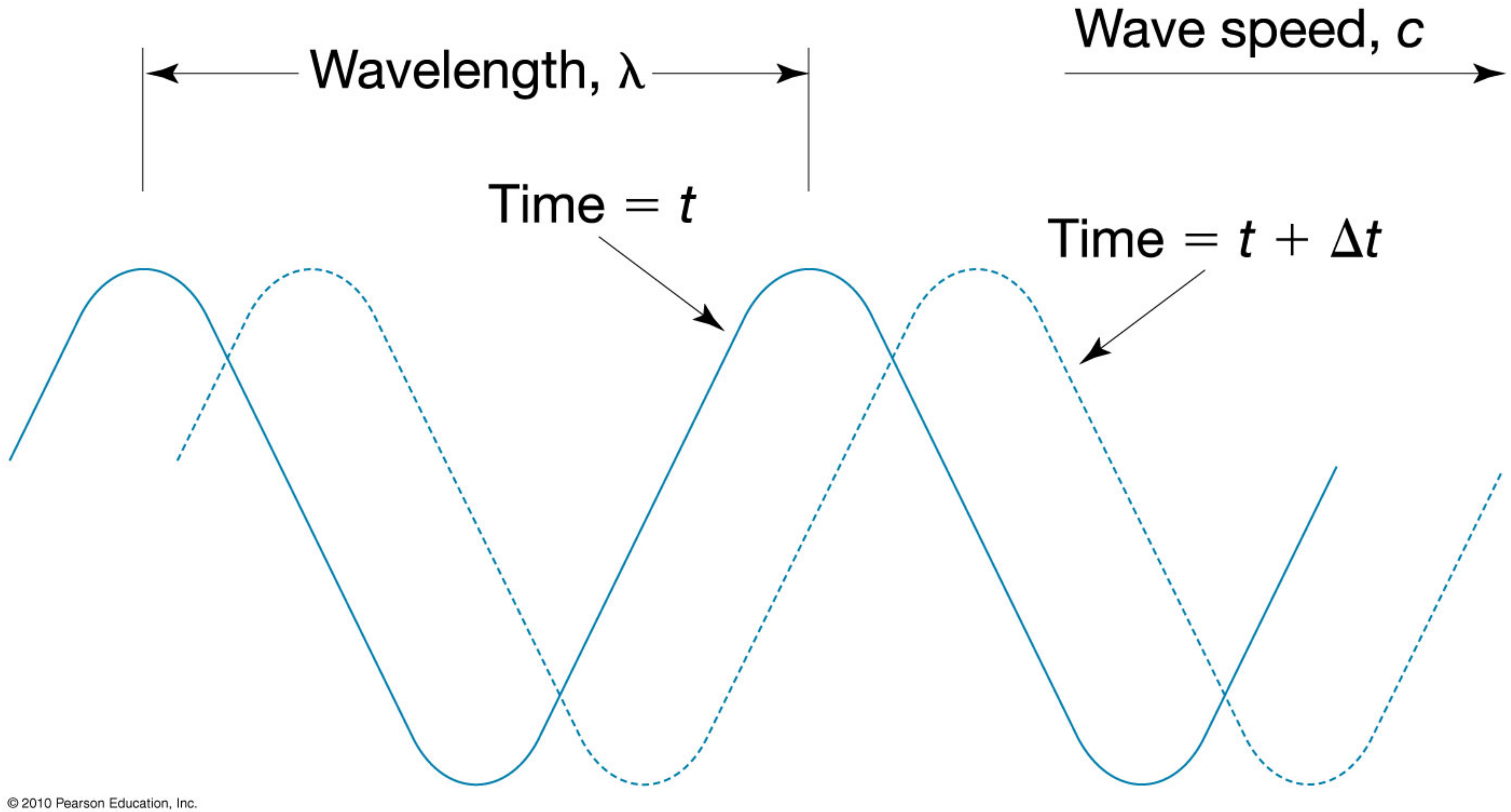
Earth: the Goldilocks Planet

Not too hot…
(460°C)

Not too cold…
(-55°C)

Fig. 3-1

Wave properties:



Wavelength, velocity, and …?

Fig. 3-2

Reviewing units:

Wavelength = distance (meters or nanometers, etc.)

Velocity = distance per unit time (miles per hour, meters per second)

$$\frac{meters}{second}$$

$$\lambda \nu = c$$

(Meters)(?) = (Meters/second)

$$\text{Frequency} = \frac{1}{time}$$

Example: $$\frac{1}{\text{second}}$$

$$\frac{1}{\text{second}} = \text{“per second”} = \text{“Hertz”}$$

Energy of *photon*:

$E = h\nu = hc/\lambda$

(h = Planck's const.)

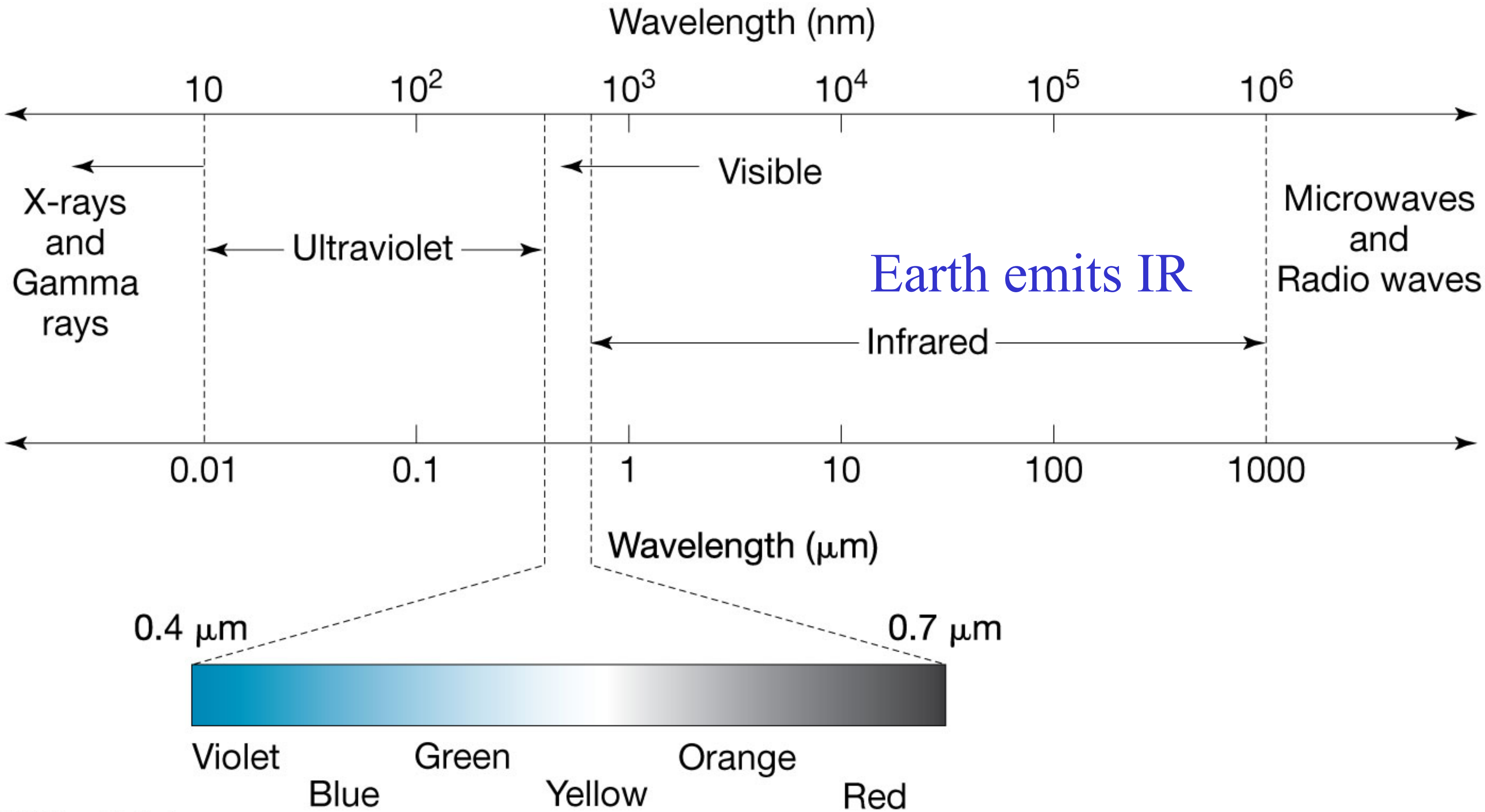
Inverse relationship:

Short λ photons are high E

Long λ photons are low E

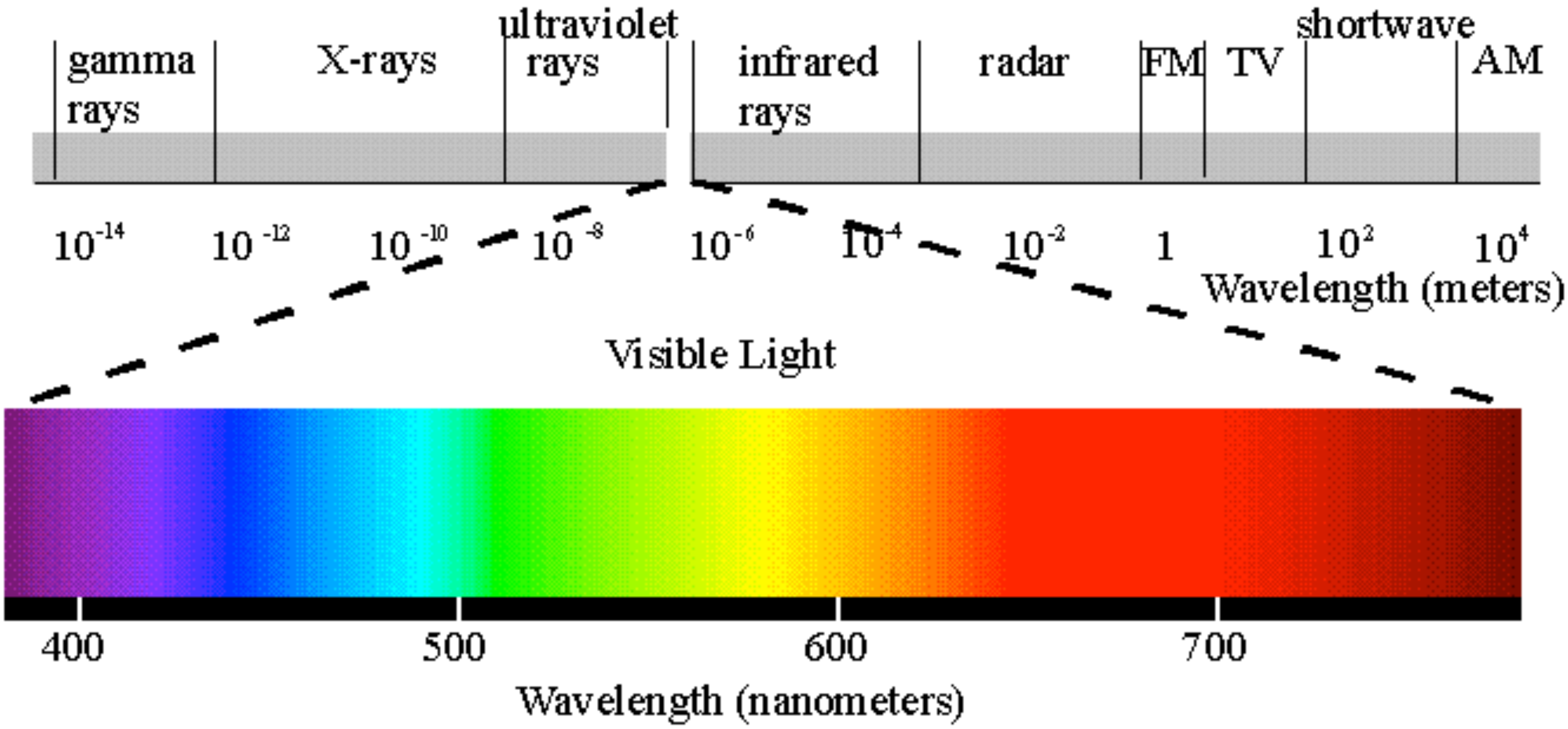
Electromagnetic Radiation:

