ASTR20A:
Introduction to Astrophysics I

Dr. Devontae Baxter

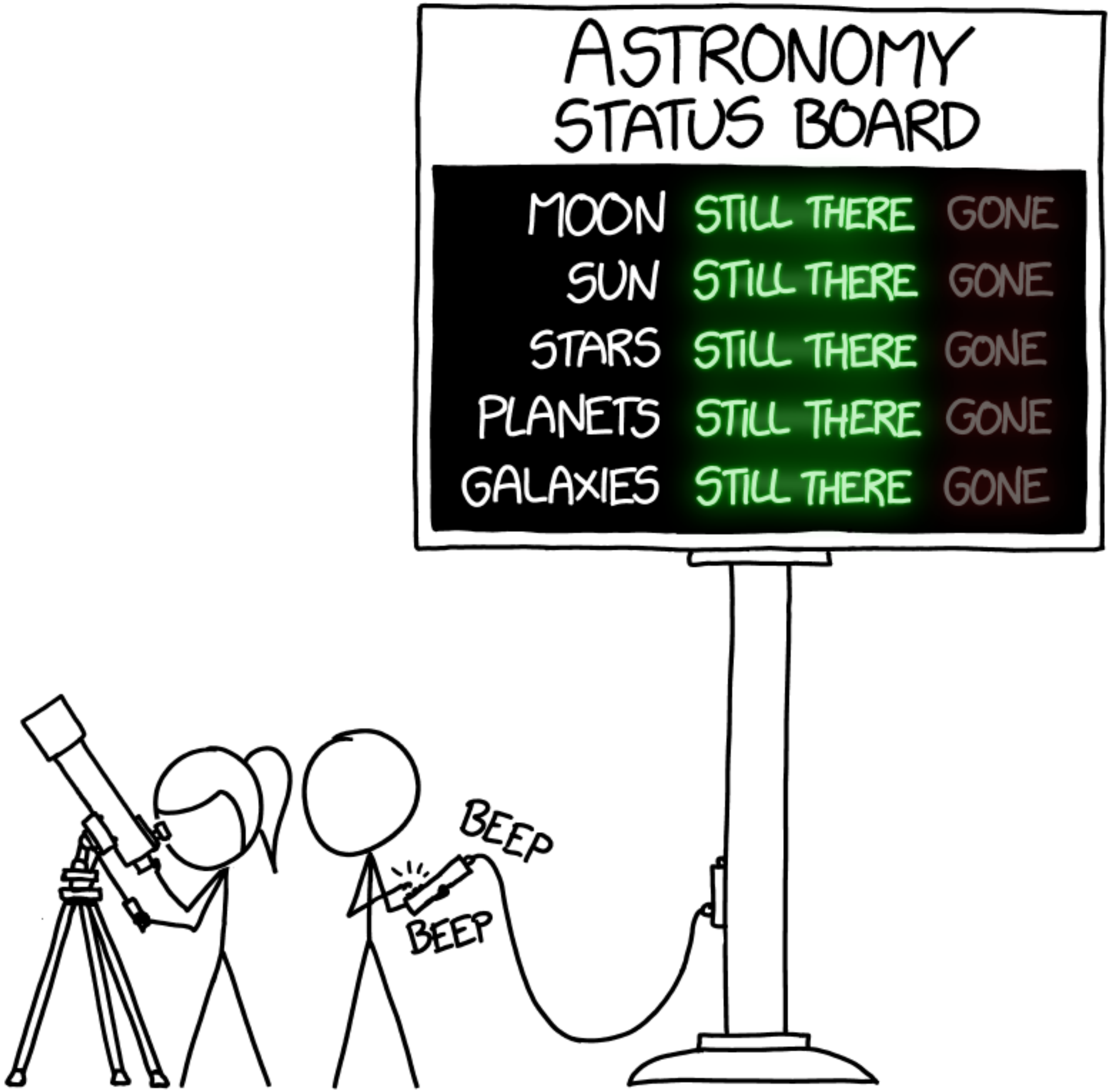
Lecture 10 | Overview of the Solar System

