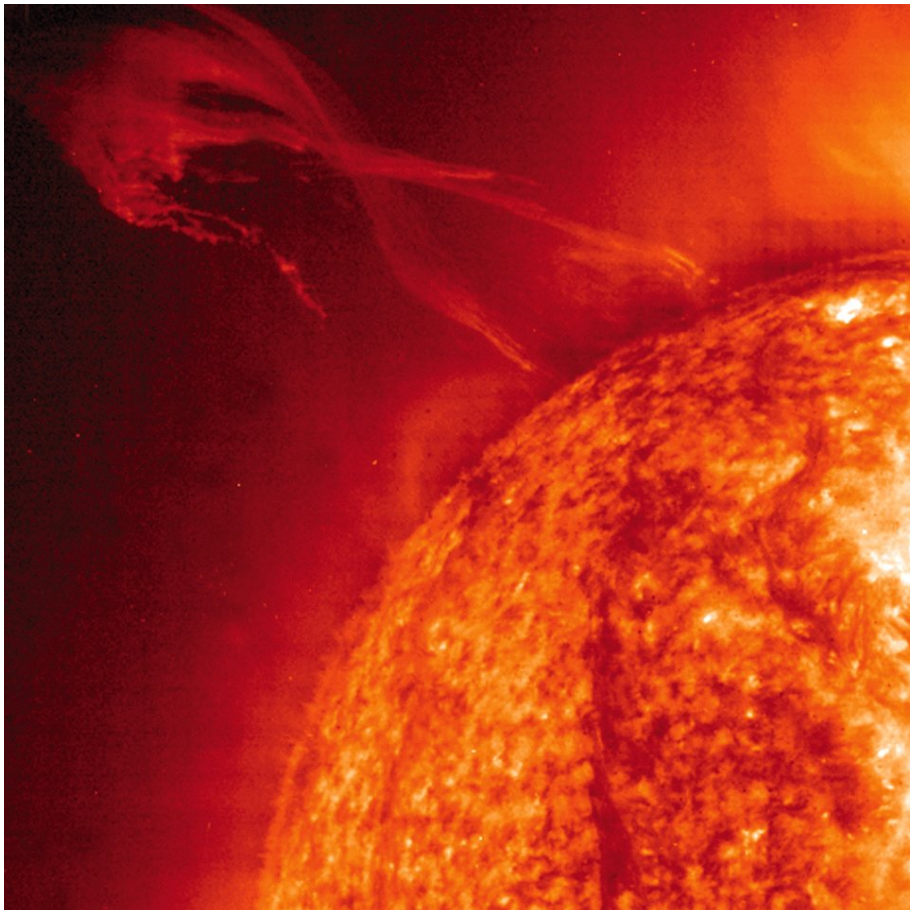
- that the Sun has two layers of atmosphere above the layer that we normally see
- how magnetic fields churn up the Sun's outer layers
- that the Sun generates energy in its core
- that some particles created in the Sun's core pass straight through it and through you

## table 18-1 | Sun Data

| | |
|---|---|
| Distance from the Earth: | Mean: 1 AU = 149,598,000 km |
| | Maximum: 152,000,000 km |
| | Minimum: 147,000,000 km |
| Light travel time to the Earth: | 8.32 min |
| Mean angular diameter: | 32 arcmin |
| Radius: | 696,000 km = 109 Earth radii |
| Mass: | $1.9891 \times 10^{30}$ kg = $3.33 \times 10^{5}$ 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 temperatures: | Surface: 5800 K; Center: $1.55 \times 10^{7}$ K |
| Luminosity: | $3.86 \times 10^{26}$ 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 |



# The Sun's energy is generated by thermonuclear reactions in its core



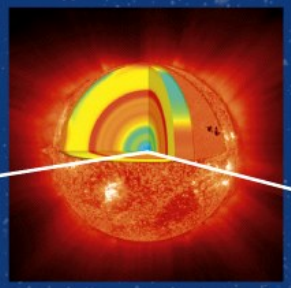
- The energy released in a nuclear reaction corresponds to a slight reduction of mass according to Einstein's equation

$E = mc^2$

- Thermonuclear fusion occurs only at very high temperatures; for example, hydrogen fusion occurs only at temperatures in excess of about $10^7$ K

- In the Sun, fusion occurs only in the dense, hot core

Hydrogen fusion in the Sun usually takes place in a sequence of steps called the proton-proton chain. Each of these steps releases energy that heats the Sun and gives it its luminosity.



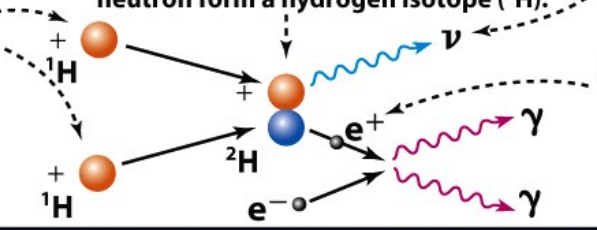
**STEP 1**

(a) Two protons (hydrogen nuclei, $^1H$) collide.

(b) One of the protons changes into a neutron (shown in blue). The proton and neutron form a hydrogen isotope ($^2H$).

(c) One byproduct of converting a proton to a neutron is a neutral, nearly massless neutrino ($\nu$). This escapes from the Sun.

(d) The other byproduct of converting a proton to a neutron is a positively charged electron, or positron ($e^+$). This encounters an ordinary electron ($e^-$), annihilating both particles and converting them into gamma-ray photons ($\gamma$). The energy of these photons goes into sustaining the Sun's internal heat.

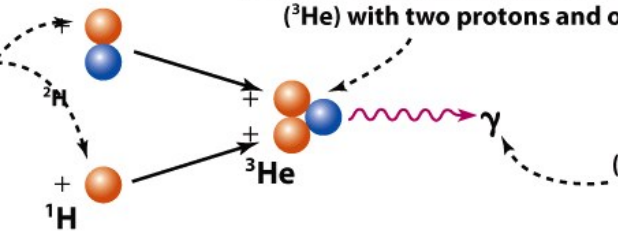



**STEP 2**

(a) The $^2H$ nucleus produced in Step 1 collides with a third proton ($^1H$).

(b) The result of the collision is a helium isotope ($^3He$) with two protons and one neutron.

(c) This nuclear reaction releases another gamma-ray photon ($\gamma$). Its energy also goes into sustaining the internal heat of the Sun.




**STEP 3**

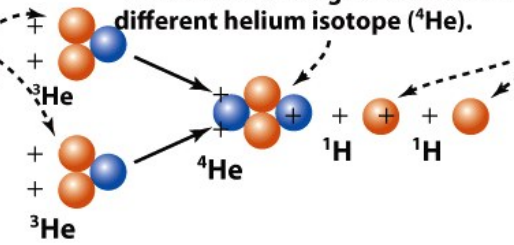
(a) The $^3He$ nucleus produced in Step 2 collides with another $^3He$ nucleus produced from three other protons.

(b) Two protons and two neutrons from the two $^3He$ nuclei rearrange themselves into a different helium isotope ($^4He$).

(c) The two remaining protons are released. The energy of their motion contributes to the Sun's internal heat.

(d) Six $^1H$ nuclei went into producing the two $^3He$ nuclei, which combine to make one $^4He$ nucleus. Since two of the original $^1H$ nuclei are returned to their original state, we can summarize the three steps as:

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




**Toolbox 10-1 part 1**

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# Fusion reaction in Sun

$p+p \rightarrow d+e^{+}+\nu$

$d+p \rightarrow {}^{3}He + \gamma$

${}^{3}He+{}^{3}He \rightarrow {}^{4}He+2p$

---

$4p \rightarrow {}^{4}He + 2\nu\text{'s} + \gamma\text{'s}$

$m(4p) = 6.693 \times 10^{-27}$ kg

$m({}^{4}He) = 6.645 \times 10^{-27}$ kg

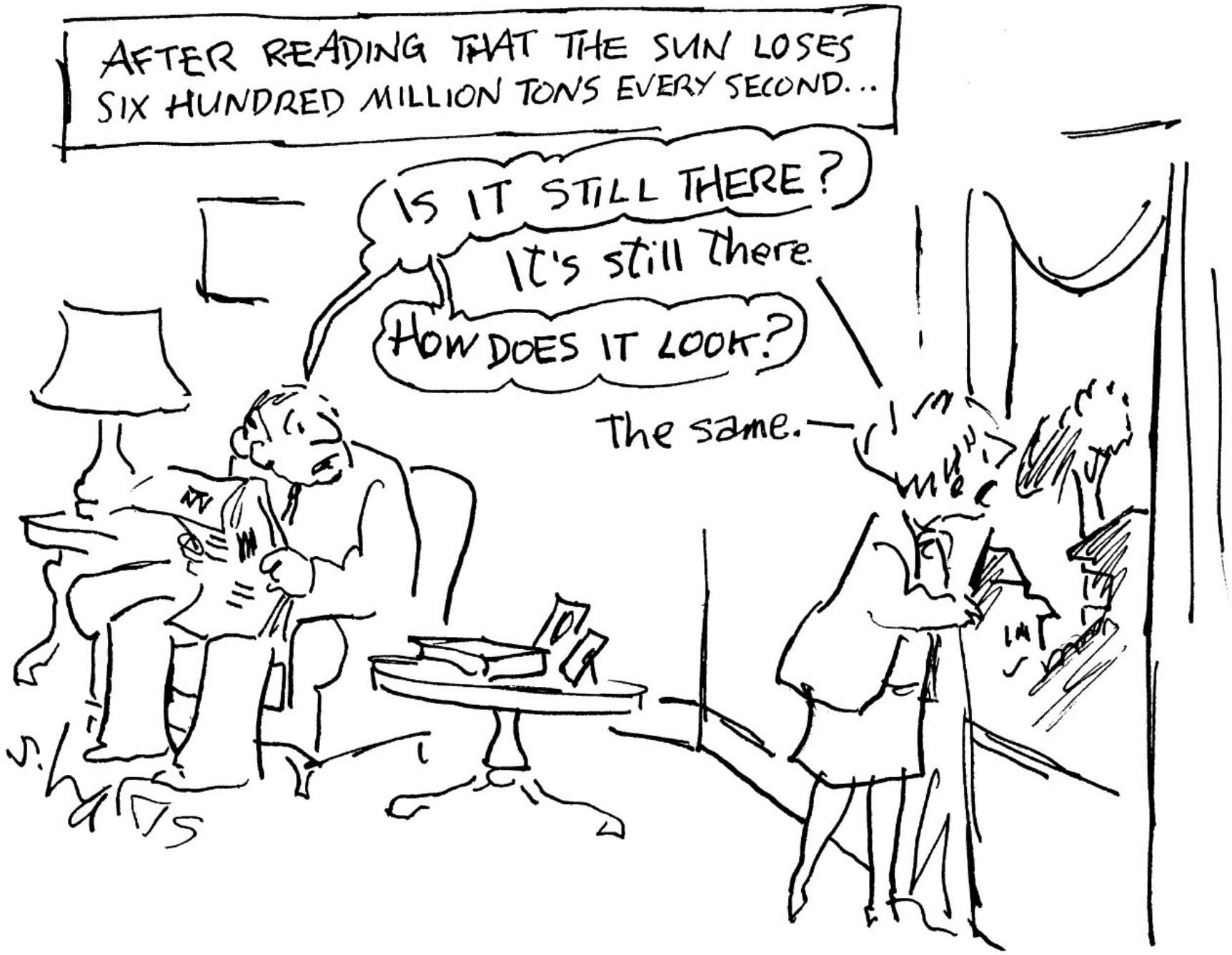
---

$0.048 \times 10^{-27}$ kg ~0.7% of mass converted into energy

$E=mc^2$

$E=0.048 \times 10^{-27} \times (3.0 \times 10^{8})^2$ J

$E = 4.3 \times 10^{-12}$ J




**Unnumbered 10 p302**
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# …wait a minute..

$L_{sun}=3.9 \times 10^{26}$ W

$E=mc^2$

Mass loss per second?

Mass conversion per second?

# How much mass does the Sun really loose per second?

$L_{sun}=3.9 \times 10^{26}$ W

# How much mass does the Sun really loose per second?

$L_{sun}=3.9 \times 10^{26}$ W

$dE_{sun}/dt = L_{sun}$

$dM_{sun}/dt = dE_{sun}/dt \times 1/c^2$

# How much mass does the Sun really loose per second?

$L_{sun}=3.9 \times 10^{26}$ W

$dE_{sun}/dt = L_{sun}$

$dM_{sun}/dt = dE_{sun}/dt \times 1/c^2$

$= 3.9 \times 10^{26} \times 1/(3\times10^8)^2$

$= 4.3 \times 10^9$ kg/s

The Sun converts 4.3 Mill tons of H per second into energy.

Since this is only 0.7% of the mass of H that is converted into energy every second, 100/0.7 times more mass is coverted into He per second.

The Sun converts 614 Mill tons of H per second into He.