Fig. 3-3



Incoming from Sun

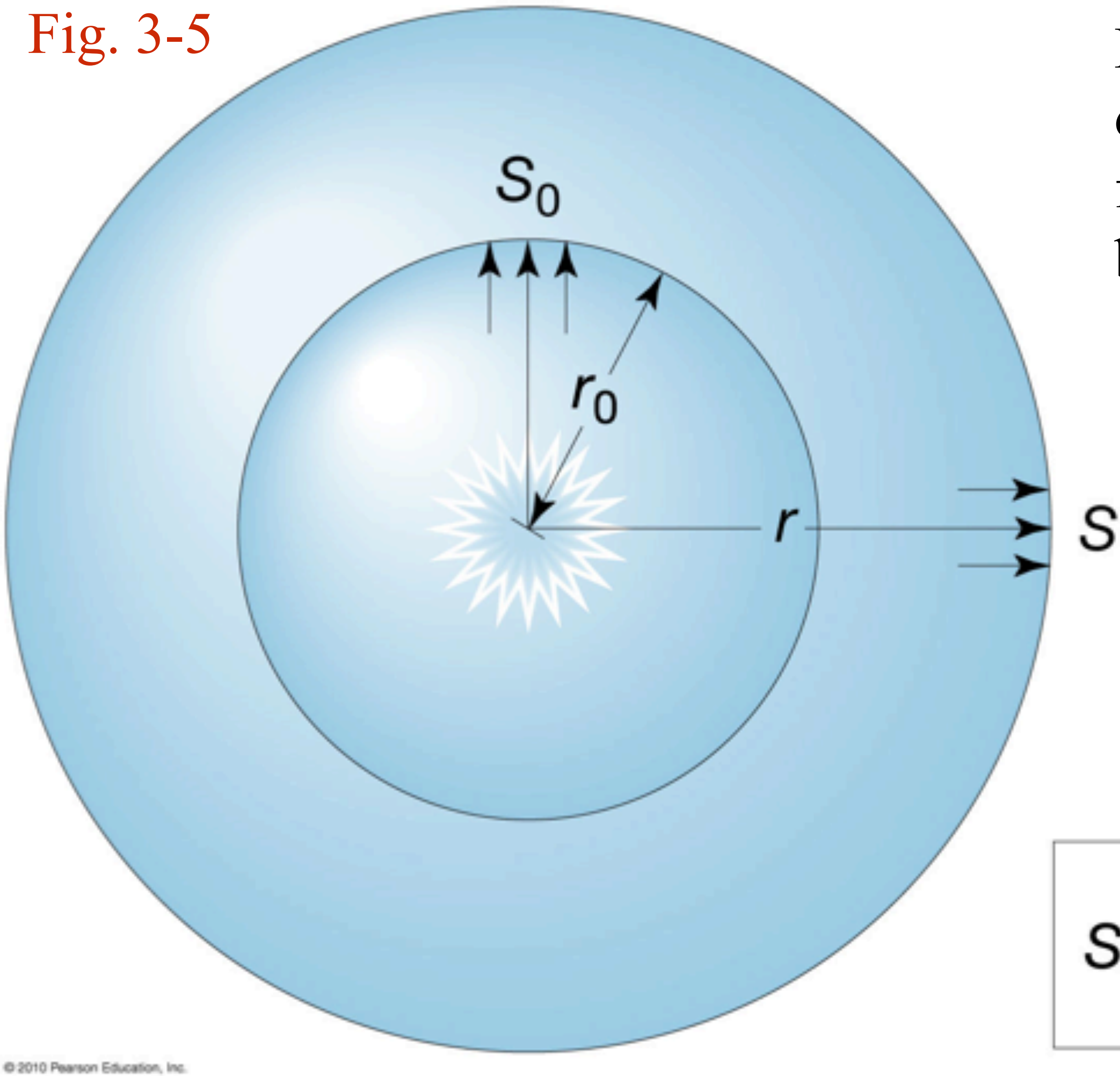
Electromagnetic ("EM") Radiation:



Flux = energy that passes through a given area per unit time

Units: watts per square meter, W/m^2

Fig. 3-5



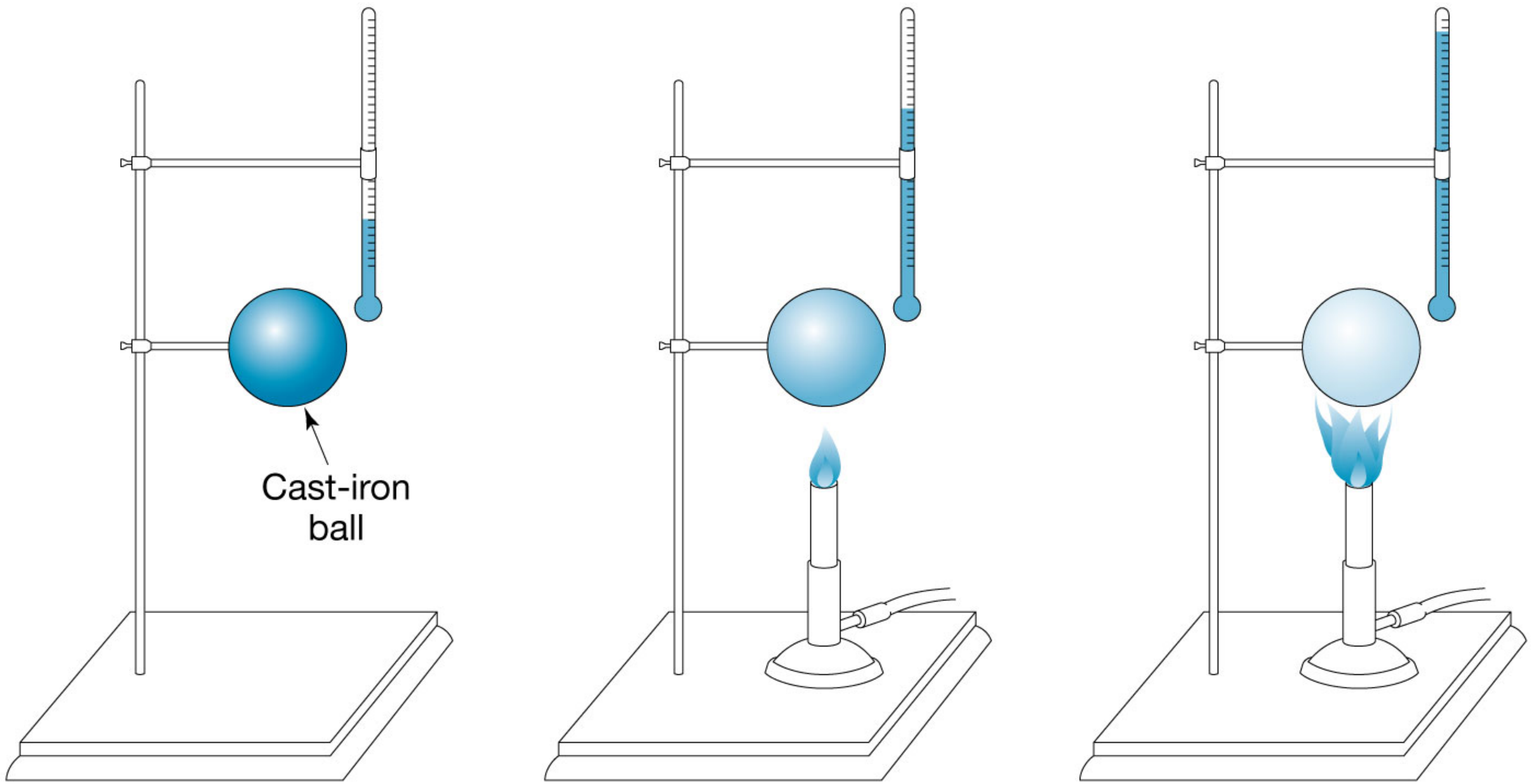
For Sun, energy flux is depends on the distance from the sun, described by inverse-square law:

$$S = S_0\left(\frac{r_0}{r}\right)^2$$

TABLE 3-1 Freezing and Boiling Points of Water by Temperature Scale

Temperature Scale	Freezing Point	Boiling Point (at sea level)
Fahrenheit	32°	212°
Celsius	0°	100°
Kelvin (absolute)	273.15	373.15