Tuesday, October 30, 2025

NASA Family portrait taken by Voyager 1

Announcements

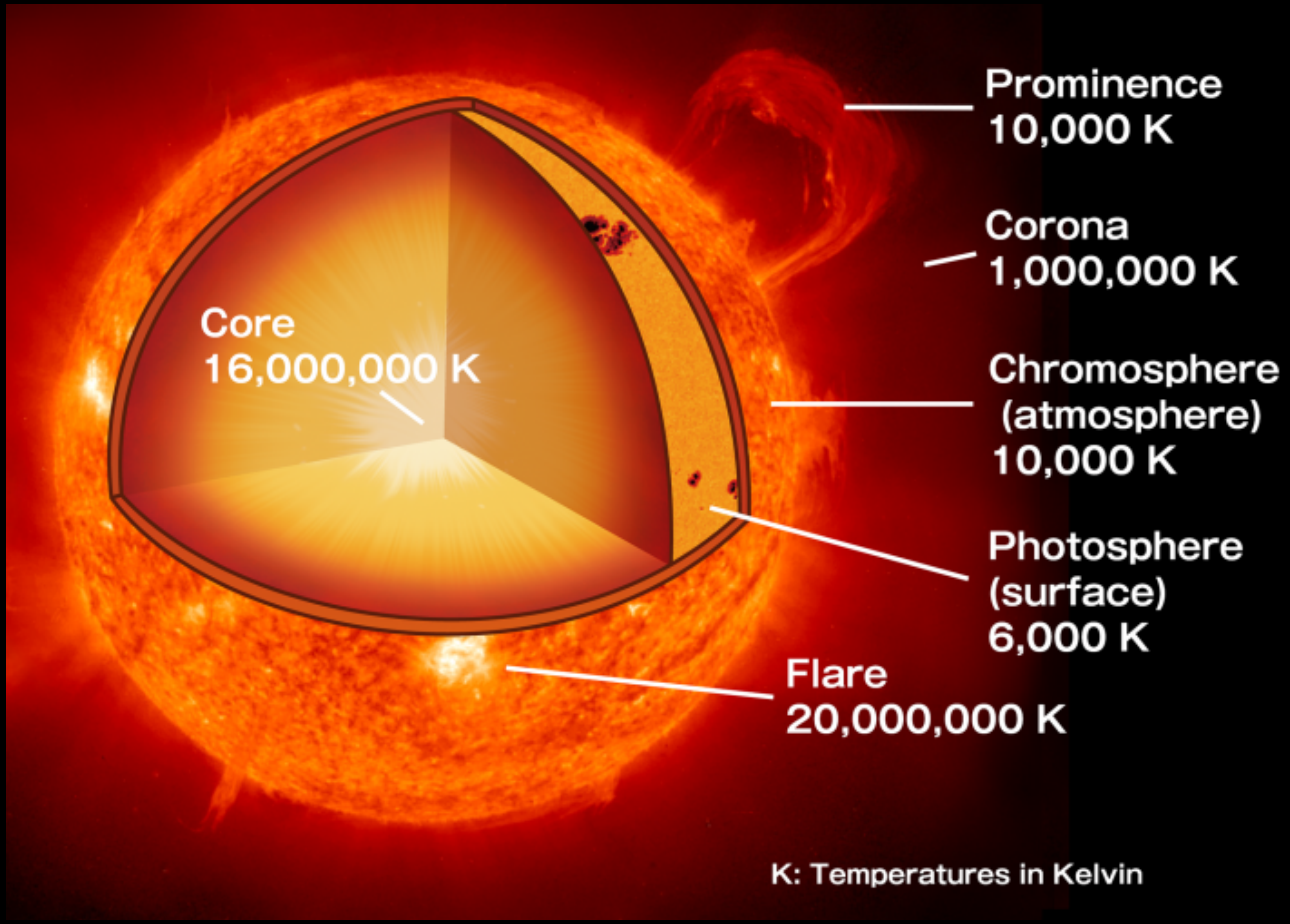
- Homework #5 due Tuesday, 11/04 by 11:59 pm via Gradescope.
- Coding assignment #3 is due Sunday, 11/02 by 11:59pm.
- Complete the anonymous student feedback survey before Sunday, 11/02 by 11:59pm to receive extra credit.




Questions?