# Energy Transfer

Conduction

Convection

(Electromagnetic) Radiation

# A theoretical model of the Sun shows how energy gets from its center to its surface

- Hydrogen fusion takes place in a core extending from the Sun's center to about 0.25 solar radius
- The core is surrounded by a radiative zone extending to about 0.71 solar radius
  - In this zone, energy travels outward through radiative diffusion
- The radiative zone is surrounded by a rather opaque convective zone of gas at relatively low temperature and pressure
  - In this zone, energy travels outward primarily through convection

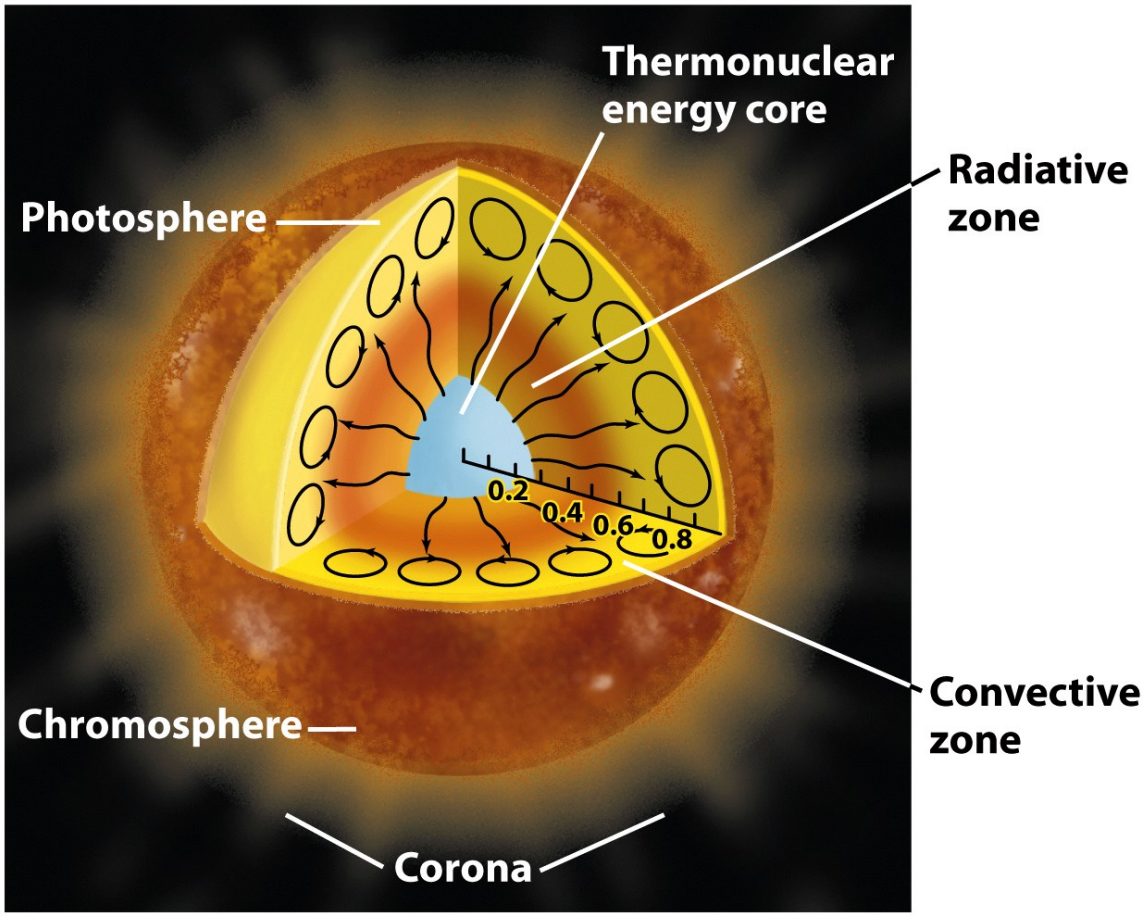


Figure 10-21a
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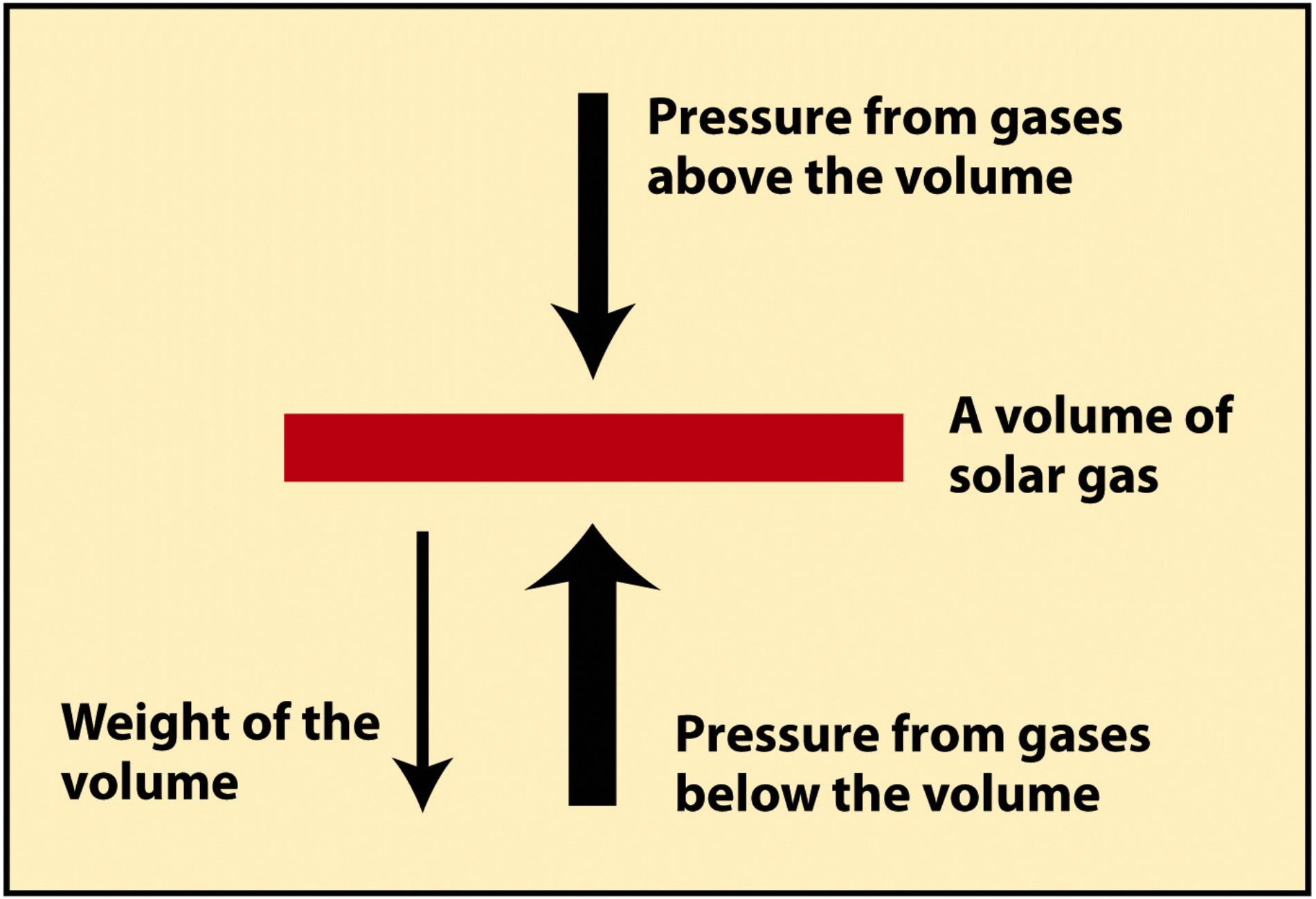


**Figure 10-20a**
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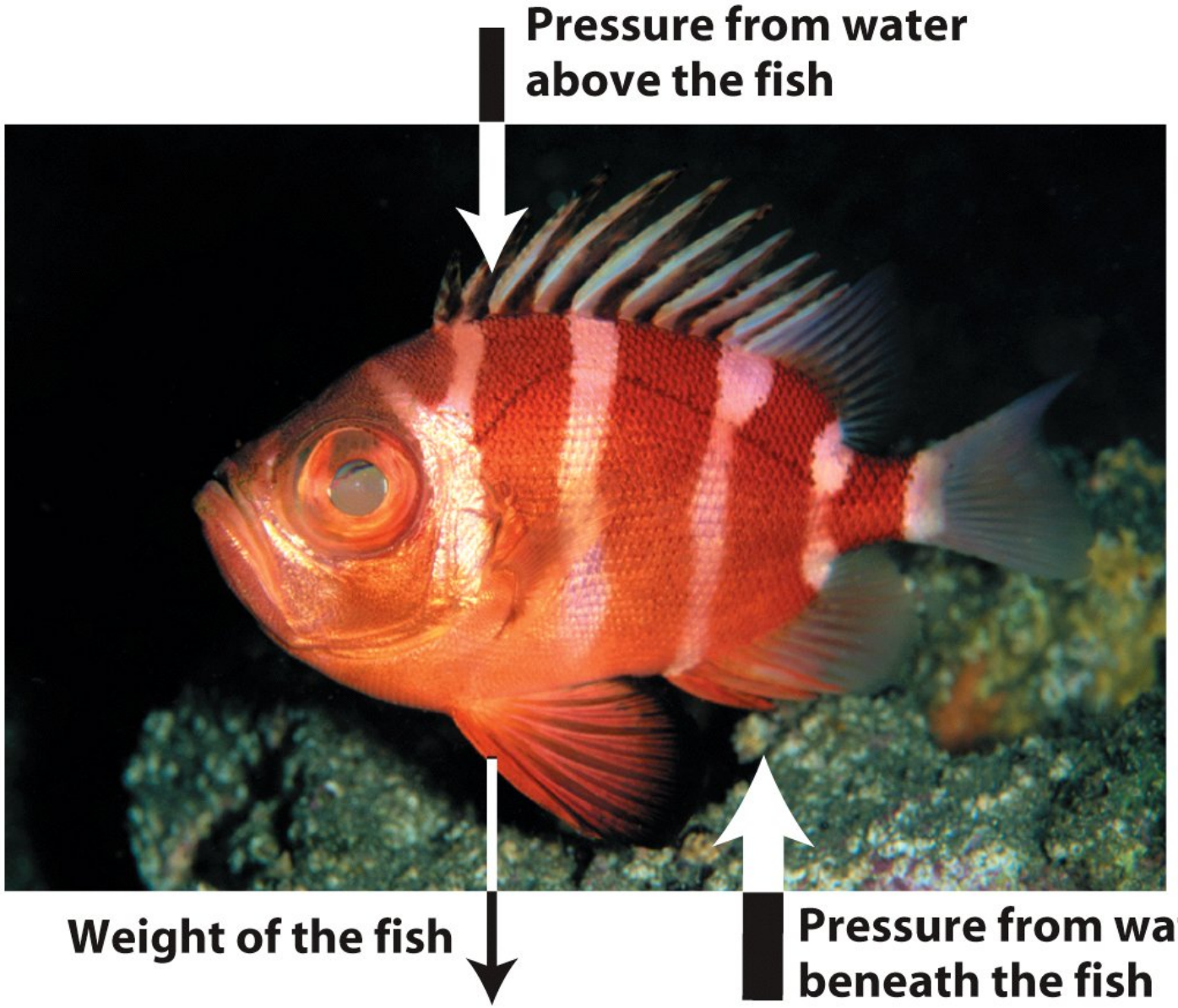
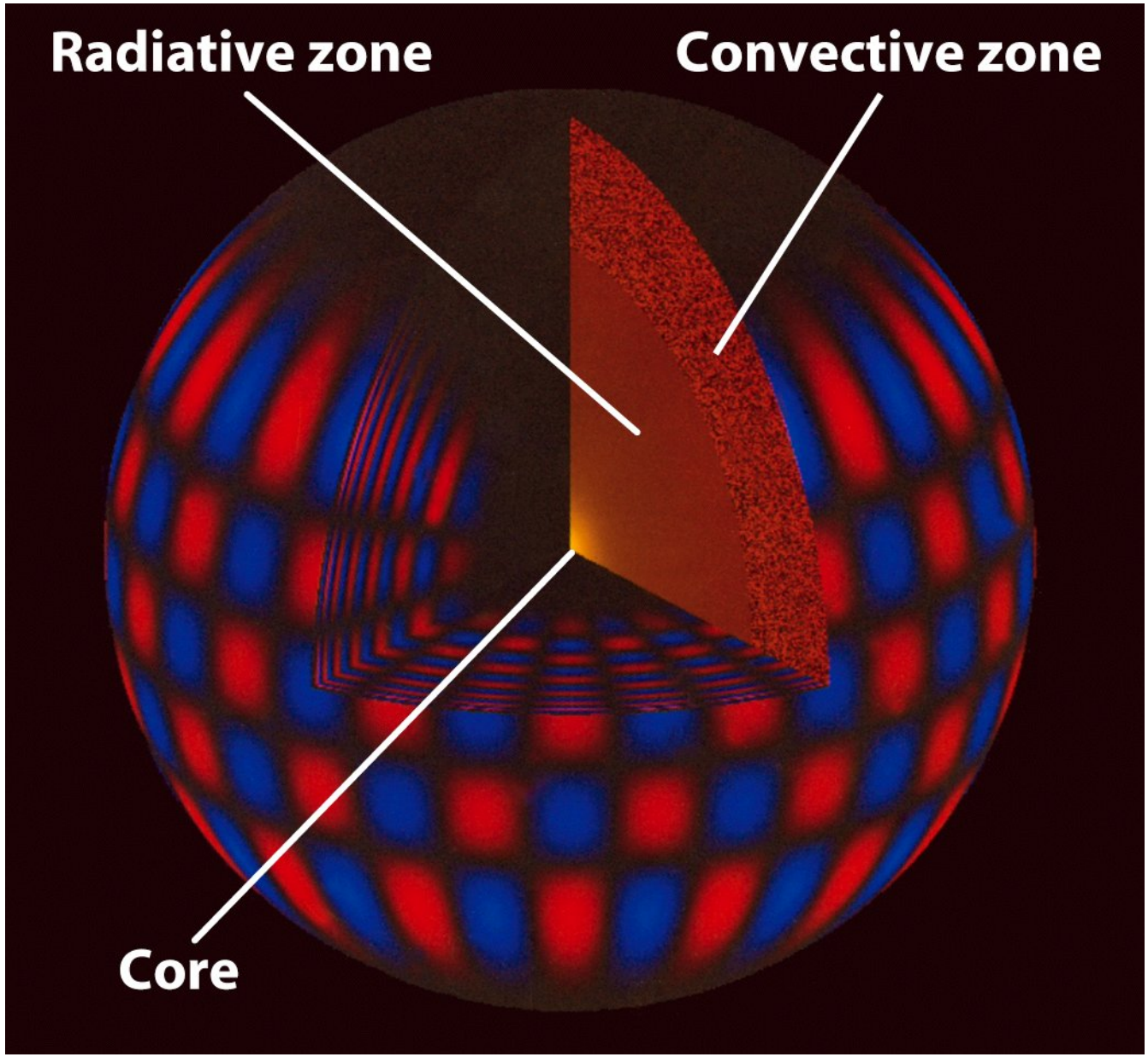
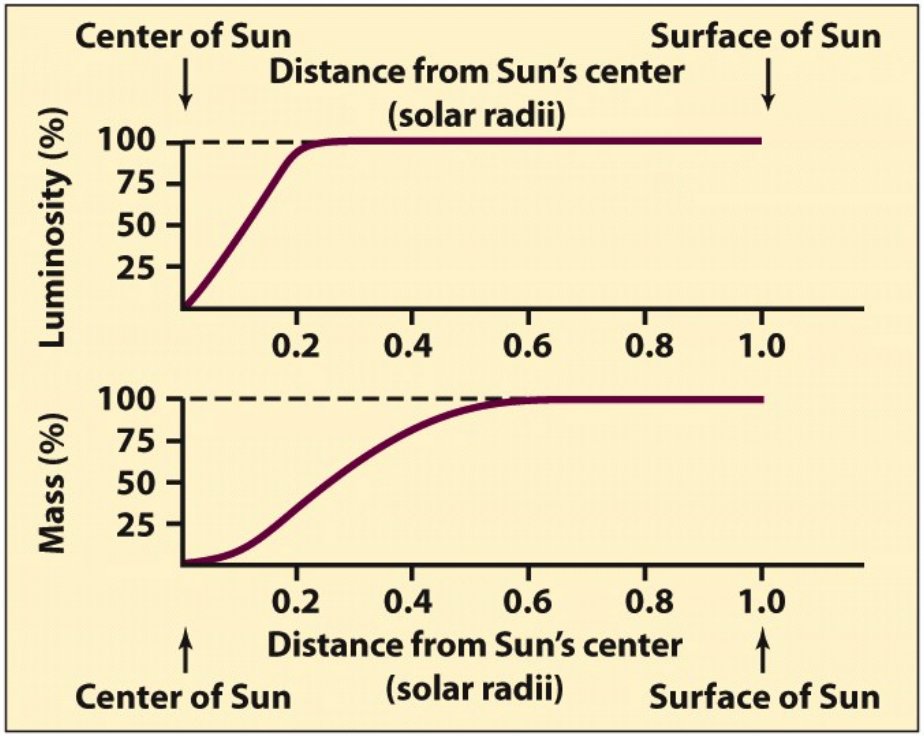