Fig. 3-6



Temperature varies with color

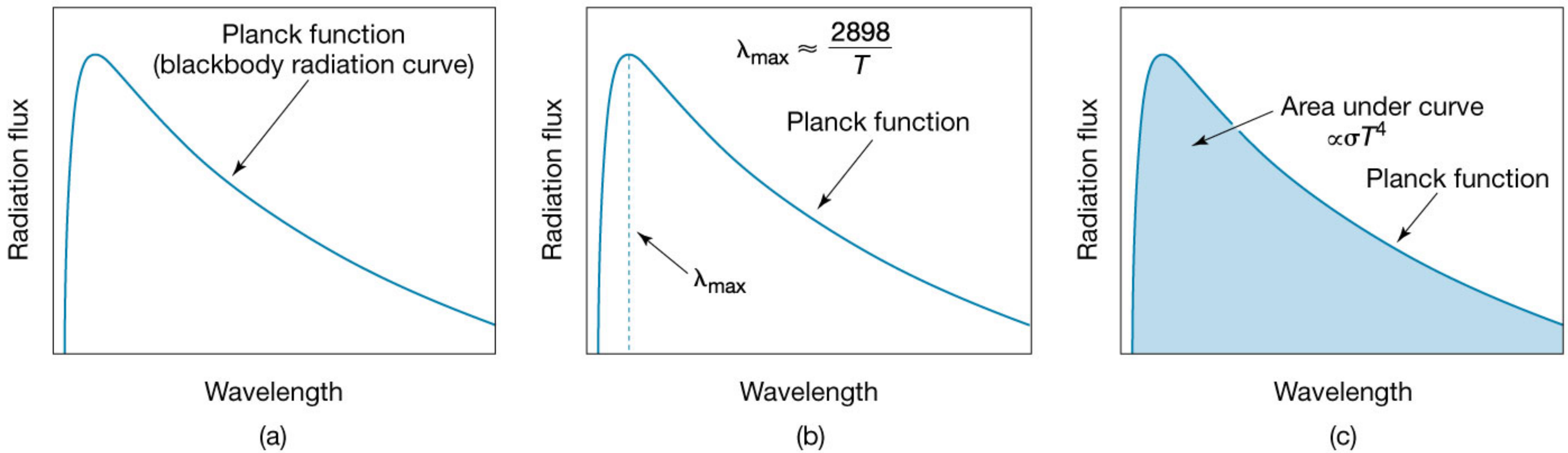
Blackbody radiation:

A blackbody absorbs & emits e-m radiation with 100% efficiency

The wavelength distribution of emitted radiation is a function of T

(red-hot vs. white-hot)

Fig. 3-7 shows a blackbody radiation curve:



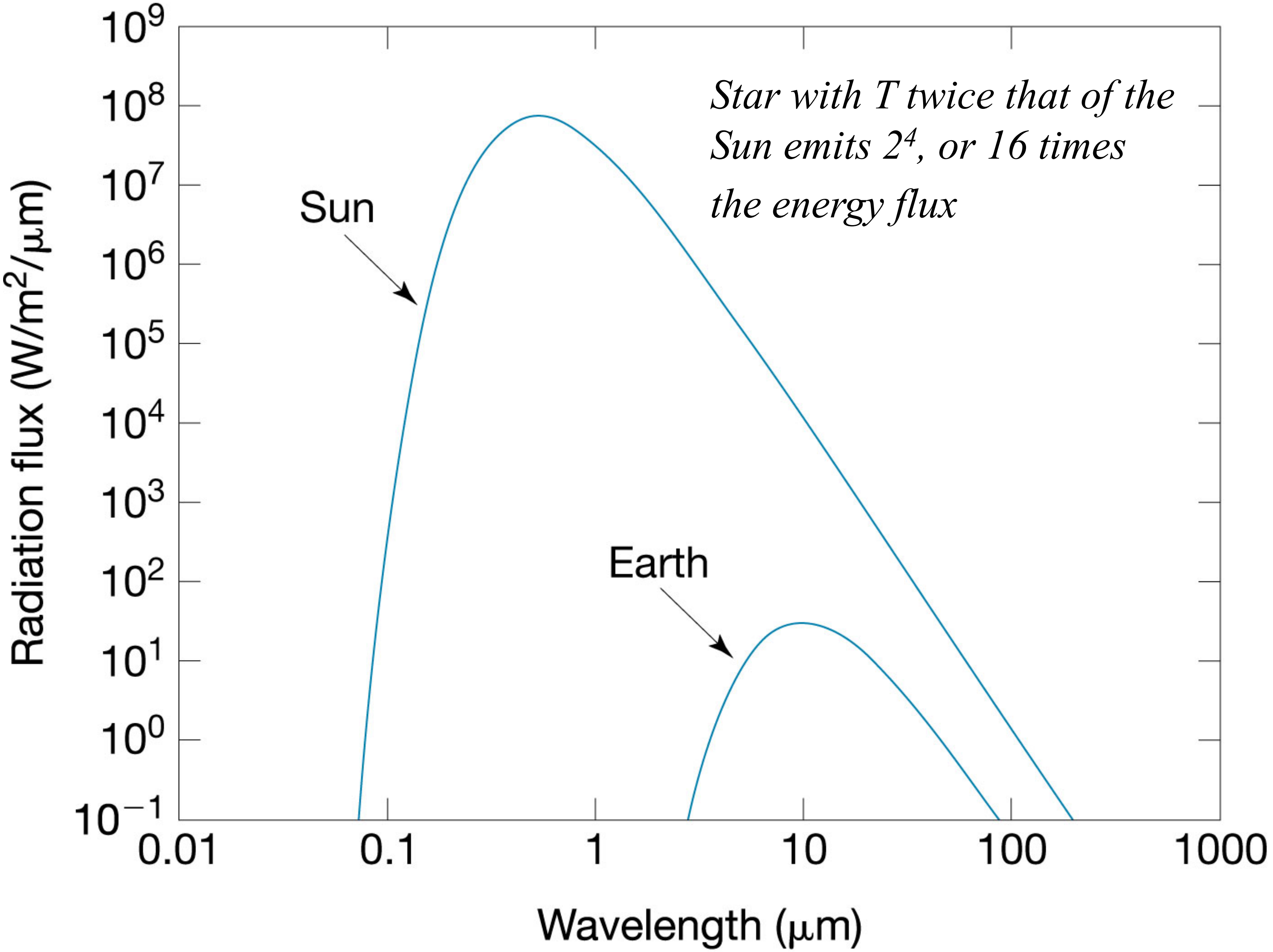
Wien's law: λ of peak flux is inversely related to body's T

λ_{max} (in micrometers) = 2898/T (in Kelvins)

Sun's T is 5780K; Earth's T is 288K; what is λ_{max}?

Stefan-Boltzmann law: total energy flux is proportional to the area under the blackbody radiation curve, and: $\mathbf{F = \sigma T^4}$, σ is a constant