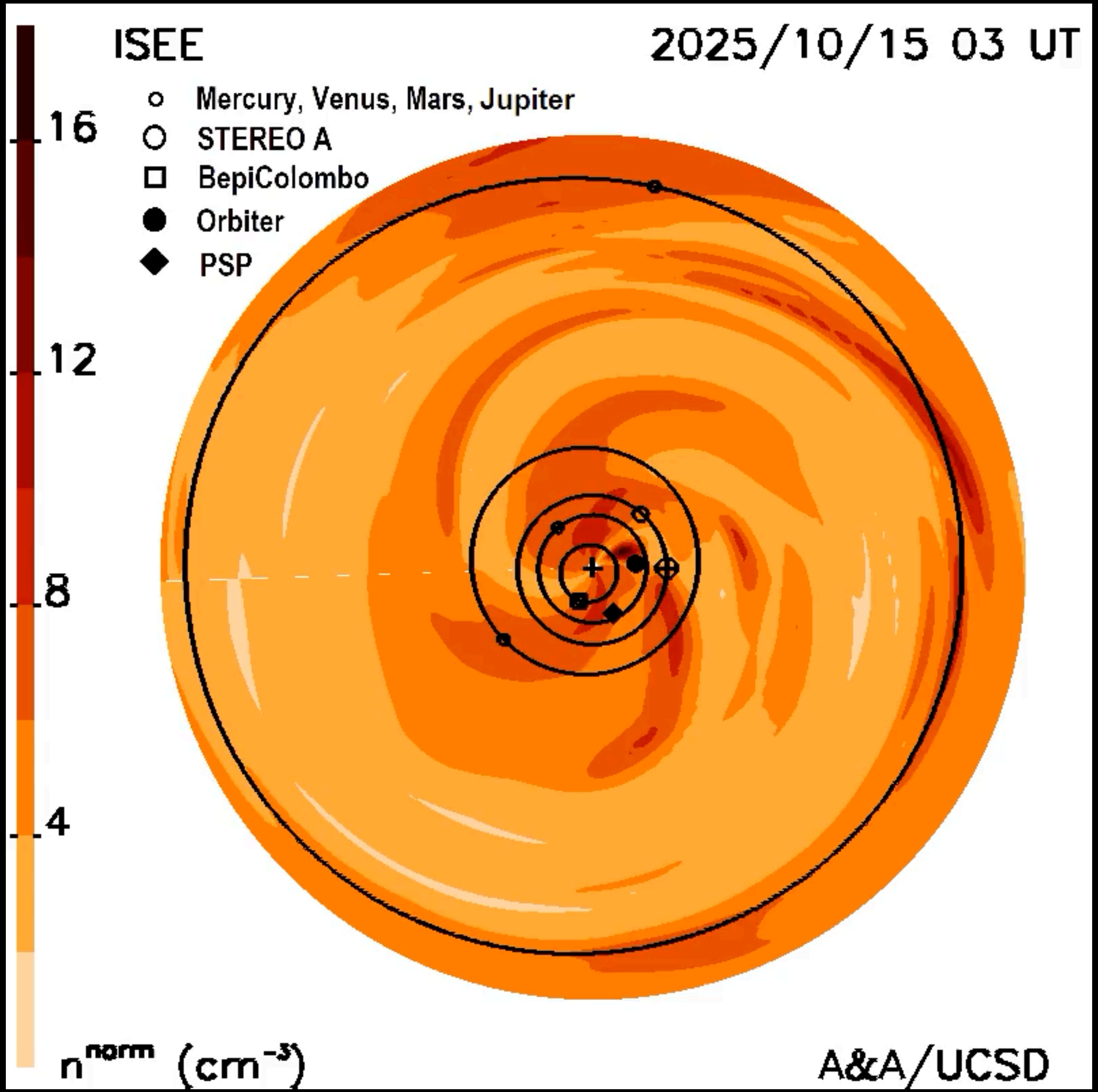
Recap of Lecture 9

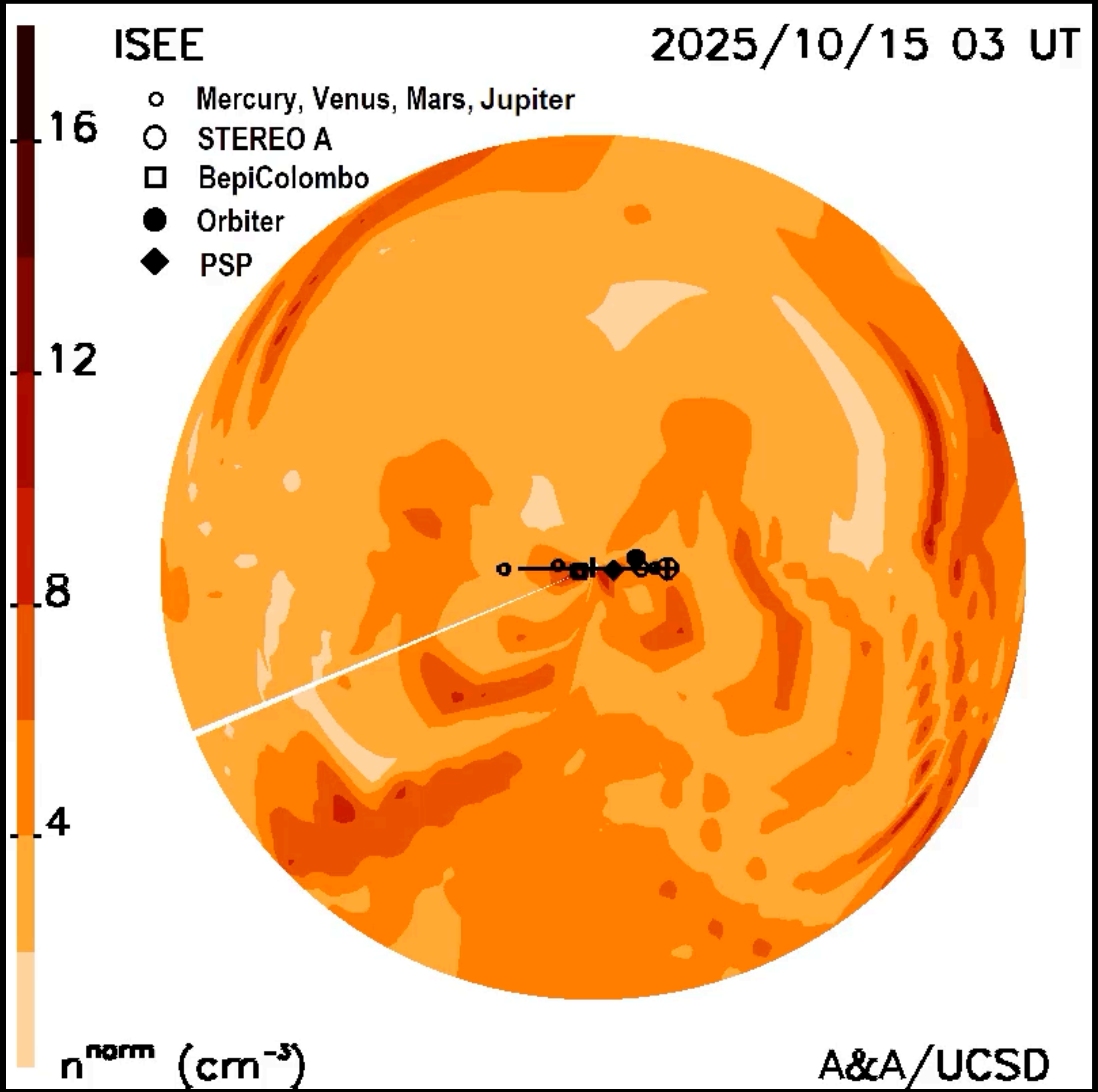
In the previous lecture, we discussed the **the Sun**. The key concepts that we discussed were the layers of the Sun, surface features on the Sun, and the drivers of Solar activity.



