

Monday, Nov. 24

Syllabus, class notes, and homeworks are at:

[www.as.utexas.edu](http://www.as.utexas.edu) → courses → AST 301, Lacy

Reading for this week: chapter 17

We won't have a help session this week.

Today: Temperatures on the surfaces of planets

## Topics for this week

How can we use the concept of thermal equilibrium to calculate the temperature of the surface of a rock orbiting the Sun?

How does the result depend on the distance of the rock from the Sun?

How does the Earth's atmosphere affect the surface temperature of the Earth?

Why do Venus and Mars have such different surface temperatures?

How are we changing the Earth's atmosphere, and how do we think this will affect the surface temperature?

## The terrestrial planets

All four terrestrial planets have interiors made mostly of partially molten metals (iron) and rocks. Mercury and Mars have about  $\frac{1}{2}$  the diameter of Earth and Venus.

Mercury has almost no atmosphere. Its surface temperature ranges from 100K to 700K (-300°F to 800°F).

Venus has about 100 times denser atmosphere than the Earth's. Its surface is a uniform 740K (880°F).

Earth has an atmosphere about 1000 times less dense than liquid water. Its average surface temperature is about 290K (60°F).

Mars has an atmosphere about 100 times less dense than the Earth's. Its surface temperature ranges from 130K to 290K (-220°F to 70°F).

Why are these atmospheres and temperatures so different?

# Equilibrium

A balance between opposing influences

Consider a can with a hole in its bottom, held under a faucet.

Is it possible for the level of water in the can to come to an equilibrium?

What are the opposing influences?

What would happen if you turned up the flow of water into the can?

## A new equilibrium

If one influence changes, we could have a new equilibrium if that made the other influence change.

If the flow of water into the can increased, the water level would rise.

That would increase the pressure in the can causing the flow out of the can to increase too.

If the flow out rose to equal the flow in, the water level would stop rising.

We would have a new equilibrium.

## A rock in space

Consider a black rock orbiting the Sun.

Energy is flowing into the rock because it is absorbing sunlight.

If there were no way for energy to flow out of the rock, what would happen?

- A. it would get hotter and hotter until it vaporized
- B. it would get hot but it would never vaporize
- C. it would be kept cool because space is cold

How does energy flow out of a rock in space?

- A. by radiation from the rock
- B. by conduction into the surrounding space
- C. by reflecting sunlight

## Flow of energy = Power

The temperature of the rock will come to an equilibrium if the flow of energy out of the rock (by radiation) balances the flow into the rock (by absorbing sunlight).

The unit used to measure energy is the Joule.

The unit used to measure the flow of energy, or power, is the Watt.

One Watt is one Joule per second.

A 100 Watt light bulb has 100 Joules of electrical energy flowing into it each second.

Less than 10 Joules of visible light come out of the light bulb each second.

The rest comes out as infrared radiation or is conducted into the air around the light bulb.

## Calculating the rock's temperature

To calculate the temperature of the rock orbiting the Sun, we need to write down the formulas for the energy going into the rock and the energy going out each second.

Power going in is the flux of sunlight multiplied by the area of the side of the rock facing the Sun.

$$P_{\text{in}} = F_{\text{sunlight}} \times A_{\text{face}}$$

Power going out depends on the temperature of the rock and its total surface area.

$$P_{\text{out}} = \sigma T^4 \times A_{\text{surface}}$$

In equilibrium,  $P_{\text{out}} = P_{\text{in}}$



Do the math

If  $P_{\text{out}} = P_{\text{in}}$ :

$$\sigma T^4 A_{\text{surface}} = F_{\text{sunlight}} A_{\text{face}}$$

$$T^4 = \frac{F_{\text{sunlight}}}{\sigma} \frac{A_{\text{face}}}{A_{\text{surface}}}$$

$$T = \sqrt[4]{\frac{F_{\text{sunlight}}}{\sigma} \frac{A_{\text{face}}}{A_{\text{surface}}}}$$

For a sphere,  $A_{\text{face}} / A_{\text{surface}} = 1/4$ .