Fig. 3-8

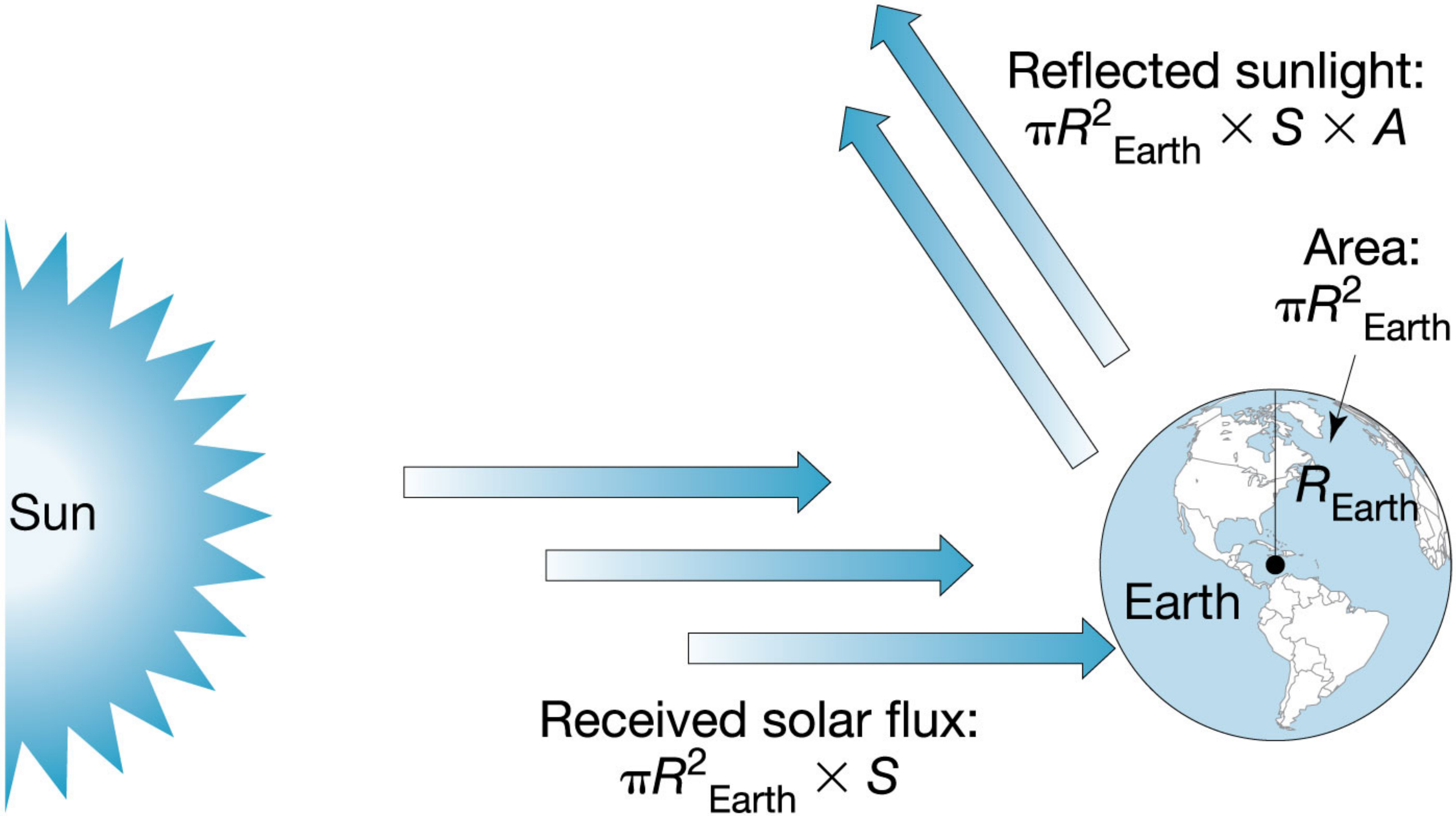


Area of circle: πR^2

Area of sphere: $4\pi R^2$

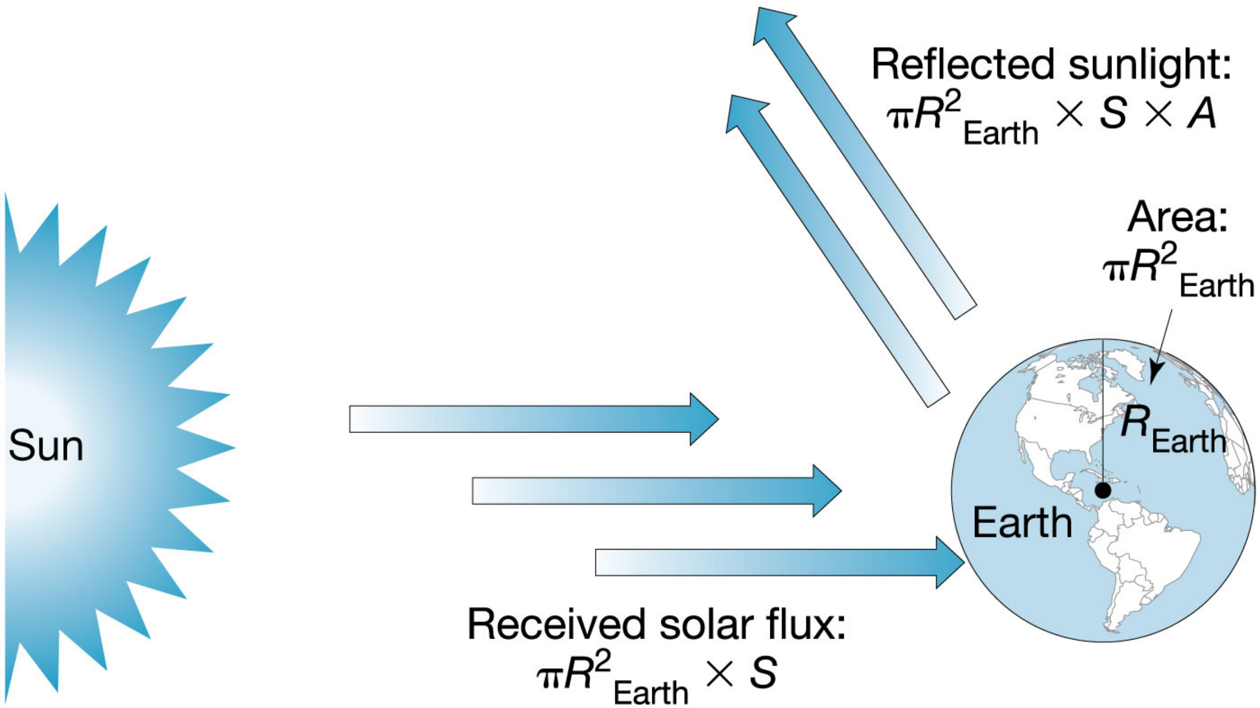
Earth's Energy Balance (Budget):

Energy absorbed = Energy emitted



Box Fig. 3-1

Planetary energy balance: E absorbed = E emitted

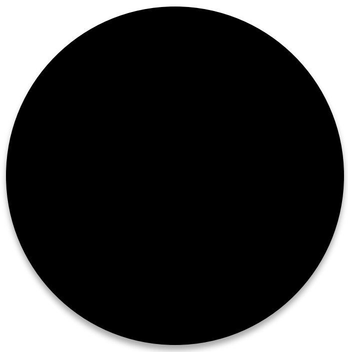


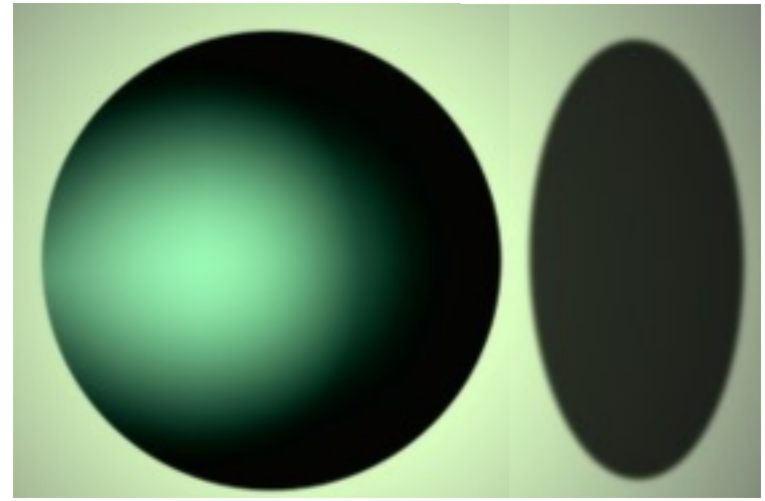
Box Fig. 3-1

S = Power flux at Earth's distance from Sun: ~ 1,367 W/m²
What is the power for each square meter of Earth's surface?

Energy absorbed = Energy Intercepted – Energy Reflected

"Intercepted" power … how many m²?





(E intercepted) - (E reflected) =

$$(\pi R^2 S) - (\pi R^2 SA) = \pi R^2 S(1-A)$$

(S = solar flux, A = albedo)

We know energy absorbed (E_{abs}), and from energy balance:

E emitted by Earth = $4\pi R^2 \times \sigma T^4$
(surface area) x (flux per unit area)

$$\mathbf{E_{emit} = E_{abs} : \quad 4\pi R^2 \sigma T^4 = \pi R^2 S(1\text{-}A)}$$

Divide both sides by $4\pi R^2$,

$$\mathbf{\sigma T^4 = (S/4)(1\text{-}A)}$$

Earth Energy Balance:

Energy received by the Earth

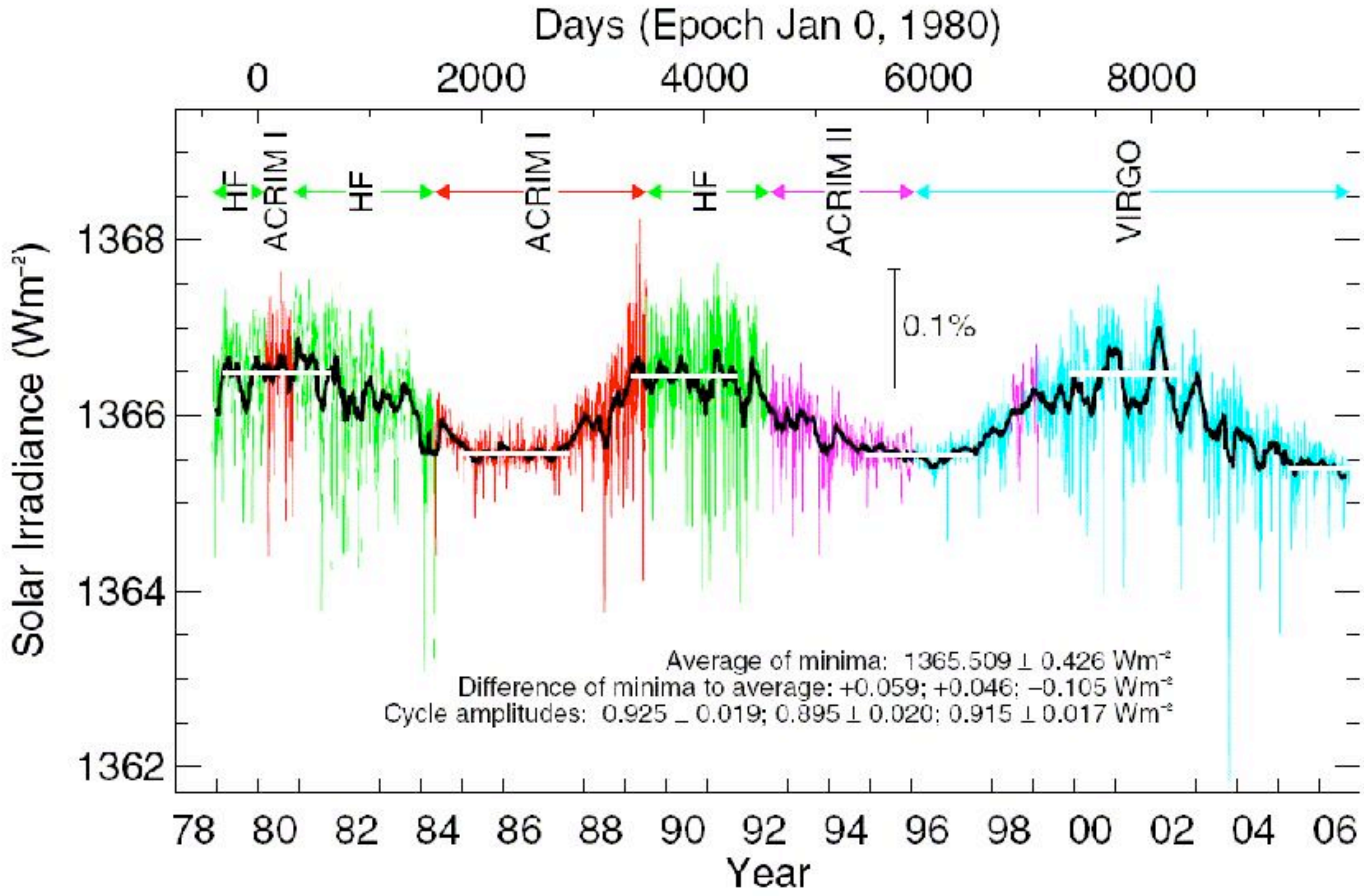
$$\sigma T_e^4 = \frac{S}{4}(1 - A)$$

Energy radiated by the Earth

$$T_e = \sqrt[4]{\frac{S}{\sigma 4}(1 - A)}$$

(Equations found on page 43)

Satellite data (different satellites over time)



Planetary energy balance: E absorbed = E emitted

Combined equation: $\sigma T^4 = (S/4)(1\text{-}A)$ (p. 43)

$S = 1370\ W/m^2$
$A = 0.3$
$\sigma = 5.67 \times 10^{-8}\ W/m^2/K^4$

Substituting these values into equation, get
$T_e \sim 255K$ (-18°C). (No greenhouse effect)

$\Delta T_g = T_s - T_e = 288\ K - 255\ K = 33°C$

If Earth had no clouds, then $A = 0.1$

If no clouds (and no greenhouse), what is T_e? 271.4 K

Composition of the atmosphere; N_2, O_2, Ar are not greenhouse gases

Table 3-2 Major Constituents of Earth's Atmosphere Today

Name and Chemical Symbol	Concentration (% by volume)
Nitrogen, N_2	78
Oxygen, O_2	21
Argon, Ar	0.9
Water vapor, H_2O	0.00001 (South Pole)–4 (tropics)
Carbon dioxide, CO_2	0.039*

*In 2008.