**A fish floating in water is in hydrostatic equilibrium, so forces balance**

# Astronomers probe the solar interior using the Sun's own vibrations




Helioseismology is the study of how the Sun vibrates.These vibrations have been used to infer pressures, densities, chemical compositions, and rotation rates within the Sun



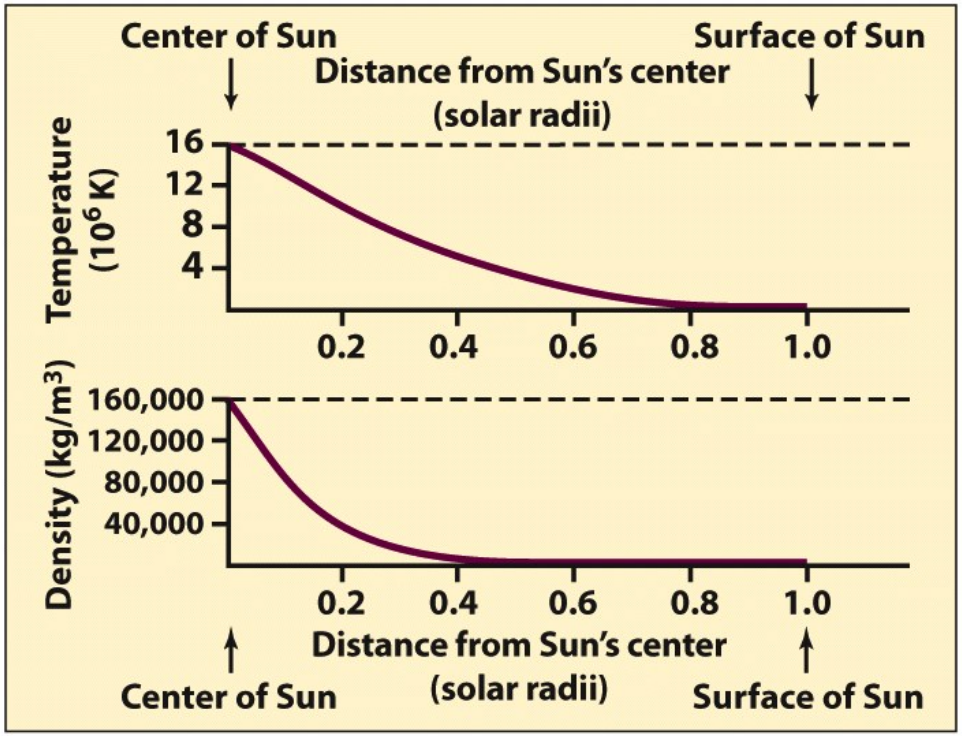




**Figure 10-21b**
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| Element | Number of atoms (percent) | Percent of total mass |
|---|---|---|
| Hydrogen | 91.2 | 71.0 |
| Helium | 8.7 | 27.1 |
| Oxygen | 0.078 | 0.97 |
| Carbon | 0.043 | 0.40 |
| Nitrogen | 0.0088 | 0.096 |
| Silicon | 0.0045 | 0.099 |
| Magnesium | 0.0038 | 0.076 |
| Neon | 0.0035 | 0.058 |
| Iron | 0.030 | 0.014 |
| Sulfur | 0.015 | 0.040 |

**Figure 10-21c**
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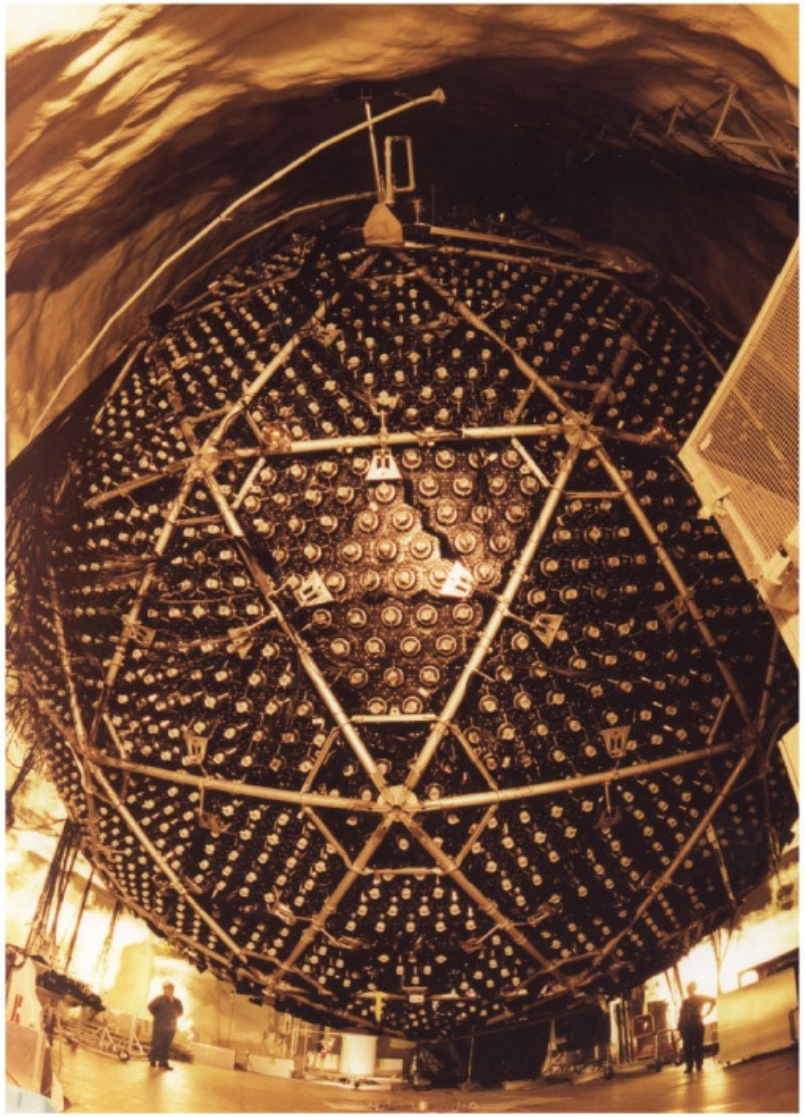
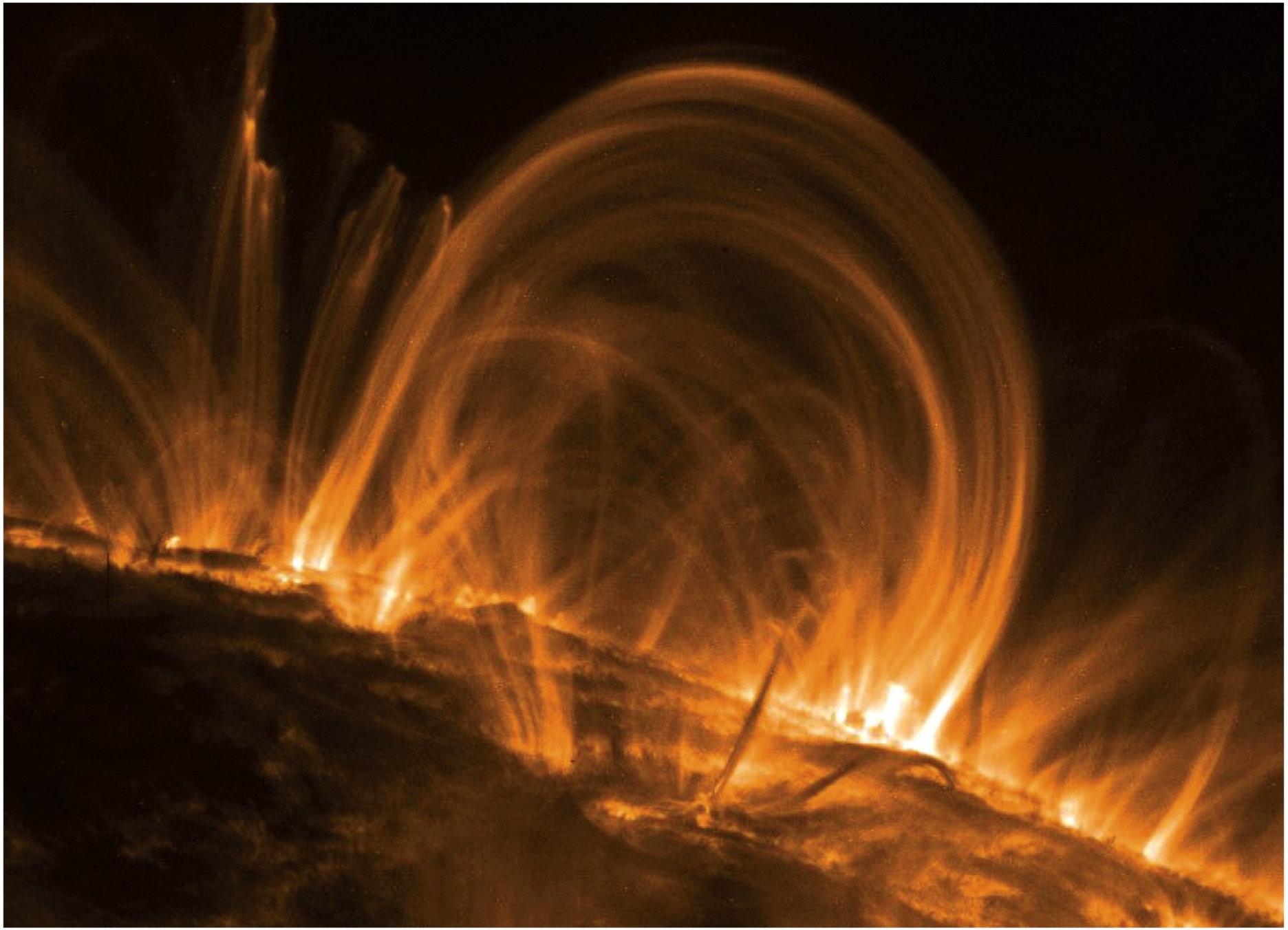
# A Solar Neutrino Experiment

Located 2703 m (6800 ft) underground in the Creighton nickel mine in Sudbury, Canada, the Sudbury Neutrino Observatory is centered around a tank that contains 1000 tons of water. Occasionally, a neutrino entering the tank interacts with one or another of the particles.