The answer comes out to 279 K, or 6° C, or 42° F.

## Different distances from the Sun

I assumed that the flux of sunlight was that which we measure at the Earth.

How would the calculation change if the rock were 2 AU from the Sun?

First, how does the flux of sunlight depend on distance from the Sun?

At 2 AU from the Sun, the flux of sunlight is...

- A. the same as at the Earth
- B.  $\frac{1}{2}$  that at the Earth
- C.  $\frac{1}{4}$  that at the Earth
- D.  $\frac{1}{8}$  that at the Earth

## Different temperatures

If the flux of sunlight is  $\frac{1}{4}$  as large 2 AU from the Sun, the temperature is multiplied by  $\sqrt[4]{1/4}$

We can calculate the temperature at the locations of the different planets:

Planet	distance	predicted T	actual surface T
Mercury	0.39 AU	450 K	100-700 K
Venus	0.72 AU	330 K	700 K
Earth	1.00 AU	280 K	290 K
Mars	1.52 AU	227 K	220 K
Jupiter	5.2 AU	123 K	130 K

## Include only sunlight absorbed

Only the sunlight absorbed (not reflected) by the planet contributes to its heating.

Recalculating the temperatures including only the absorbed sunlight we get lower temperatures:

Planet	black rock	recalculated	actual surface T
Mercury	450 K	440 K	100-700 K
Venus	330 K	230 K	700 K
Earth	280 K	250 K	290 K
Mars	227 K	217 K	220 K
Jupiter	123 K	103 K	130 K

## The effect of the atmosphere

We assumed that all of the infrared radiation emitted by the surface of the planet escaped to space, and so carried heat away from the planet.

This is not correct because the Earth's atmosphere is not transparent at all wavelengths.

Molecules in the Earth's atmosphere absorb many wavelengths of infrared radiation.

Molecules absorb infrared radiation when they rotate and vibrate.