Table 3-3 Important Atmospheric Greenhouse Gases

Name and Chemical Symbol	Concentration (ppm by volume)
Water vapor, H_2O	0.1 (South Pole)–40,000 (tropics)
Carbon dioxide, CO_2	390
Methane, CH_4	1.7
Nitrous oxide, N_2O	0.3
Ozone, O_3	0.01 (at the surface)
Freon-11, CCl_3F	0.00026
Freon-12, CCl_2F_2	0.00048

Structure of the atmosphere

P decreases exponentially with increased altitude

T decreases then increases from surface up through stratosphere

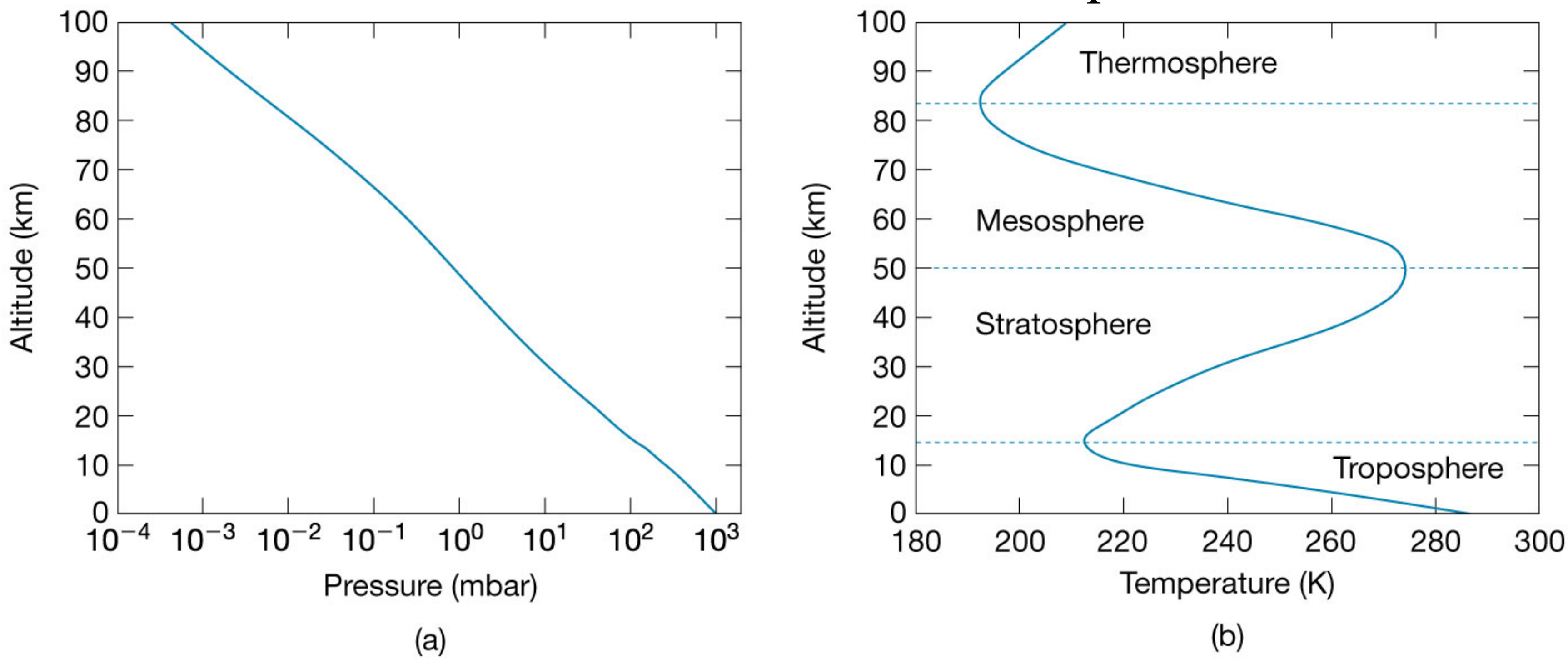


Fig. 3-9

But why does T increase in stratosphere?

Why does T go up in stratosphere at ~50 km?: Ozone absorbs solar UV radiation. (Ozone conc. is highest at 30 km, but more UV is available at 50 km.) This means ozone is a greenhouse gas.

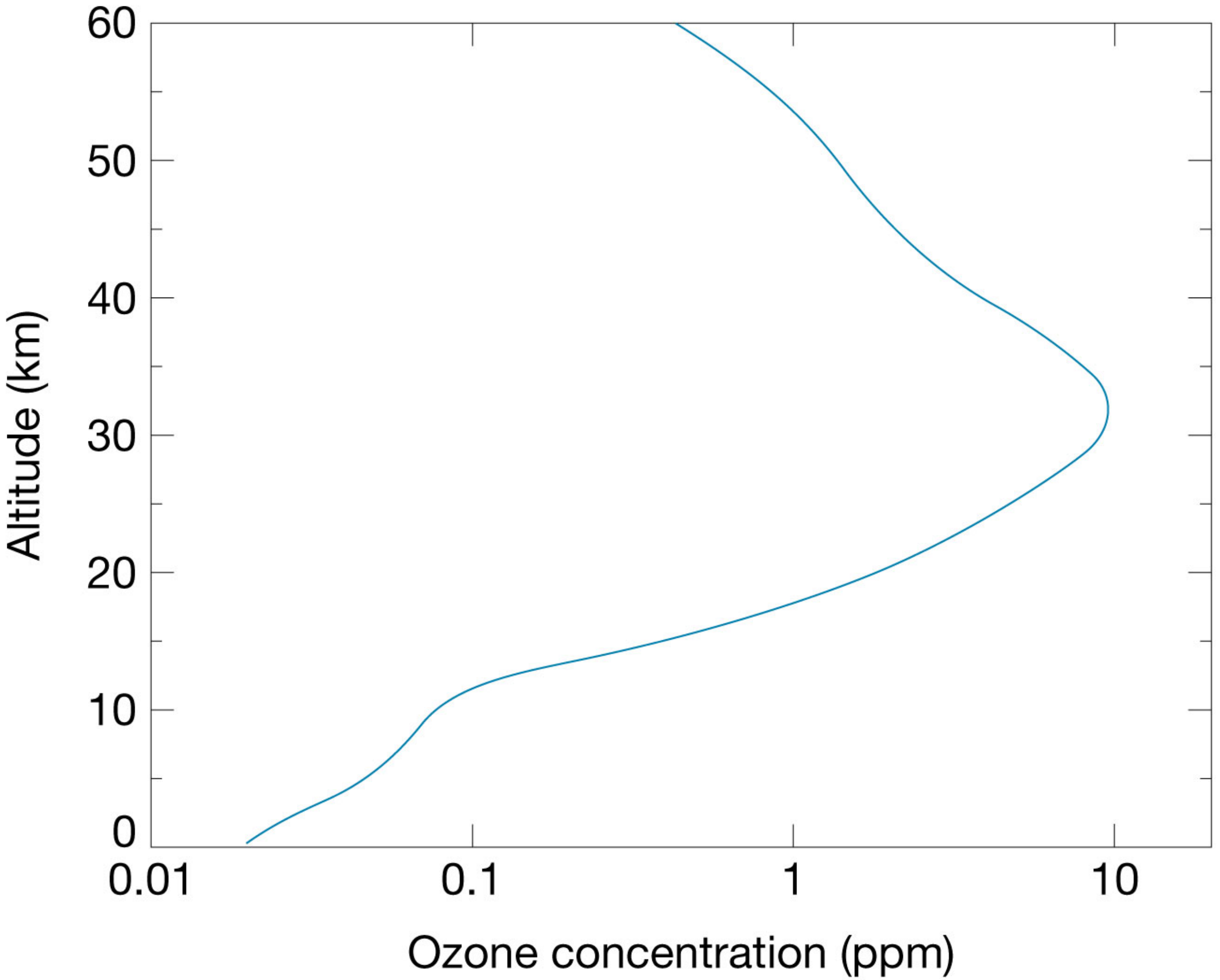
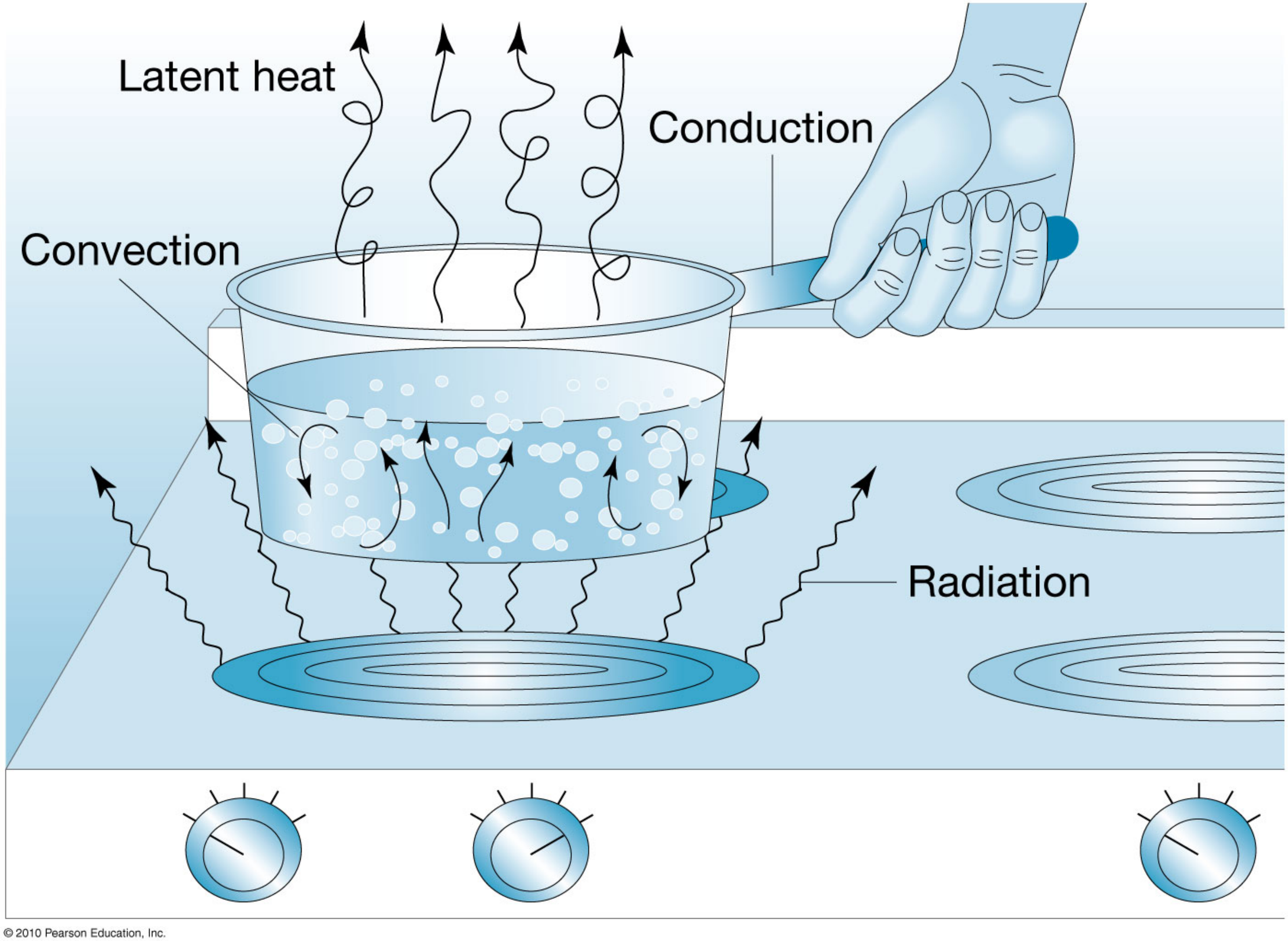