Neutrinos emitted in thermonuclear reactions in the Sun's core have been detected, but in smaller numbers than originally expected.
Now we know that neutrinos have mass and show oscillations changing their type:

➔Now observations consistent with theory



**Chapter 10 Opener**
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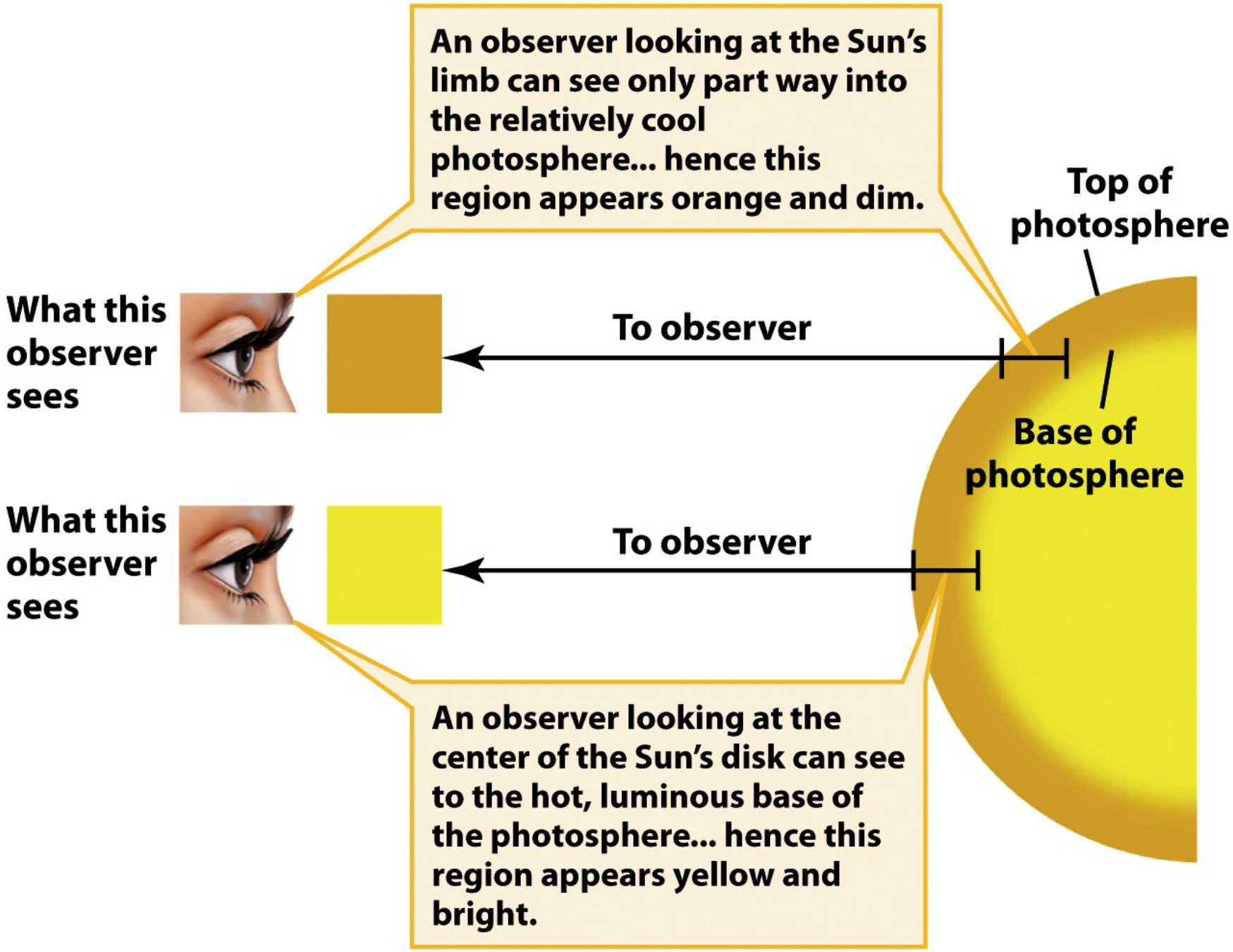


**Figure 10-2**
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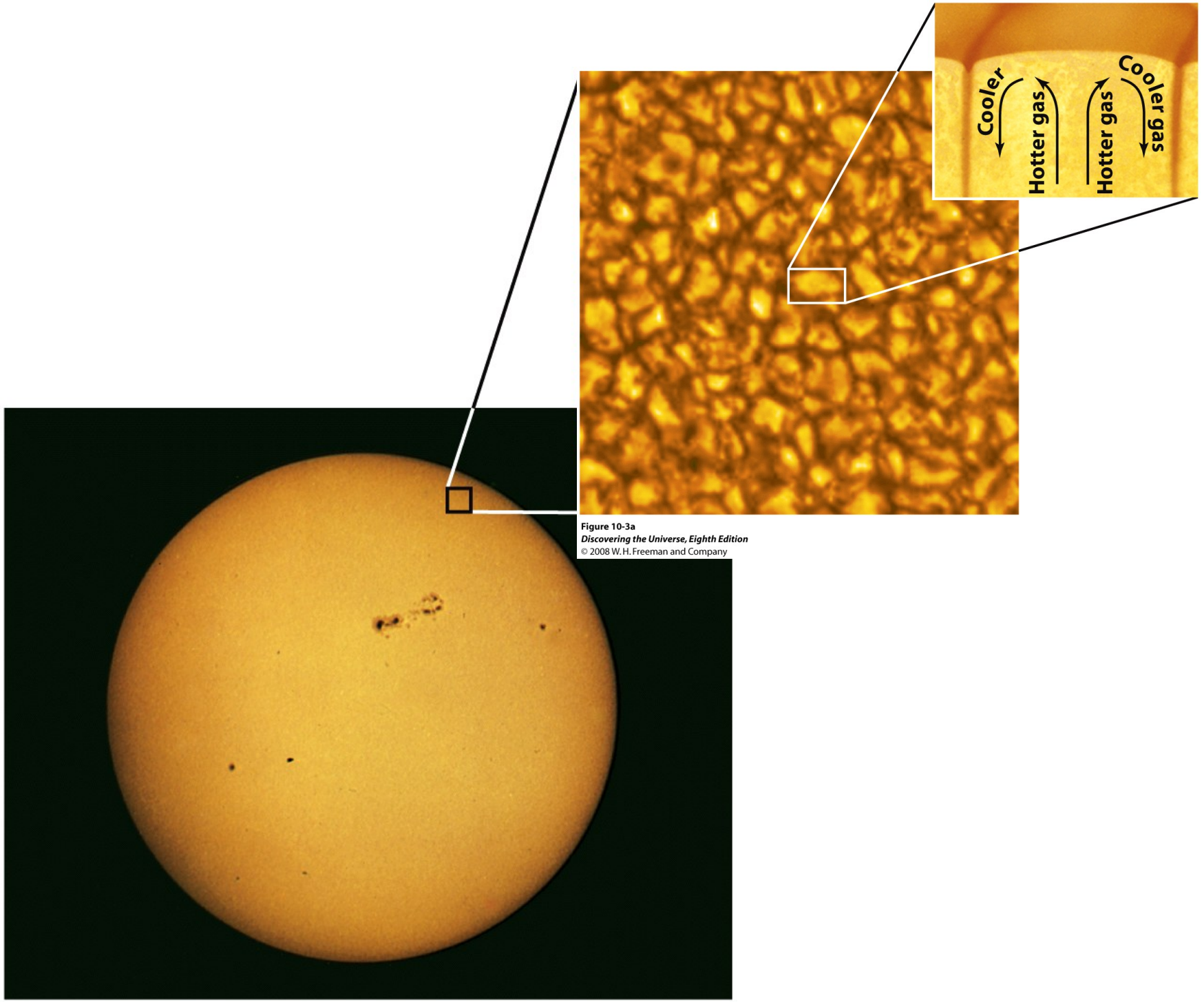


**Figure 10-3a**
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**Figure 10-3b**

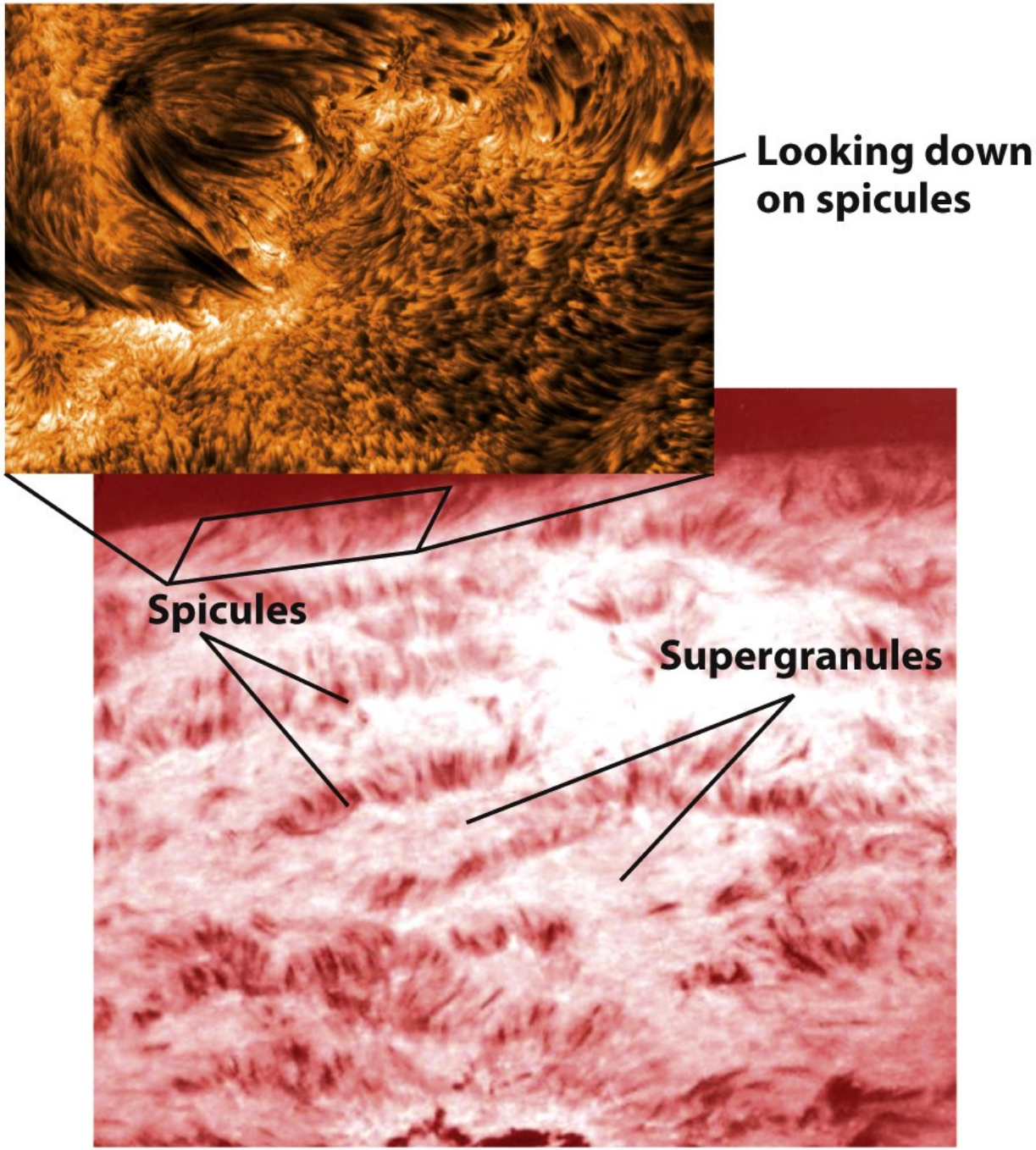


**Figure 10-5a**
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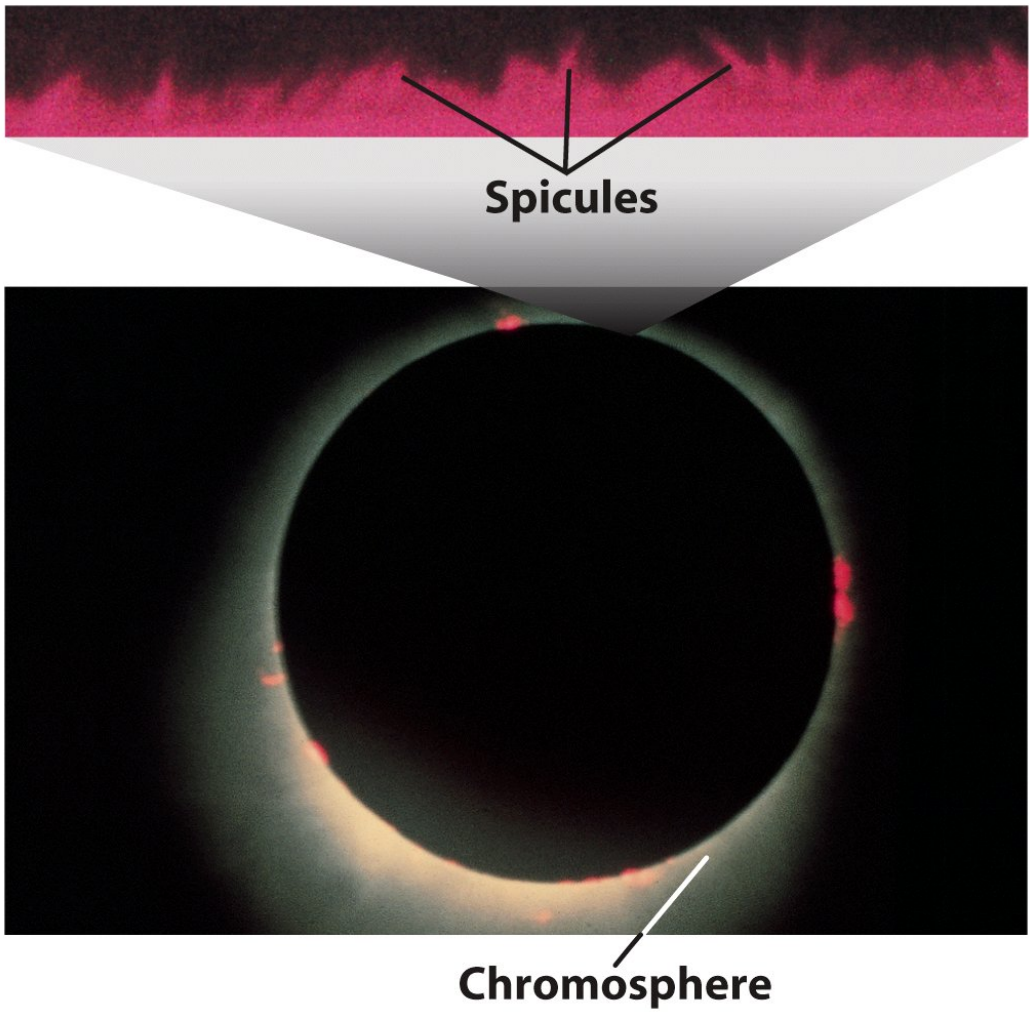
# The chromosphere is characterized by spikes of rising gas