Today's lecture will focus on the Solar System!

Space Weather Forecasting at UCSD
(shared by your classmate Eric Chen)





Learning Objectives

By the end of today's lecture you will be able to:

- Calculate the mass and density of a planet.
- Describe the different classes of solar system objects — i.e., Jovian, Terrestrial, and dwarf planets, Trans-Neptunian Objects, and Kuiper-belt objects.
- Explain how albedo and the luminosity of the Sun impact Earth's equilibrium temperature.
- Explain why the Greenhouse Effect keeps the Earth warm.
- Describe the formation of the Solar System.

Introduction

The goal of the next few lectures will be to **understand the basic characteristics of the Solar System.**

This information will guide us as we construct a self-consistent picture of **how the Solar System formed** and **how it has evolved with time.**

In the pursuit of our goal, we need to keep in mind a few basic facts:

1. **The Sun contains 99.8% of the total mass** of the solar system.
2. The remaining 0.2% is confined to a flattened disk.
   a. Within this disk **all planets orbit in the same direction.**
   b. With the exception of Venus and Uranus **all other planets rotate in a counterclockwise direction** — the same direction as the Sun.
   c. **All planets have similar ages** (~4.6 billion years) — check out this article by Prof. Burgasser (UCSD) explaining how we estimate the ages of planets.