Fig. 3-11

Fig. 3-10

Heat Transfer…



Greenhouse gas: must absorb & emit IR radiation

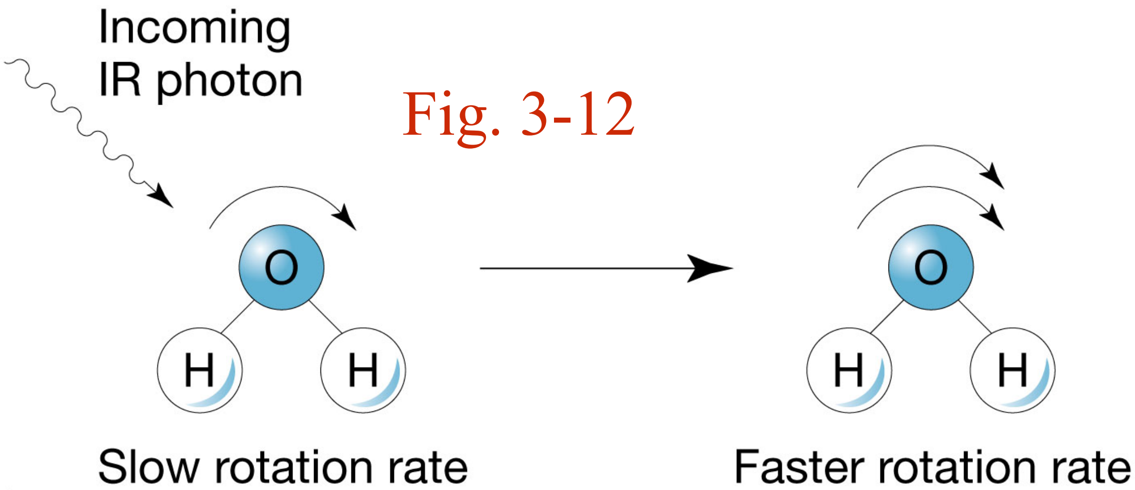


Fig. 3-12

If e-m wave has just the Right frequency, molecule can absorb it, which makes the molecule rotation rate increase. The frequency needed depends on the molecule's structure.

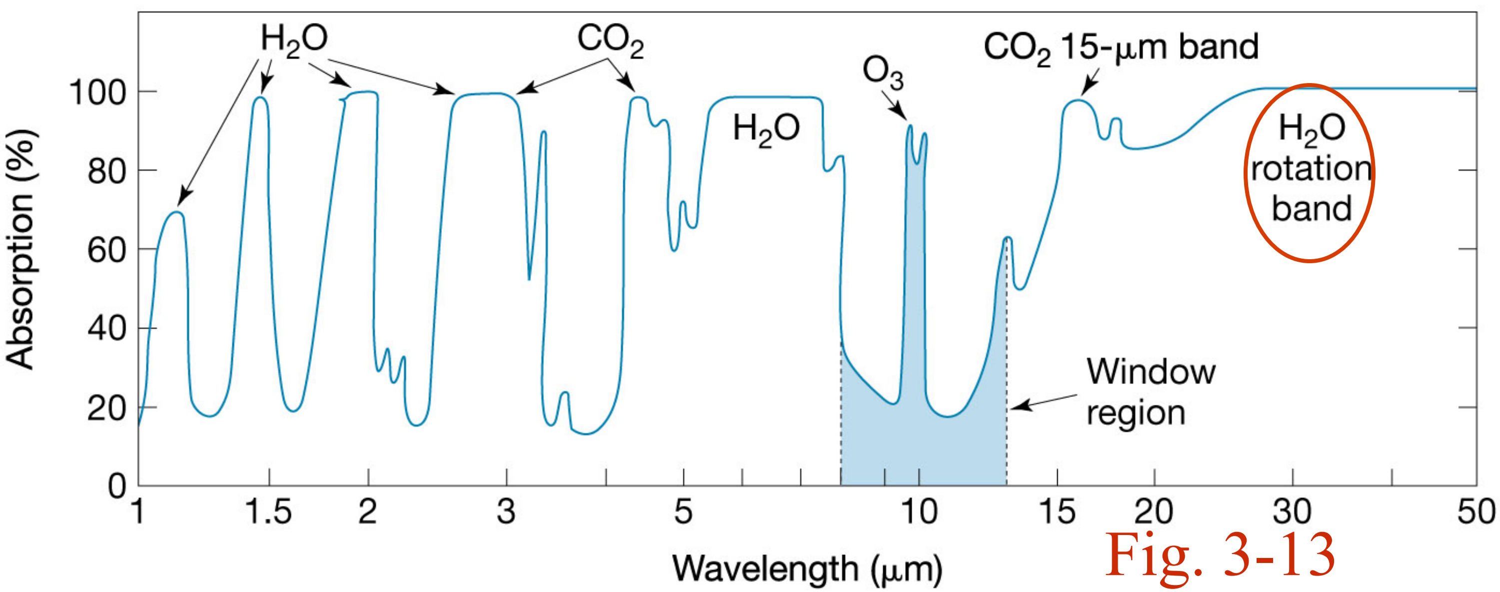
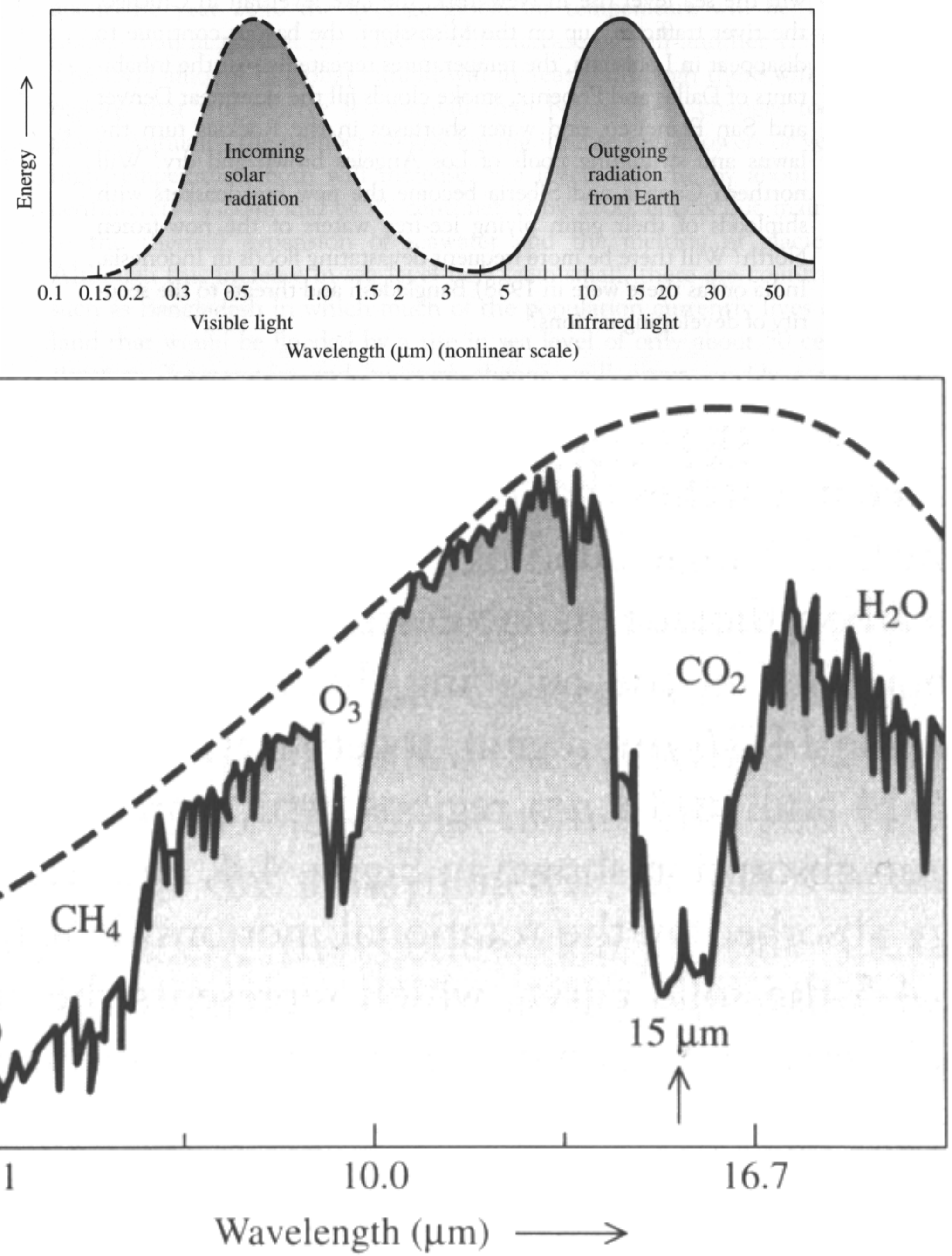