- Above the photosphere is a layer of less dense but higher temperature gases called the chromosphere
- Spicules extend upward from the photosphere into the chromosphere along the boundaries of supergranules



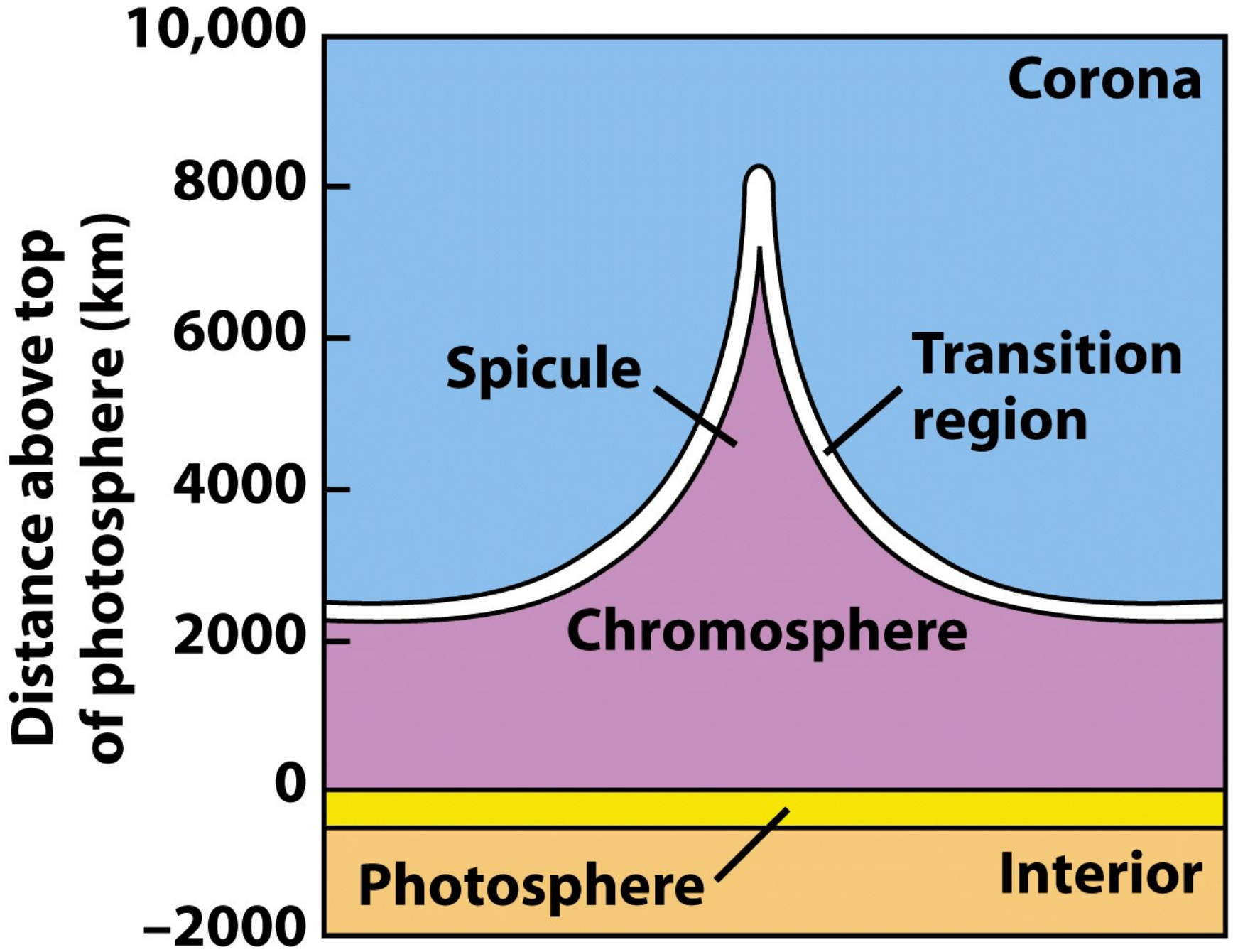



**Figure 10-5b**
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**Figure 10-6a**
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# X-ray picture of the Sun