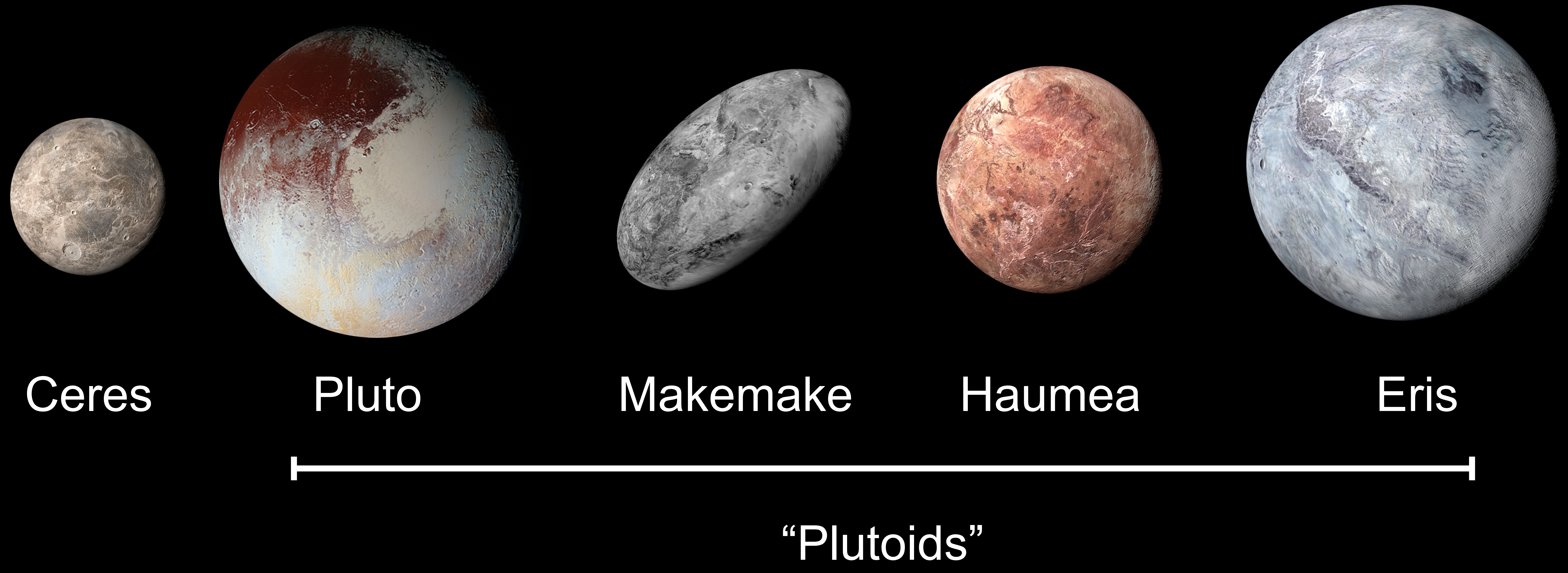
The Largest Worlds Orbiting the Sun

THE PLANETARY SOCIETY

Image data from NASA/JPL-Caltech/SSI/SwRI/CIW/ISRO/Daniel Chang. Processed by Björn Jónsson, Emily Lakdawalla, Daniel Macháček, Mattias Malmer, Alex Parker, Jason Perry, Ted Stryk, and Gordan Ugarkovic.

The Five Official "Dwarf Planets"

We'll explore the definition of "planet" and "dwarf planet" in Lecture 13.



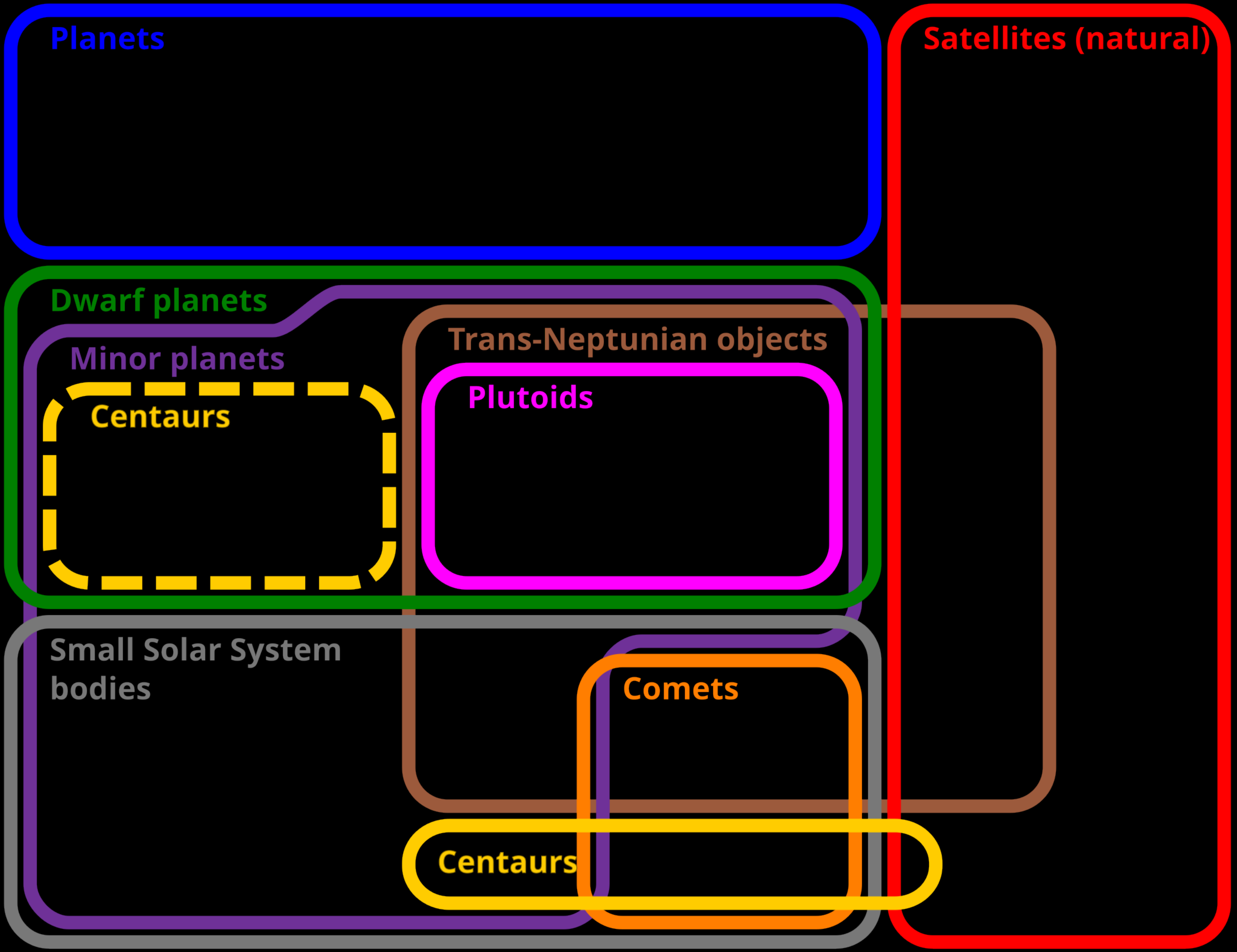
TNOs are divided into Kuiper Belt Objects (KBOs), which include Pluto and Eris, and scattered disk objects, with inclined & eccentric orbits