Fig. 3-13

Water absorbs E with 12 to 1000 microns λ (microwaves)



Energy
Incoming solar radiation
Outgoing radiation from Earth
0.1 0.15 0.2 0.3 0.5 1.0 1.5 2 3 5 10 15 20 30 50
Visible light
Infrared light
Wavelength (μm) (nonlinear scale)
Light intensity
H_2O
CH_4
O_3
CO_2
H_2O
15 μm
0
7.1
10.0
16.7
Wavelength (μm)

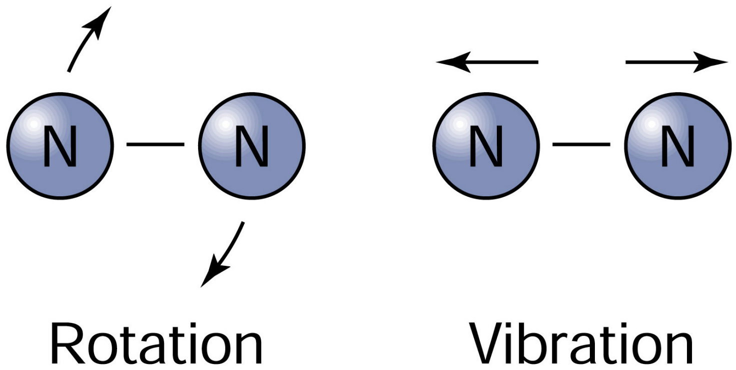
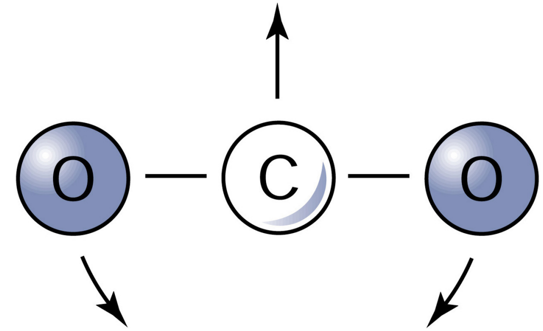


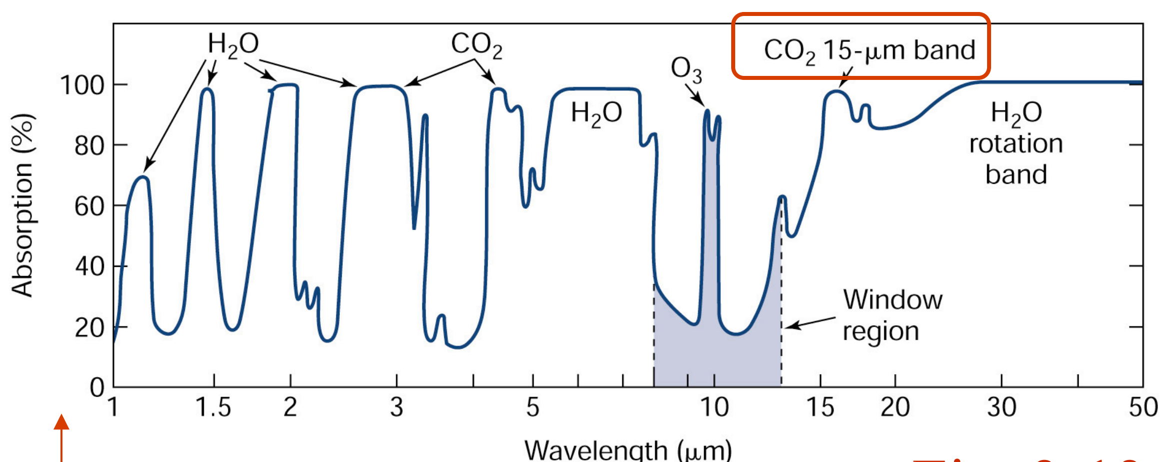
Fig. 3-14,15



Bending mode
(15-μm band)

If frequency of wave matches frequency of vibration, photon can be absorbed and molecule vibrates more vigorously.

A CO_2 molecule can vibrate in several ways including by bending. The bending mode has a 15 micron wavelength.



Visible light

Fig. 3-13

Earth's IR emissions peak at ~ 15 microns, which is why CO_2 is such an important greenhouse gas.

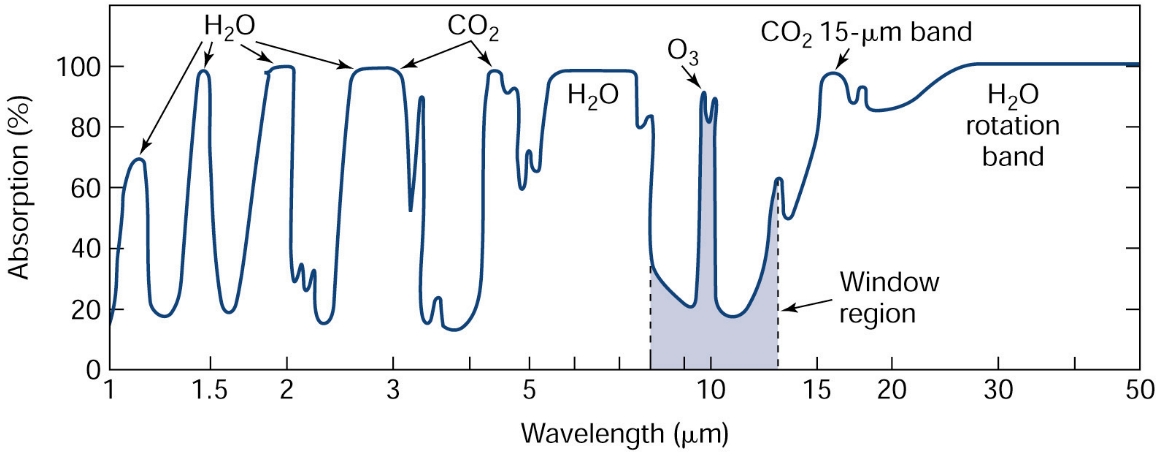


Fig. 3-13

"Window region" is where H_2O and CO_2 are poor absorbers. Freons absorb in this frequency range, so does ozone.

On a separate note…

N_2 and O_2 are perfectly covalent and have no separation of positive and negative charge in the molecule (no dipole); the molecule is also symmetrical. An e-m wave can't have a ***net*** interaction with a totally symmetric molecule.

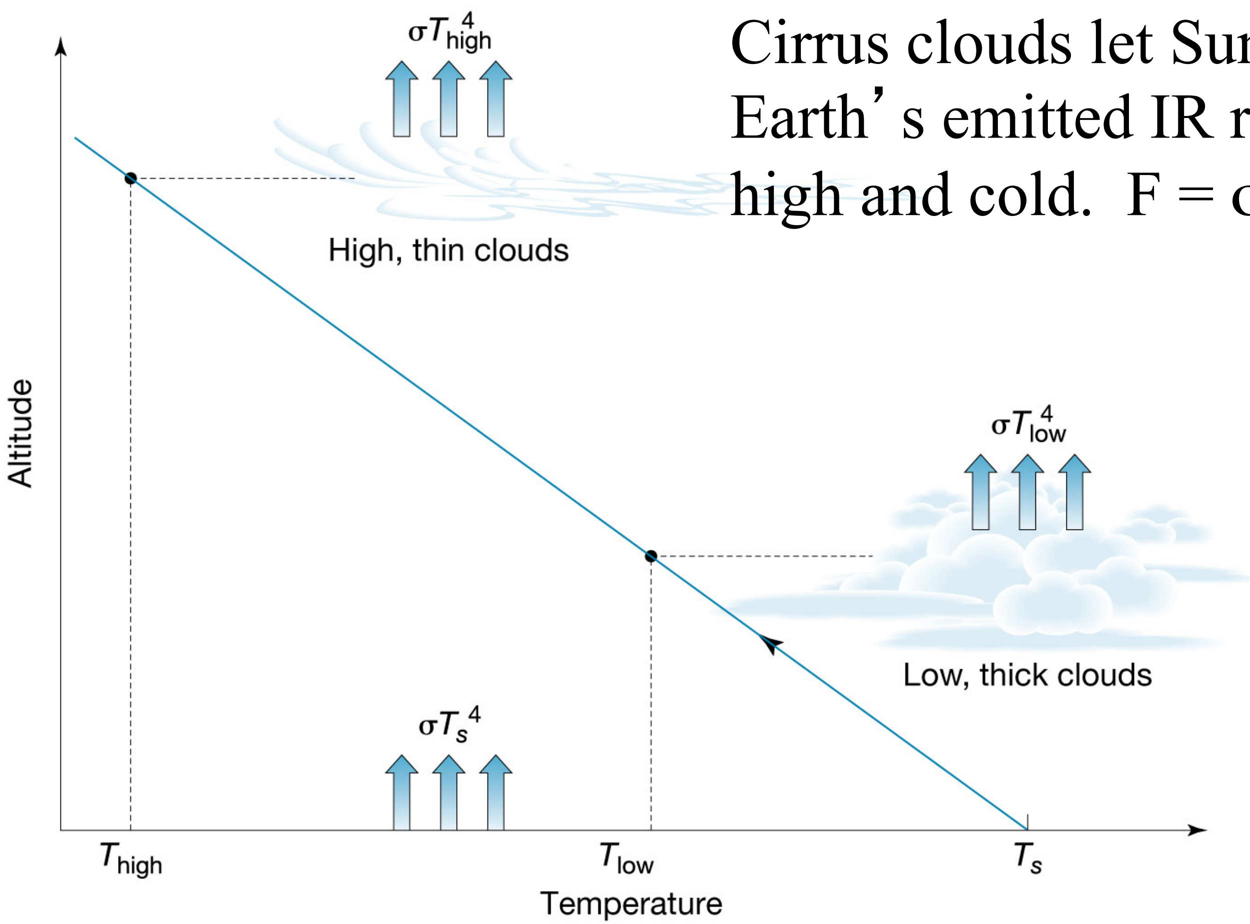
(a)

Fig. 3-17a

(b)

Fig. 3-17b

Clouds: they are white, and increase Earth's albedo
They are made of H_2O and absorb some IR radiation emitted by Earth. They both cool and warm!



Cirrus clouds let Sun E through, but absorb Earth's emitted IR radiation. They are up high and cold. $F = \sigma T^4$

Stratus clouds reflect Sun's rays. They are warmer, so they radiate more IR energy to space.