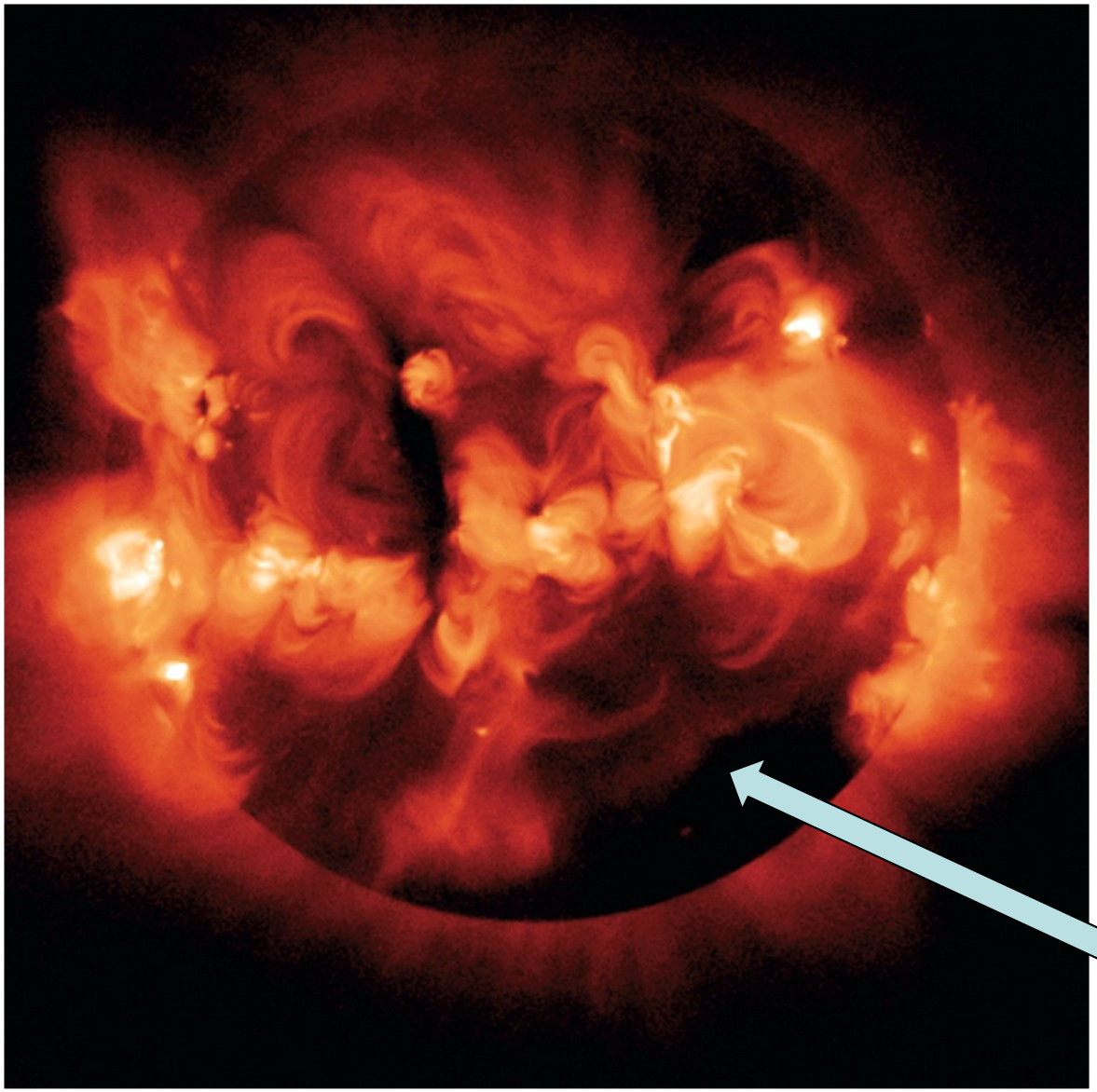


**Figure 10-6b**
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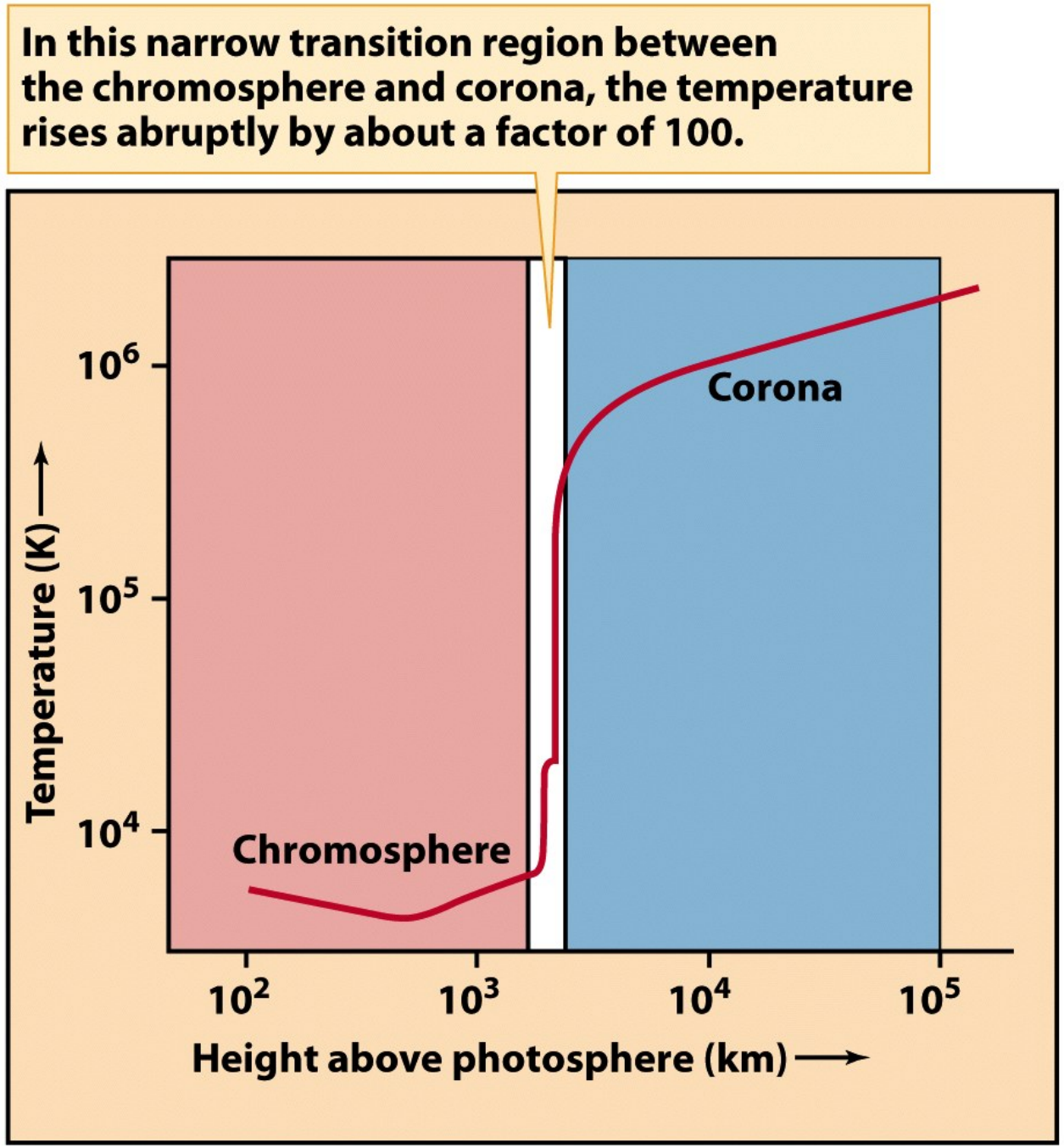


**Figure 10-6c**
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# The active sun

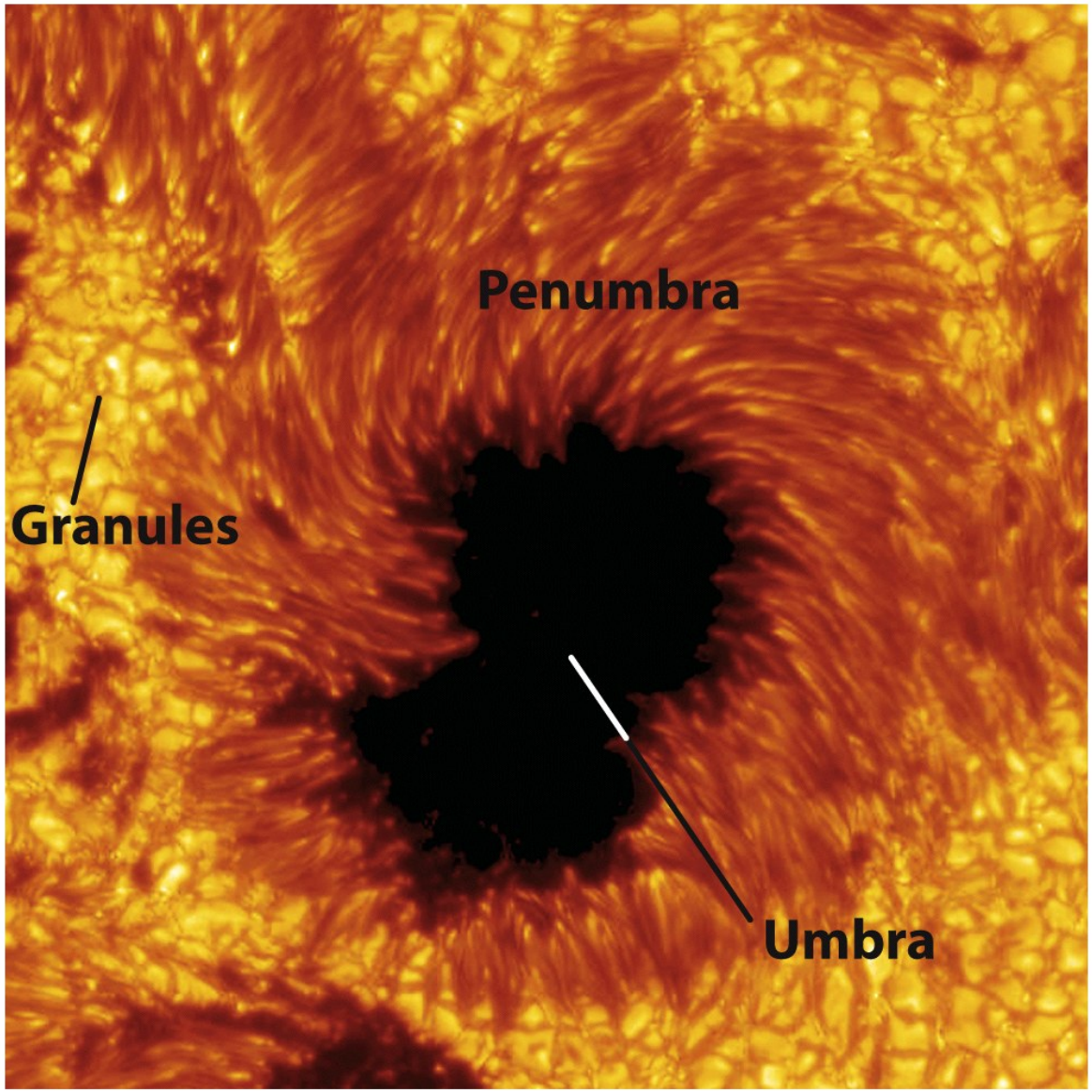


**Figure 10-7a**
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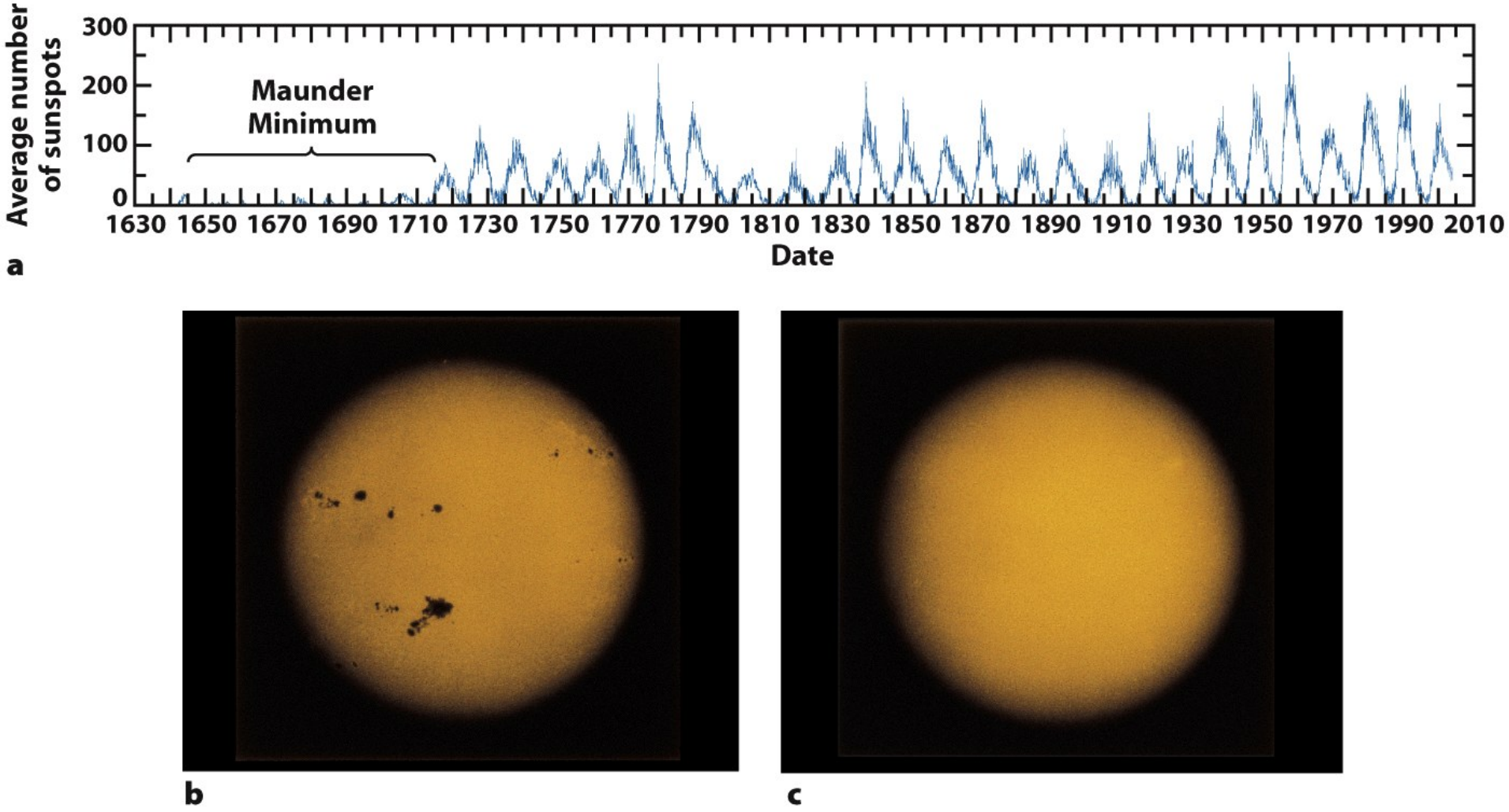


**Figure 10-8**
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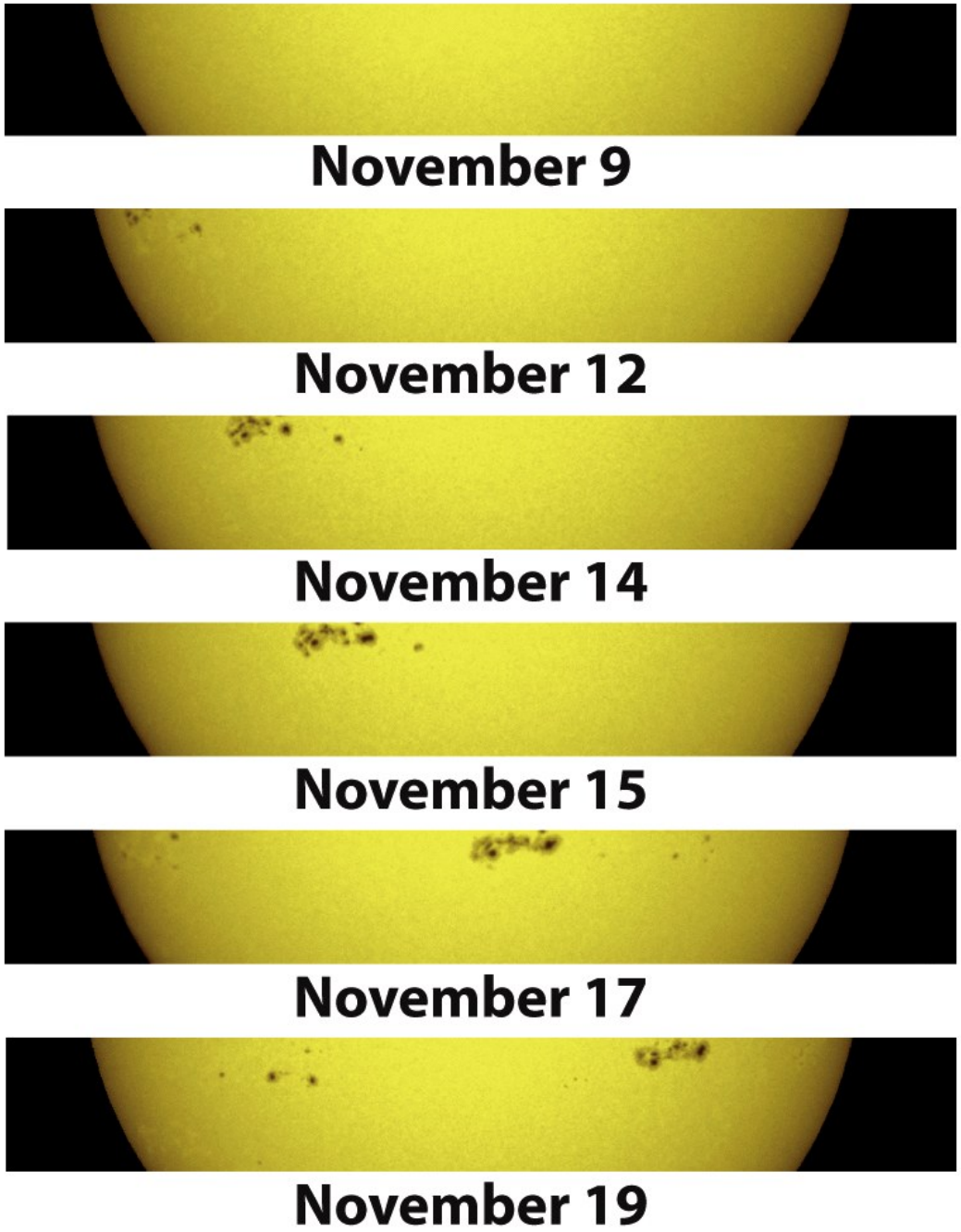


**Figure 10-9**
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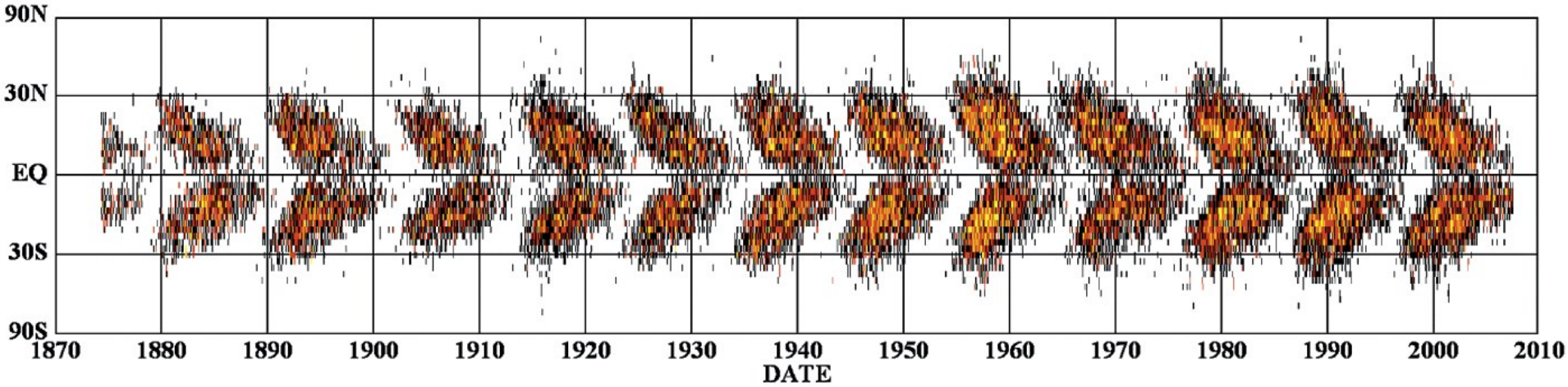