Relation between objects in the Solar System

- In 2006, the International Astronomical Union (IAU) defined the term “Small Solar System Bodies” (SSSBs) as:

  “All other objects, except satellites, orbiting the Sun”

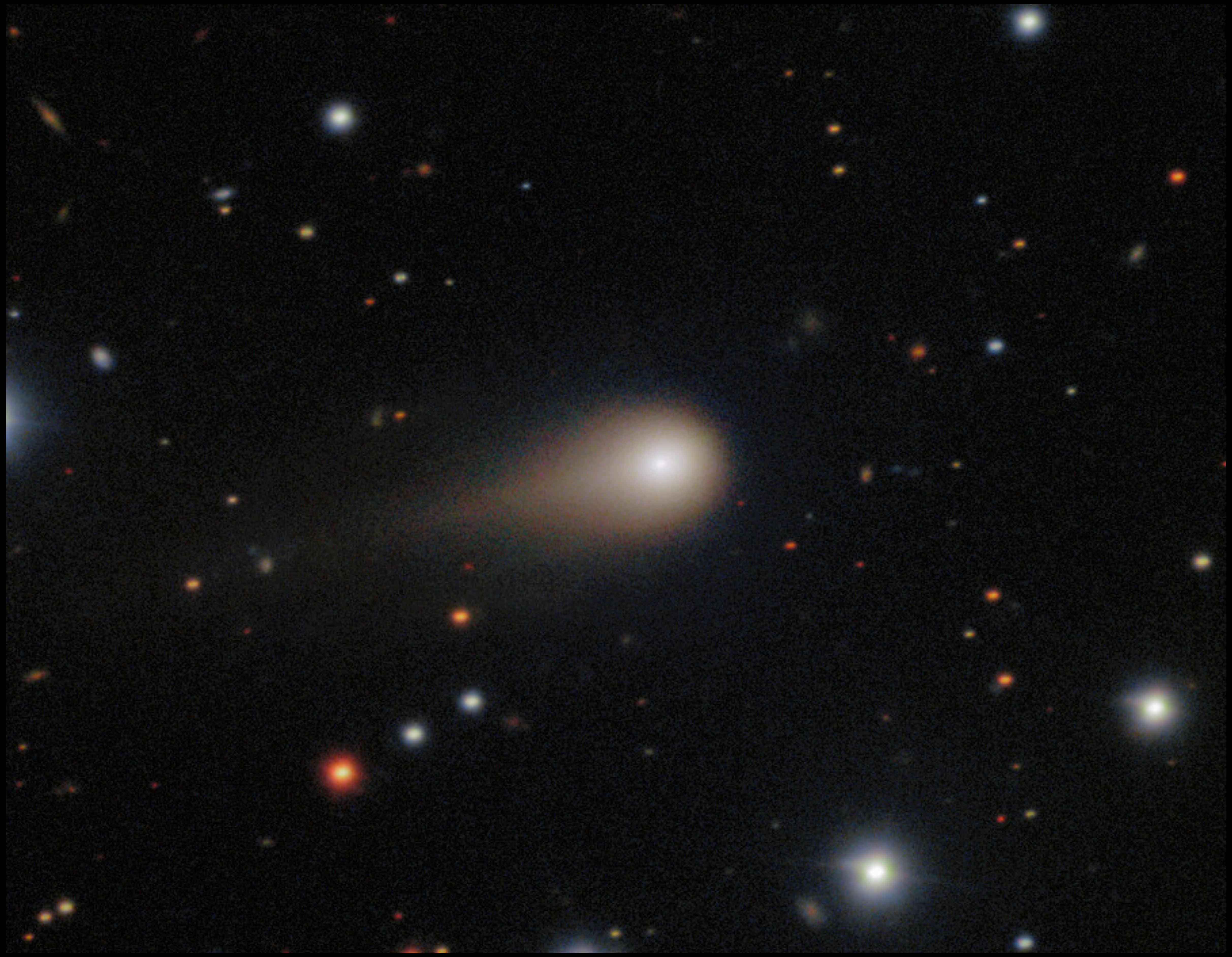
- This includes all comets, asteroids, and minor planets (excluding the dwarf planets).



Astronomy in the News

3I/ATLAS to make closest approach to the Sun on Oct 30th

- Third object discovered by humans to come from interstellar space.
  - First was 1I/Oumuamua (2017)
  - Second as 2I/Borisov (2019)
- A signs points towards it being a comet.
- Some astronomers have explored the possibility of it being alien technology…. though its most likely a space rock.



How did the Solar System Form?