Fig. 3-18

Clouds are tricky in climate models!

Earth's atmospheric energy budget, setting solar radiation to 100

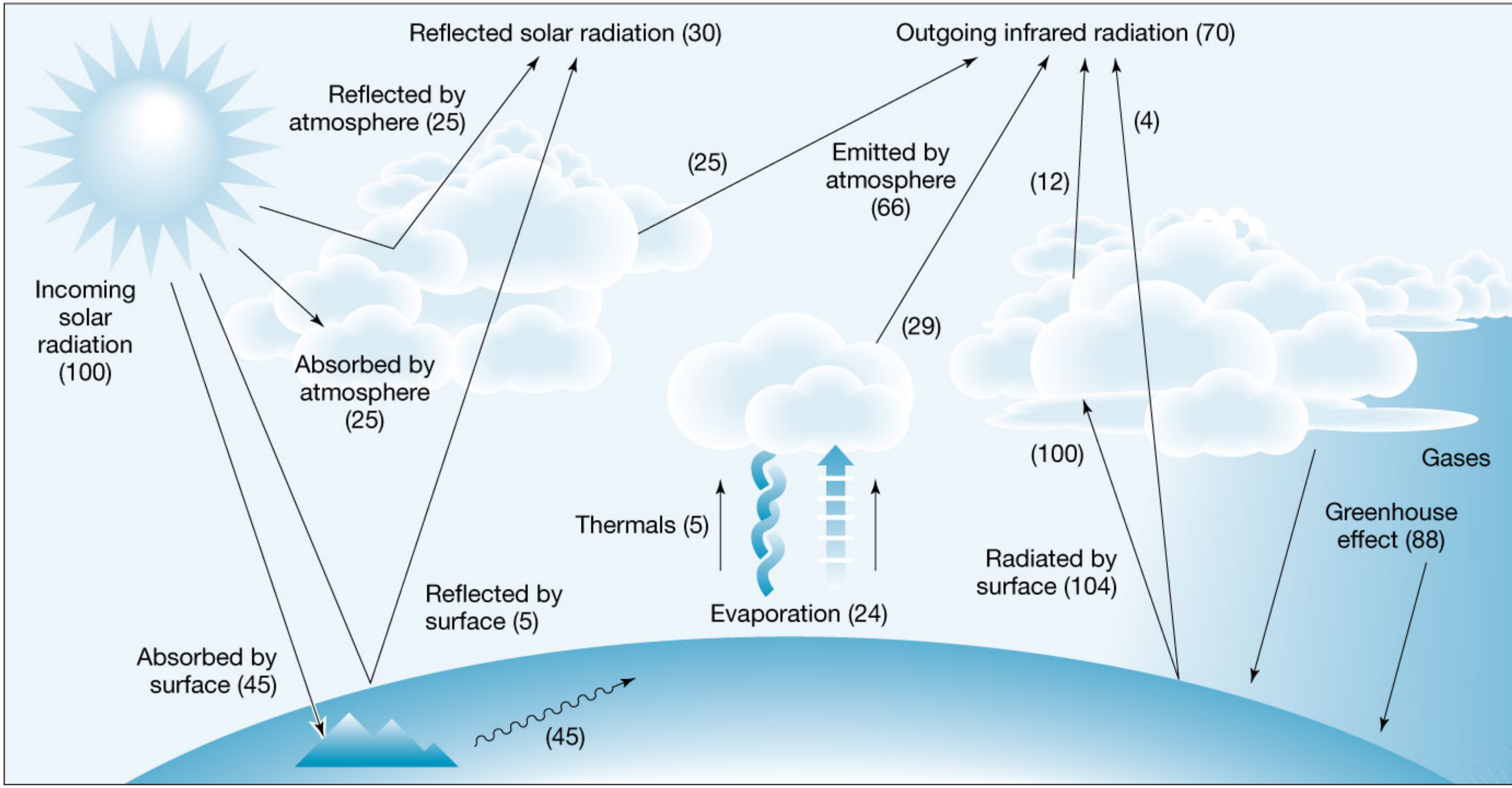


Fig. 3-19

Climate feedbacks:

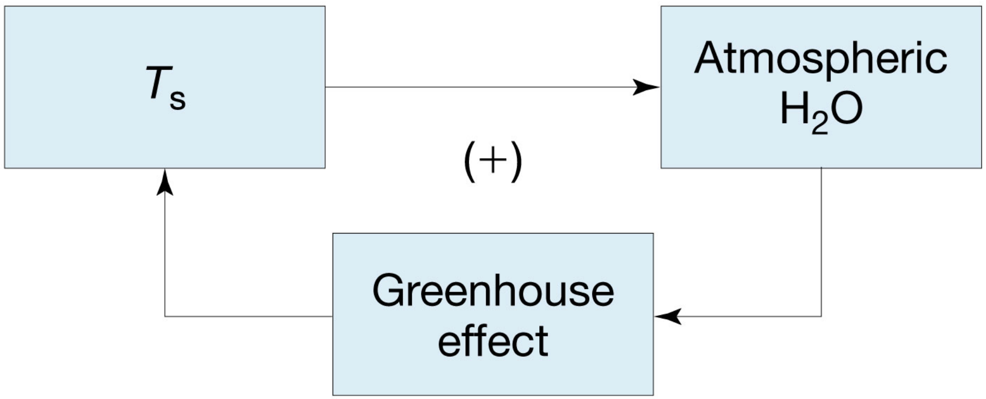


Fig. 3-20

Water vapor: if T goes up (maybe due to more CO_2)…

(this pos. fb. doubles effect of surface T increase in response to CO_2 increase)

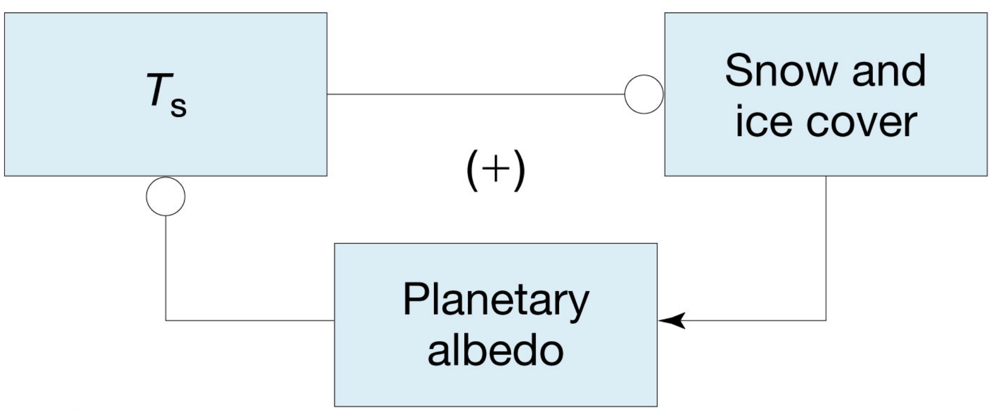


Fig. 3-21

Snow and Ice: if T goes down…

We' d be in trouble if it weren' t for IR flux/T feedback!

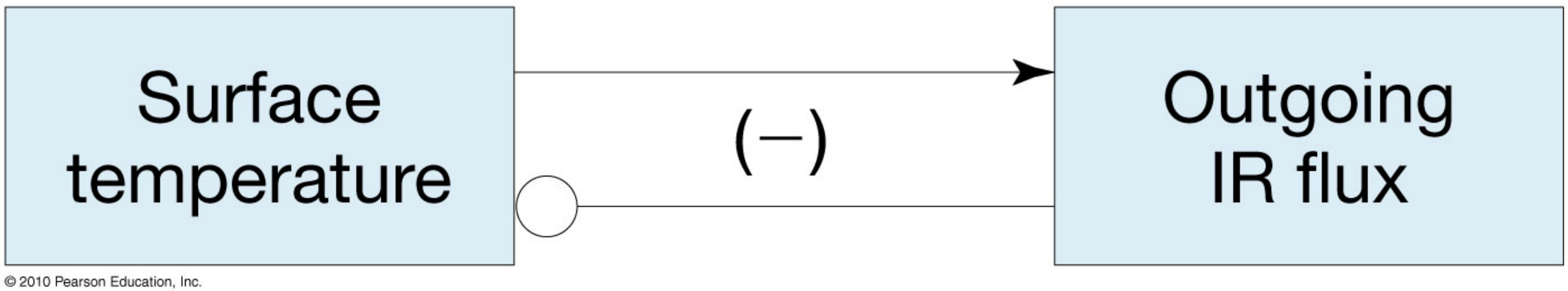
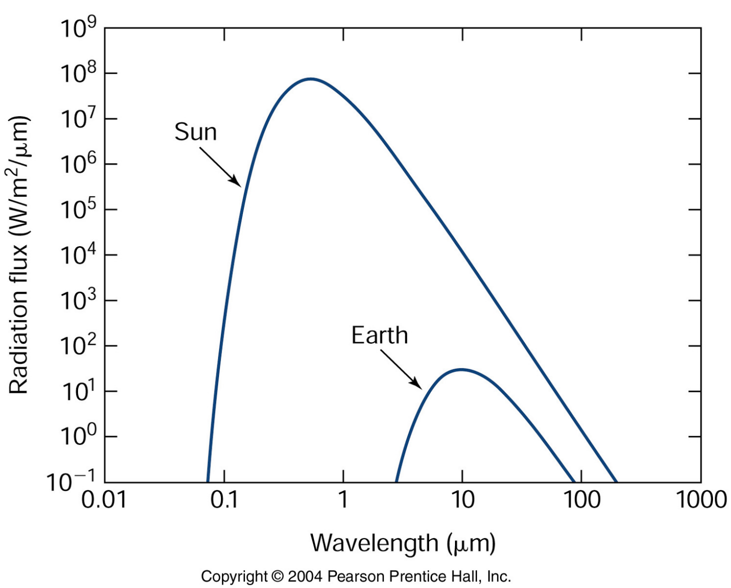


Fig. 3-22



Stefan-Boltzmann law:

$F = \sigma T^4$, where σ is a constant

Fig. 3-8

Global E balance

- Earth is warmed by absorption of visible light from the Sun and cooled by emission of IR radiation to space
- Greenhouse gases absorb IR radiation by increasing rotation or vibration rates. Each gas absorbs particular wavelengths
- Feedbacks regulate climate change:
  - Water vapor, snow and ice positive fb loops
  - IR flux-T negative feedback loop
  - Clouds contribute to climate feedback but effect is not well known.