**Figure 10-10a**
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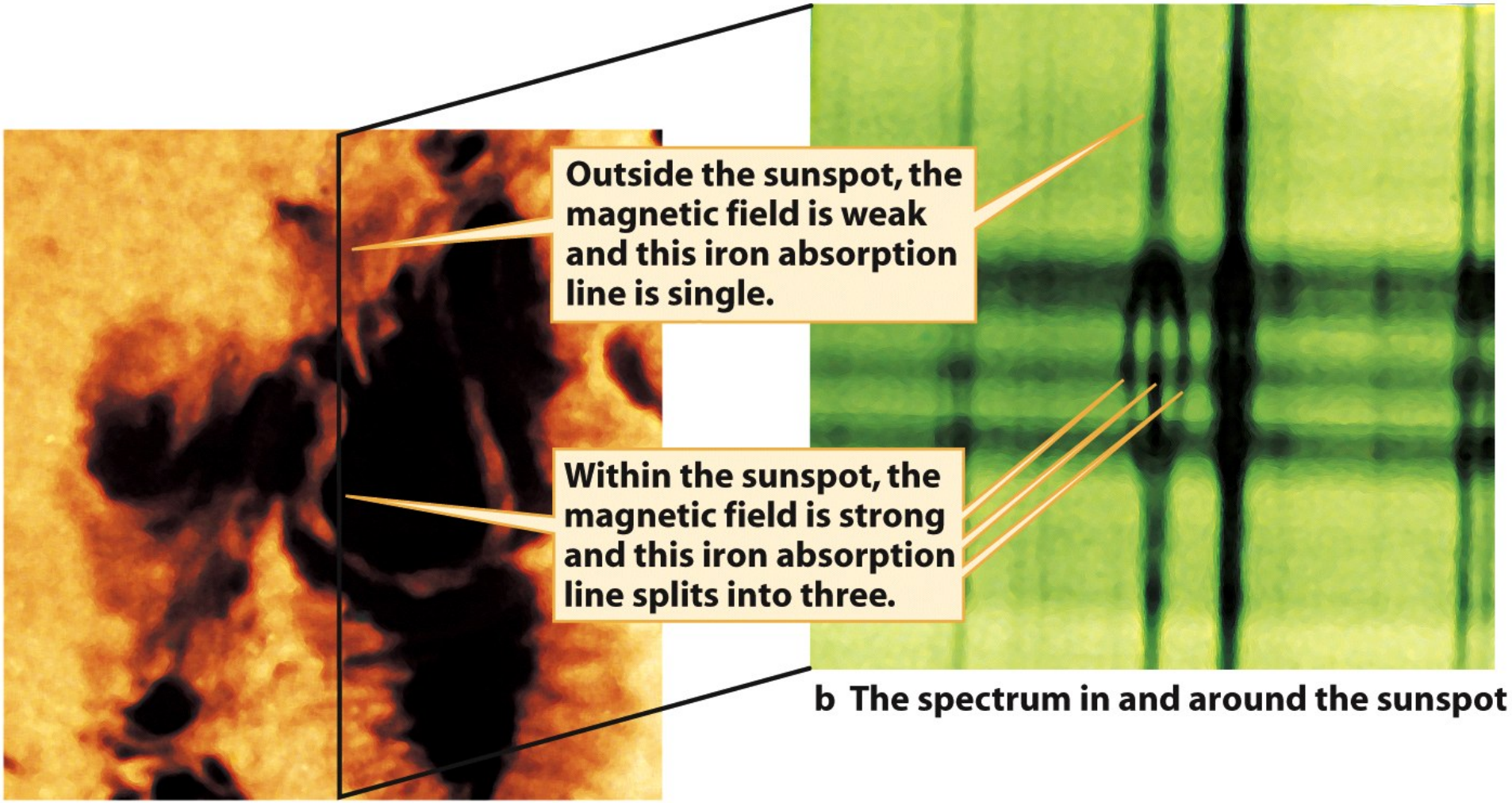


**Figure 10-11**
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# Rotation of the solar interior

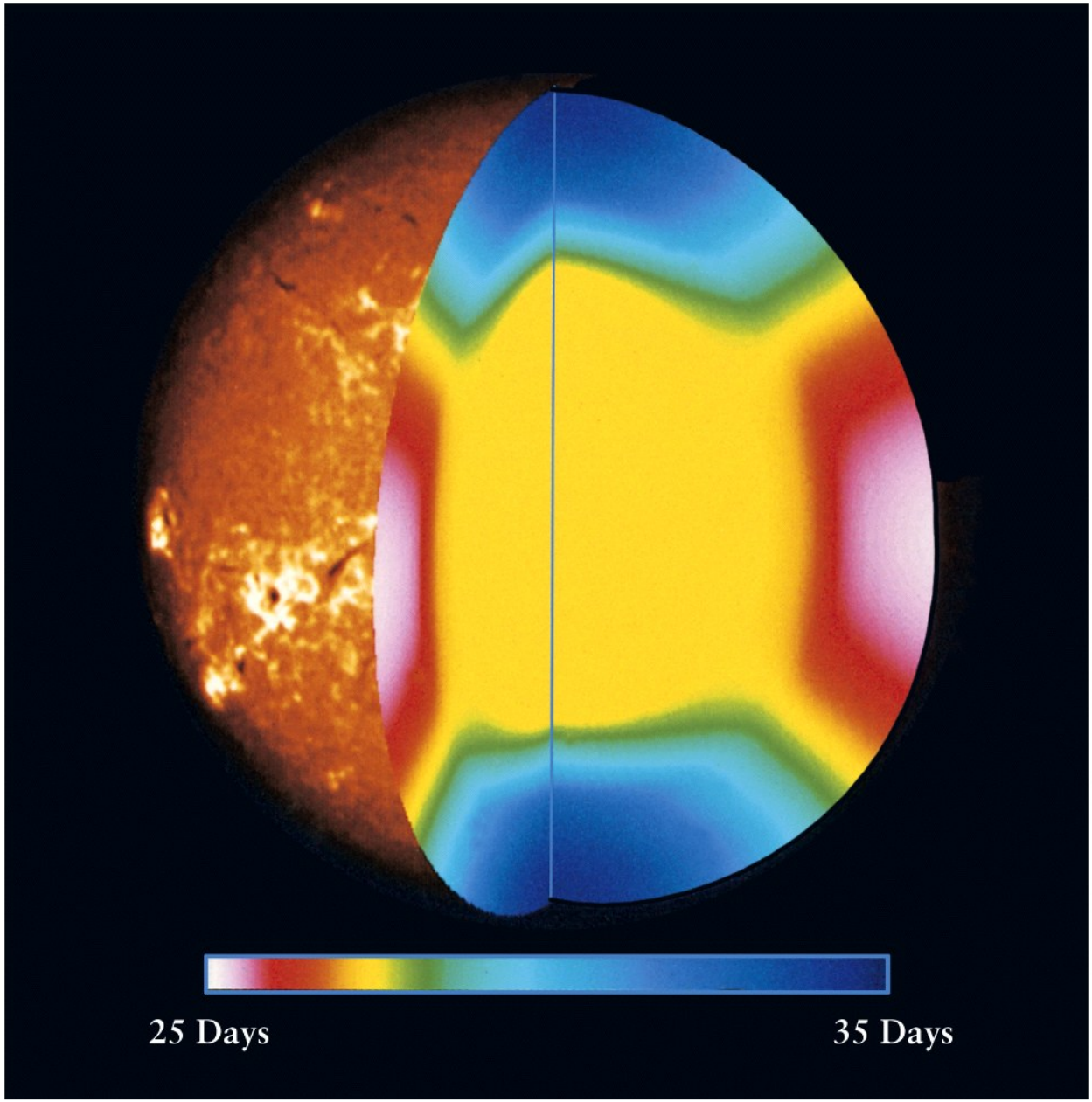


**Figure 10-12b**
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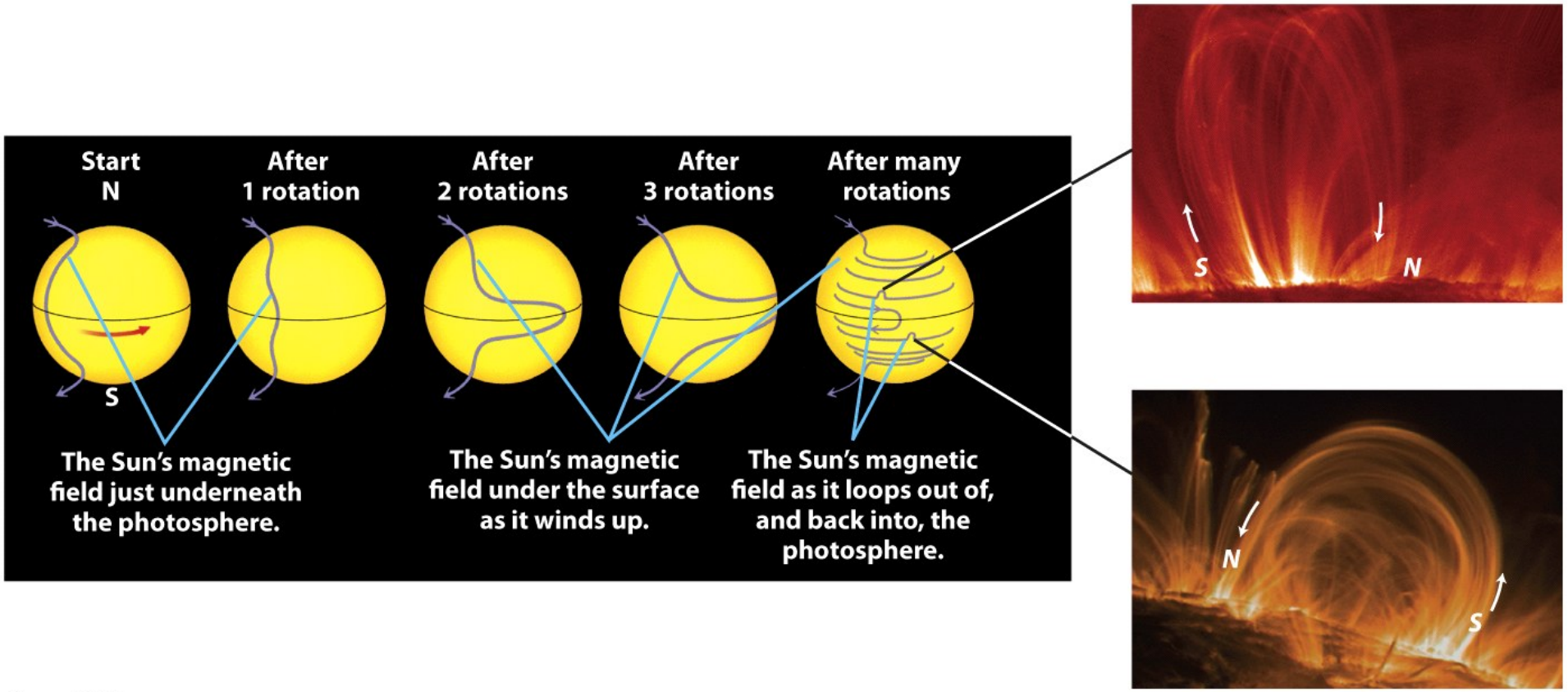


**Figure 10-13**
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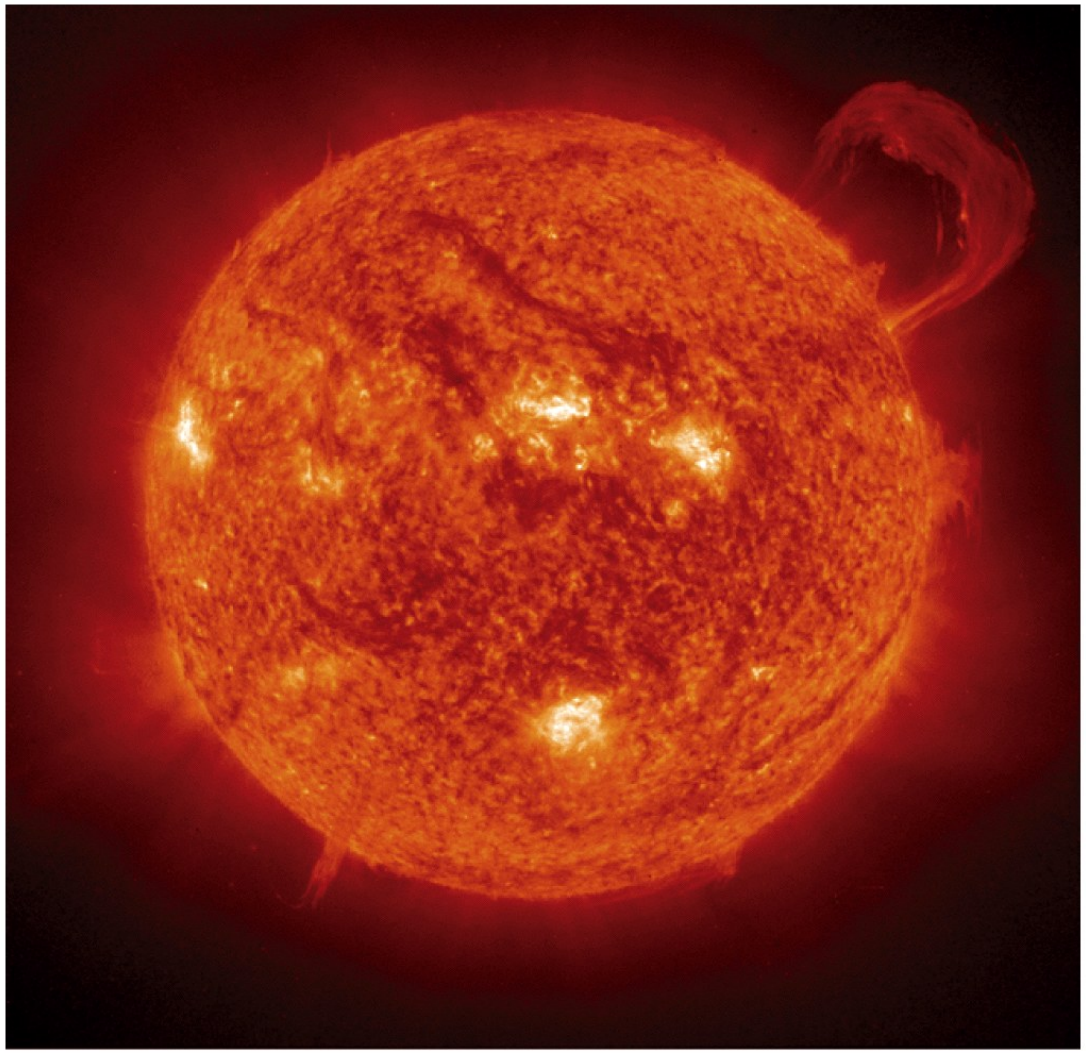
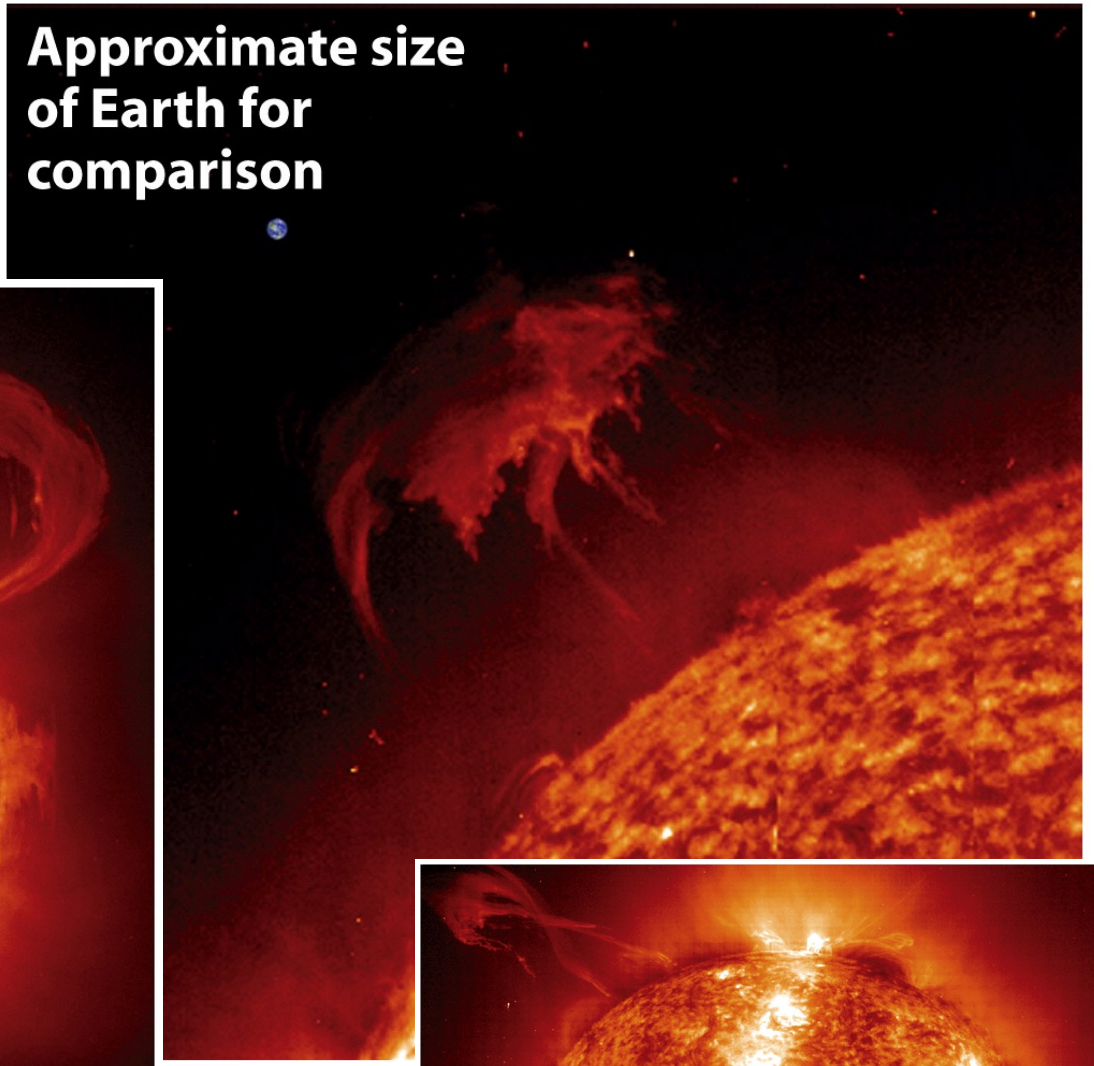
Prominences: arches of gas