A useful theory of the origin of the solar system must to be able to explain:

- Why are planetary orbits nearly circular?
- What is the nature and origin of the small “debris,” such as comets and asteroids?
- What is the origin of the planetary satellites?
- Why are there differences in chemical composition among bodies in the solar system?
- Why are there rings around the Jovian planets (and not around the terrestrial planets)?
- Why are the terrestrial planets chemically differentiated, with a rocky outer layer wrapped around a metallic core?

Physical Properties of Planets - Mass & Density

The mass of a star with an orbiting planet can be found using Kepler's 3rd Law.

$$P^2 \propto a^3$$

$$\Rightarrow P^2 = \frac{4\pi^2}{G(M+m)} a^3$$

Note: You can <u>only</u> measure masses for binary (or higher) order systems

Physical Properties of Planets - Mass & Density

If a planet of mass M_p has an orbiting satellite of mass m_s, we can use the acceleration of the satellite to find the **mass of the planet.**

$$P^2 = \frac{4\pi^2}{G(M_p + m_s)} a^3 \simeq \frac{4\pi^2}{GM_p} a^3 \quad \text{if } M_p \gg m_s$$

$$\Rightarrow M_p \simeq \frac{4\pi^2 a^3}{GP^2}$$

Where P & a are for the satellite

Physical Properties of Planets - Mass & Density

We can directly measure the size of the planet (R) through its **angular size** (θ) and distance (which can be measured using radar).

Therefore, we can use the mass and size to compute the **"mean" density**

$$\rho = \frac{M}{V} = \frac{3M}{4\pi R^3}$$

The densities of the Jovian and Terrestrial planets are found to be:

Jovian planets: $\rho \sim 700 - 2000\ \mathrm{kg/m^3}$ (mostly gas or ice)

Terrestrial planets: $\rho \sim 3000 - 5500\ \mathrm{kg/m^3}$ (mostly rock or metal)

Physical Properties of Planets - Temperature

The surface temperature of objects in the Solar System depend on multiple factors.

1. The **distance from Sun.**

2. The **"albedo"** (or reflectivity) of the planet.
   - A **white object has a high albedo ($A \sim 1$)** since it reflects most of the light that strike it, whereas a **black object has a low albedo ($A \sim 0$).**
   - The average albedo of the Earth is $A \sim 0.4$.

3. Whether or not the object has **internal heat sources.**

4. Whether it has **an atmosphere that can act as an insulation blanket** wrapped around its surface.

Note: "Albedo" comes from the latin word *albus*, meaning "white".

Physical Properties of Planets - Temperature

As discussed a few lectures back, the Sun can be approximated to radiate like a **blackbody**. The Sun's luminosity is therefore

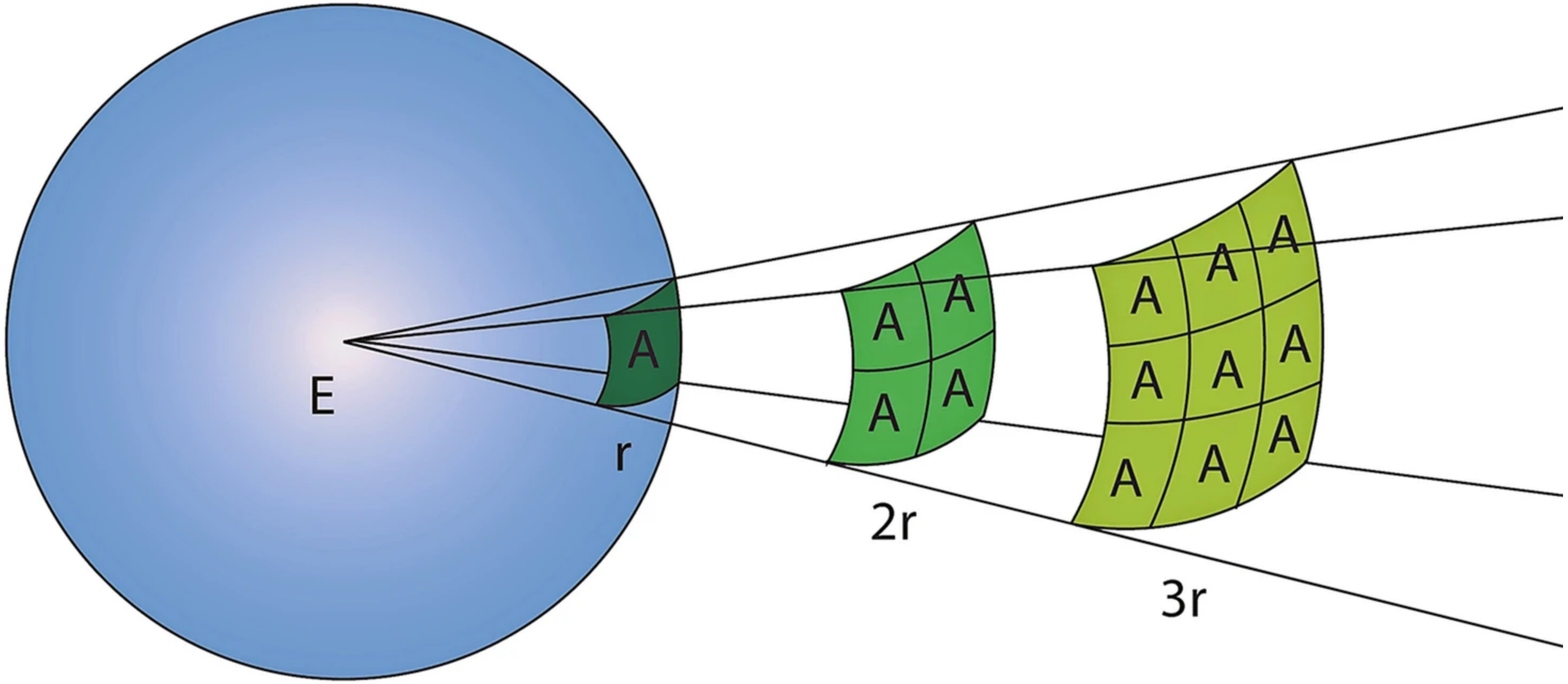
$$L_\odot = 4\pi R_\odot^2 \sigma_{\rm SB} T_\odot^4$$ (Stefan-Boltzmann Law)