## The greenhouse effect

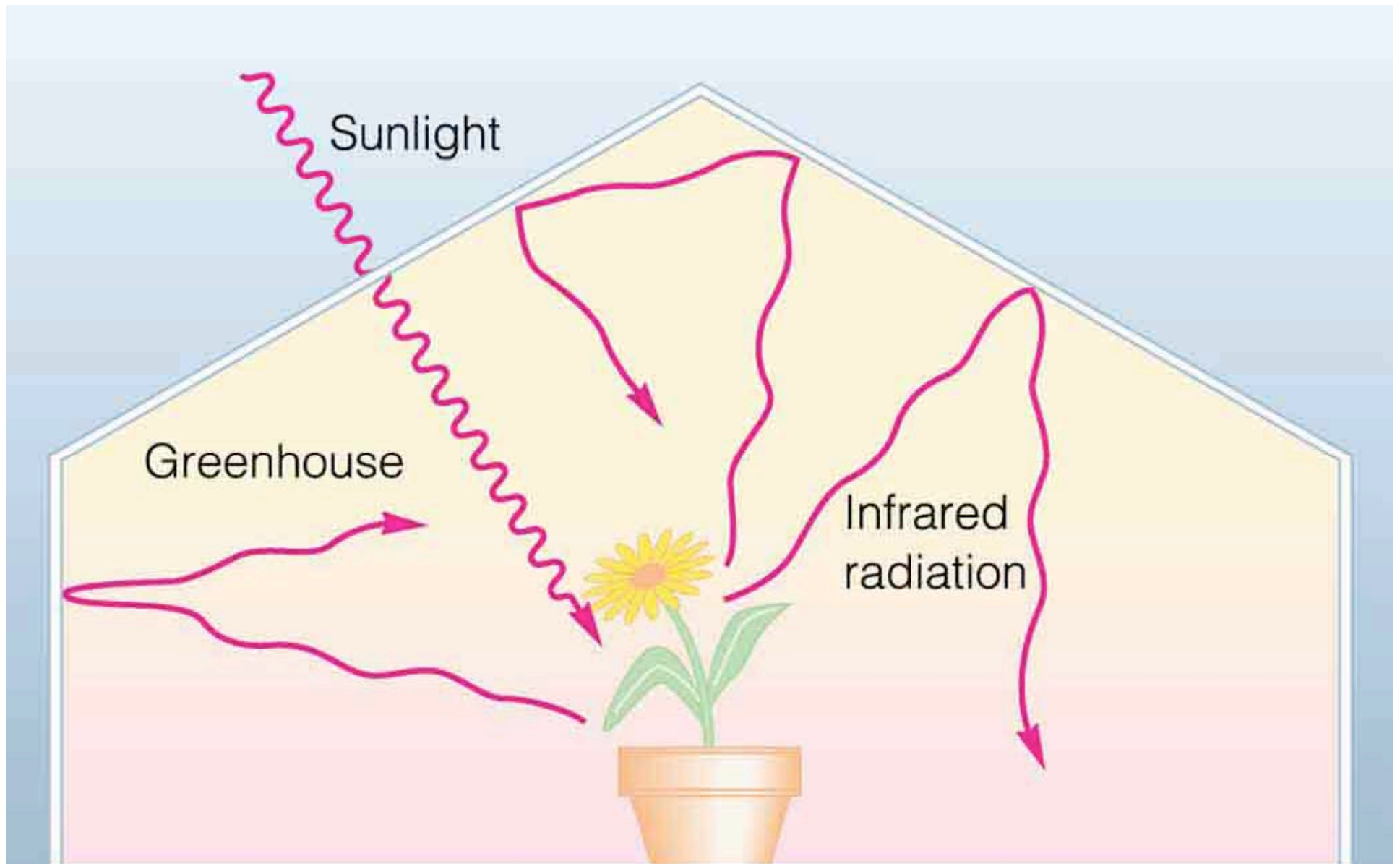
By blocking some of the outgoing infrared radiation, molecules in the Earth's atmosphere force the temperature of the surface of the Earth to rise until the outgoing flow of energy matches the incoming flow.