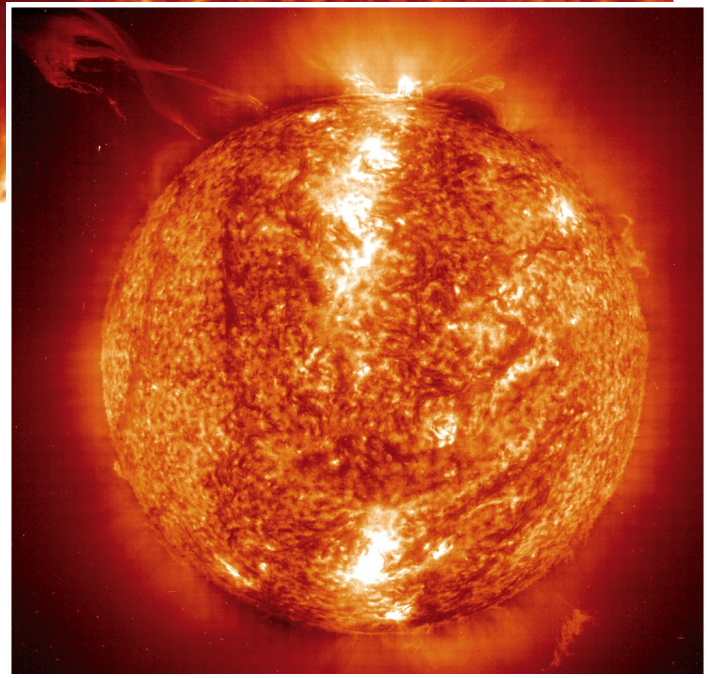



Figure 10-15a
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Flares: violent eruptive events

# Tracing the interplanetary magnetic field

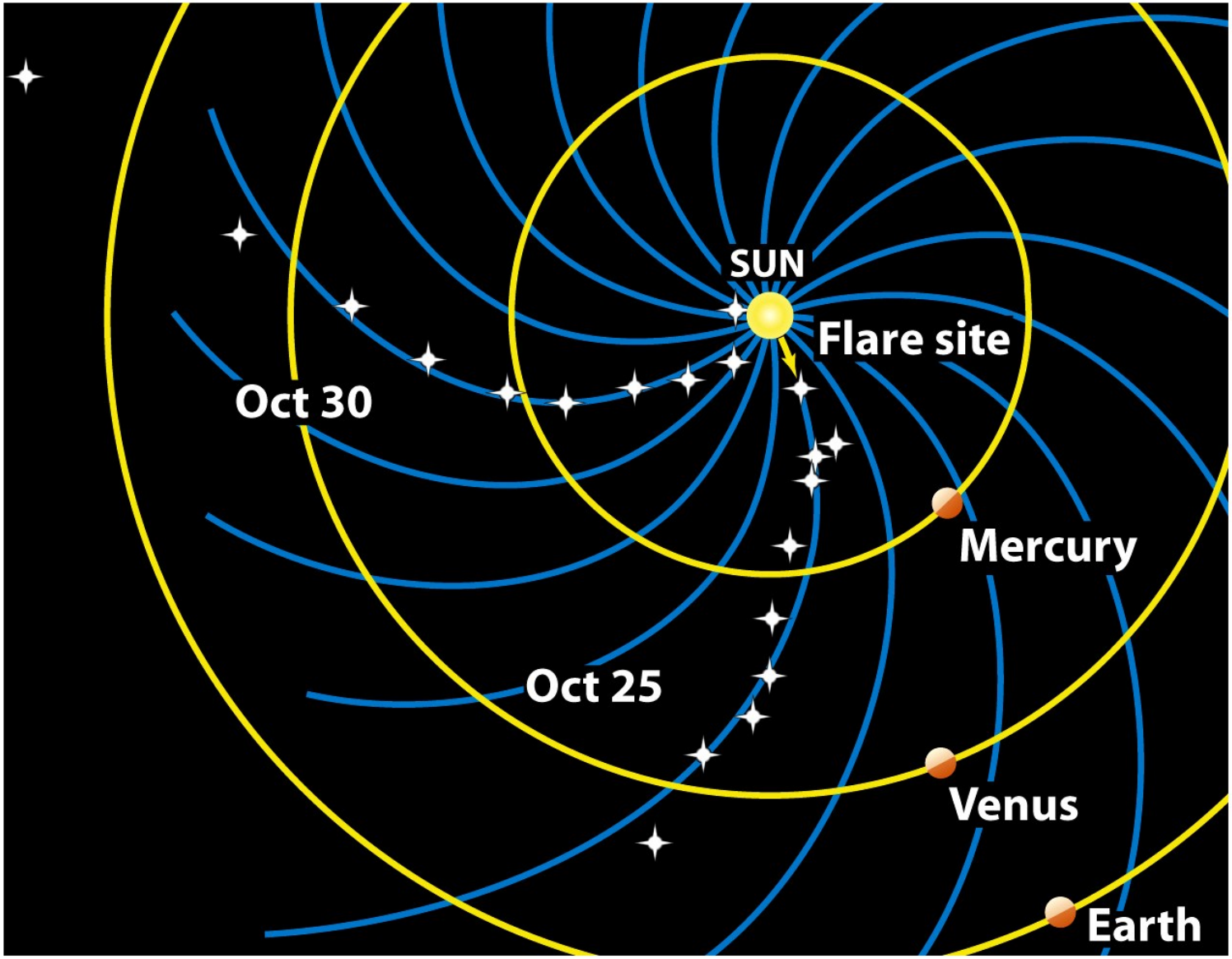


**Figure 10-18**
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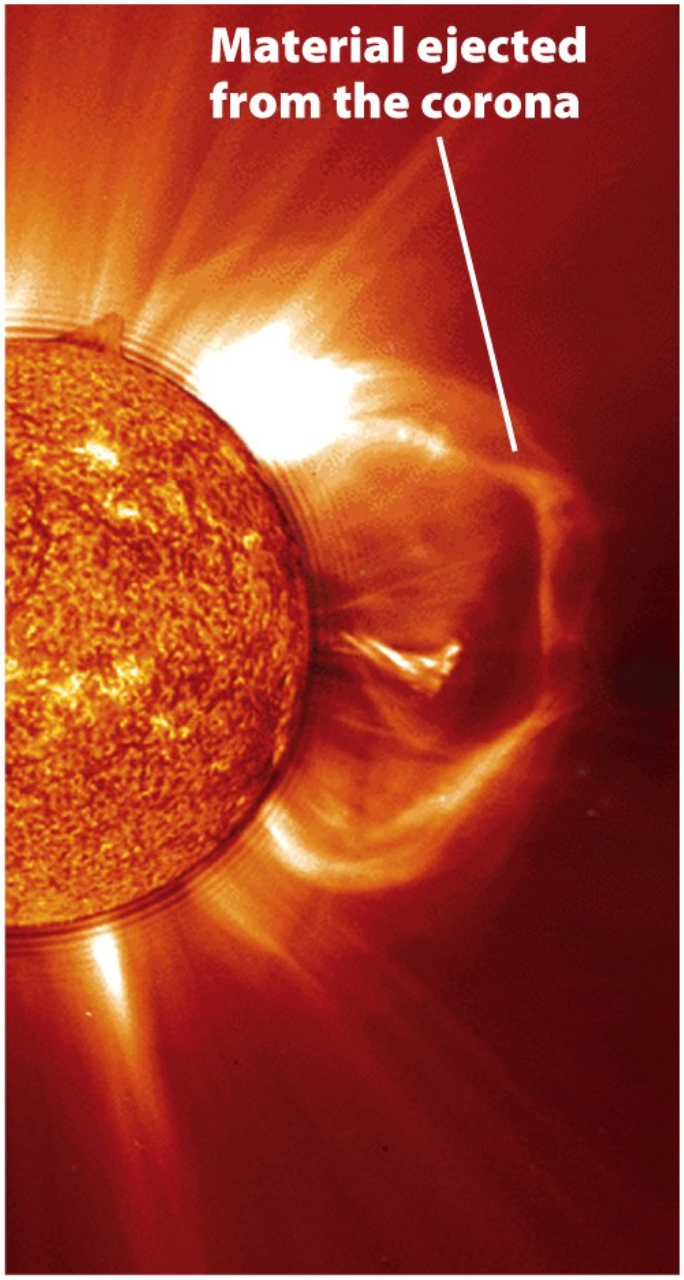
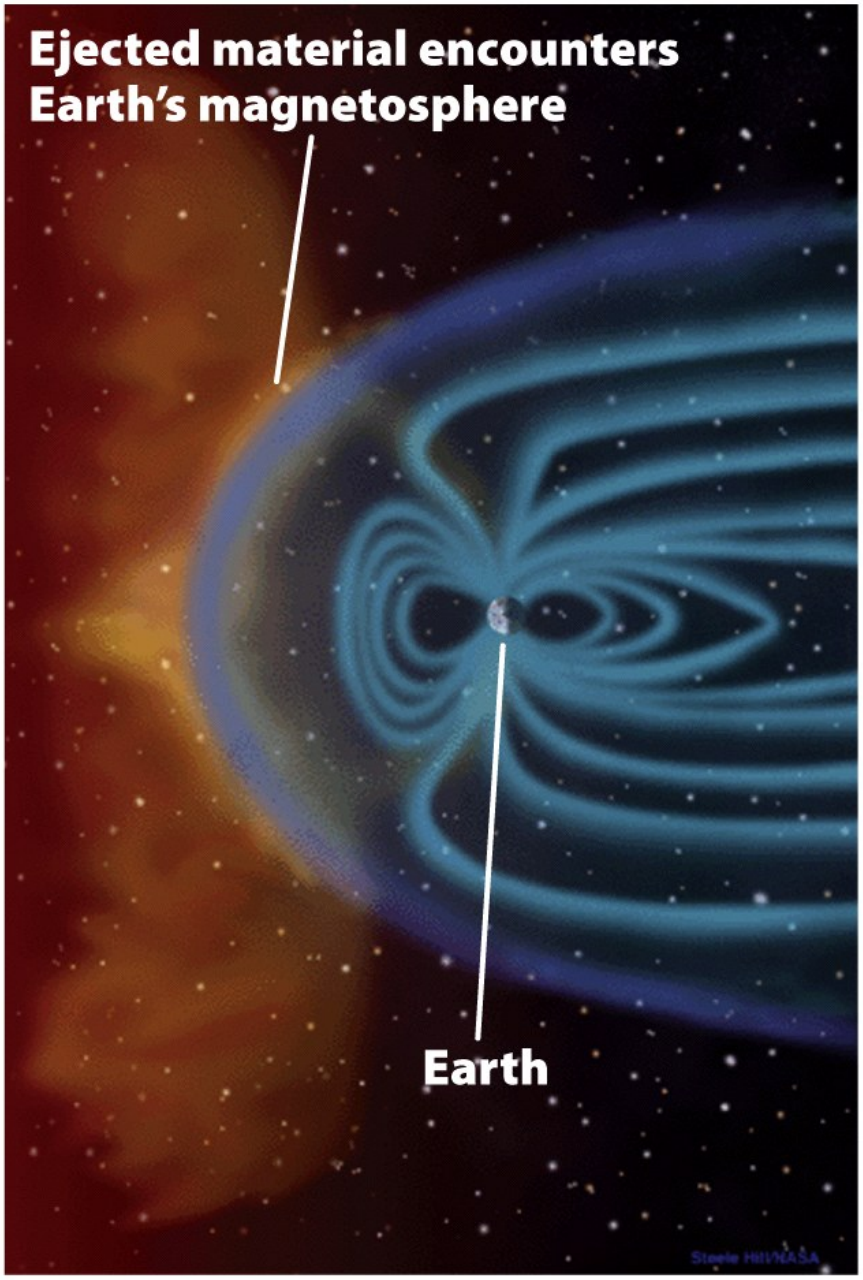



a A coronal mass ejection




b Two to four days later

**Figure 10-19**
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