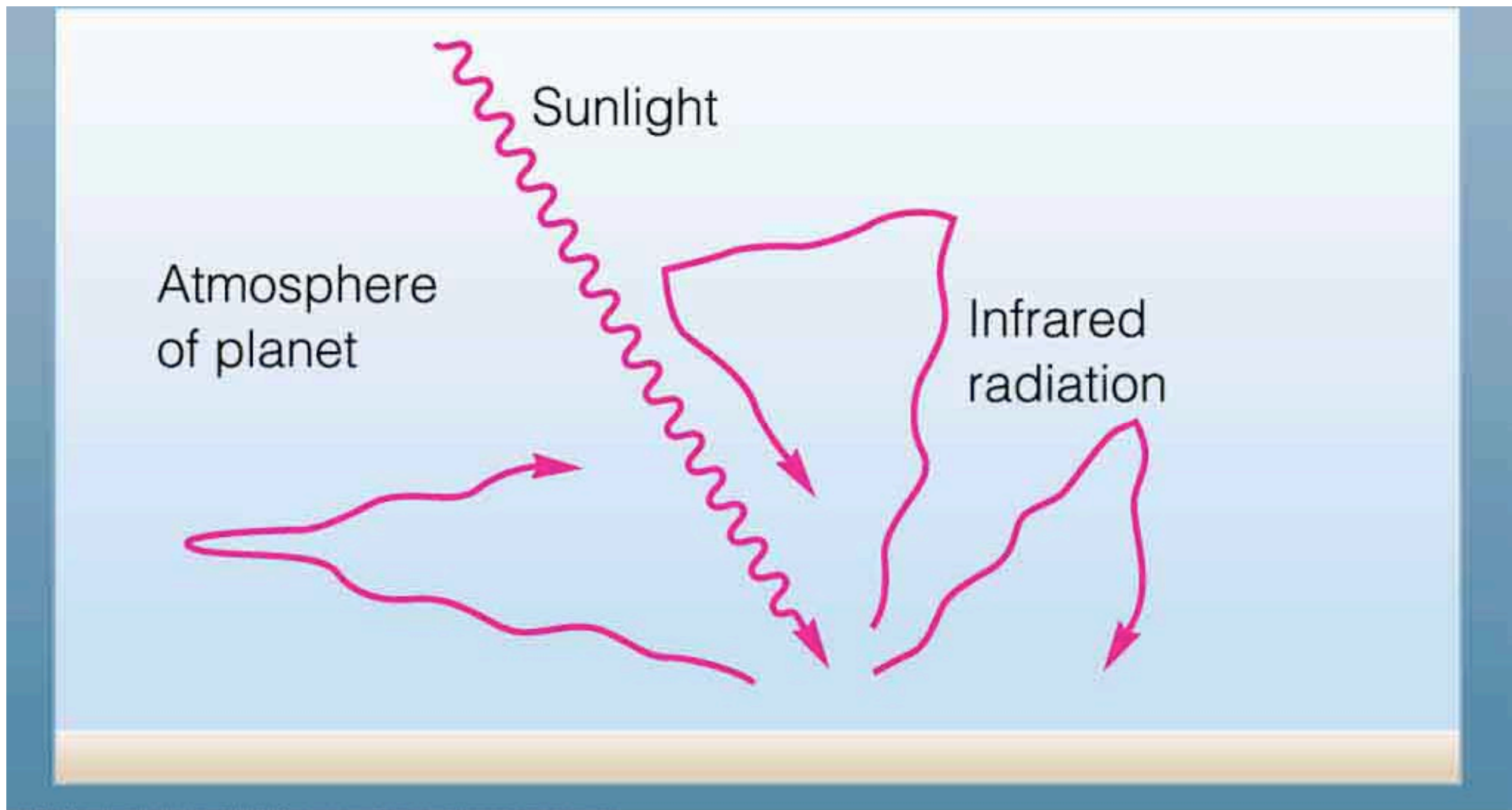
This is the greenhouse effect.

Because of the greenhouse effect, the surface of the Earth is warm enough for us to live here.

Only about one half of the radiation emitted by the surface of the Earth escapes to carry heat away from the Earth.

As a result, the average temperature of the surface of the Earth is warm enough for life.







## Greenhouse gasses and Goldilocks

The molecules in the Earth's atmosphere which absorb the most infrared radiation are:

water vapor ( $\text{H}_2\text{O}$ )

carbon dioxide ( $\text{CO}_2$ )

methane ( $\text{CH}_4$ )

nitrous oxide ( $\text{N}_2\text{O}$ )

ozone ( $\text{O}_3$ )

Both Venus and Mars have atmospheres rich in  $\text{CO}_2$ , but Venus' atmosphere is about 100 times denser than ours, whereas Mars' atmosphere is about 100 times thinner.

Including the greenhouse effect we can explain why Venus is so hot and Mars so cold.

## Differences between our atmospheres

Why do Venus, Earth, and Mars have such different atmospheres?

Our atmosphere probably once was rich in  $\text{CO}_2$ , but when  $\text{CO}_2$  is dissolved in water it can react with metal ions to form limestone. Plankton and shellfish make this happen faster. Also, plants make cellulose from  $\text{CO}_2$ , releasing  $\text{O}_2$ .

Venus has always been too hot for water to be liquid, so it had no way to remove the  $\text{CO}_2$  from its atmosphere. So it has a very strong greenhouse effect.

Mars probably once had oceans or lakes where limestone could form. It is also cold enough at its poles for  $\text{CO}_2$  to freeze. And almost all of its water is frozen. So it has a very weak greenhouse effect.