The flux of energy received by a planet at a distance r from the Sun is

$$F(r) = \frac{L_\odot}{4\pi r^2}$$ (Net Flow of Radiant Energy Through a Unit Area)

Physical Properties of Planets - Temperature

Doubling (tripling) the distance from the source diminishes the energy by a factor of four (nine) and so forth, according to the *inverse square of the distance.*



$$F(r) = \frac{L_\odot}{4\pi r^2}$$ (Net Flow of Radiant Energy Through a Unit Area)

Physical Properties of Planets - Temperature

The energy a planet *absorbs* per second is the flux F times the cross-section of the planet (πR^2) times the fraction of the incident light absorbed rather than reflected.

Since the albedo A of the planet *is the fraction of the light energy reflected*, the **fraction that is absorbed is $1 - A$.**

Therefore, the **rate at which the planet absorbs energy is**

$$W_p = \left(\frac{L_\odot}{4\pi r^2}\right)(\pi R_p^2)(1 - A) \quad \text{(Energy absorbed)}$$

Physical Properties of Planets - Temperature

The energy absorbed by the planet will increase the surface temperature by some value T_p.

If we **assume that all of the energy absorbed is re-radiated as thermal energy** (i.e., blackbody approximation) then the planet will radiate at a rate

$$L_p = 4\pi R_p^2 \sigma T_p^4$$

(Energy radiated away)

The **equilibrium temperature** is obtained by balancing the energies

Energy out

Energy in

$$4\pi R_p^2 \sigma T_p^4 = \left(\frac{L_\odot}{4\pi r^2}\right)(\pi R_p^2)(1 - A)$$

Physical Properties of Planets - Temperature

Solving for the equilibrium temperature T_p, we find

$$T_p = \sqrt{\frac{R_\odot}{r}} \left(\frac{1 - A}{4} \right)^{1/4} T_\odot \qquad \text{(Equilibrium surface temperature)}$$

Inserting numerical values for $R_\odot$ and $T_\odot$, and expressing the distance from the Sun in astronomical units, we find

$$T_p \approx 279 \text{ K}(1 - A)^{1/4} \left(\frac{r}{1 \text{ AU}} \right)^{-1/2} \qquad \text{(Equilibrium surface temperature)}$$

Physical Properties of Planets - Temperature

If the object being heated by the Sun is a blackbody, then $A = 0$.

$$T_{\mathrm{bb}} \approx 279\ \mathrm{K} \left(\frac{r}{1\ \mathrm{AU}} \right)^{-1/2}$$ (Equilibrium blackbody temperature)

The assumption of uniform surface temperature is a good approximation for planets that are rotating rapidly or have efficient atmospheric circulation.

However, for planets that **rotate slowly and are not good conductors of heat**, the equilibrium temperature becomes

$$T_{\mathrm{ss}} \approx 395\ \mathrm{K} \left(\frac{r}{1\ \mathrm{AU}} \right)^{-1/2}$$ (Subsolar blackbody temperature)

Brain Break – Think-pair-share

Imagine two separate, immediate, and permanent global events occur:

Scenario A: The Yellowstone Caldera erupts, covering Earth with a widespread haze of clouds, smoke, and ash that increases the planet's albedo at visible wavelengths (A) by a **factor of three** (i.e., $A_f = 3 \times A_i$).

Scenario B: The luminosity of the Sun ($L_\odot$) suddenly and permanently decreases by **25%**.

Based on the equilibrium temperature formula ($T_p \propto L_\odot^{1/4}(1 - A)^{1/4}$), which of these two scenarios would have the **larger cooling effect** on the Earth? Would humanity survive either of these scenarios? Why?

Physical Properties of Planets - Temperature

We find that all planets are warmer than expected based on assumptions that the Sun is the only source of heat.

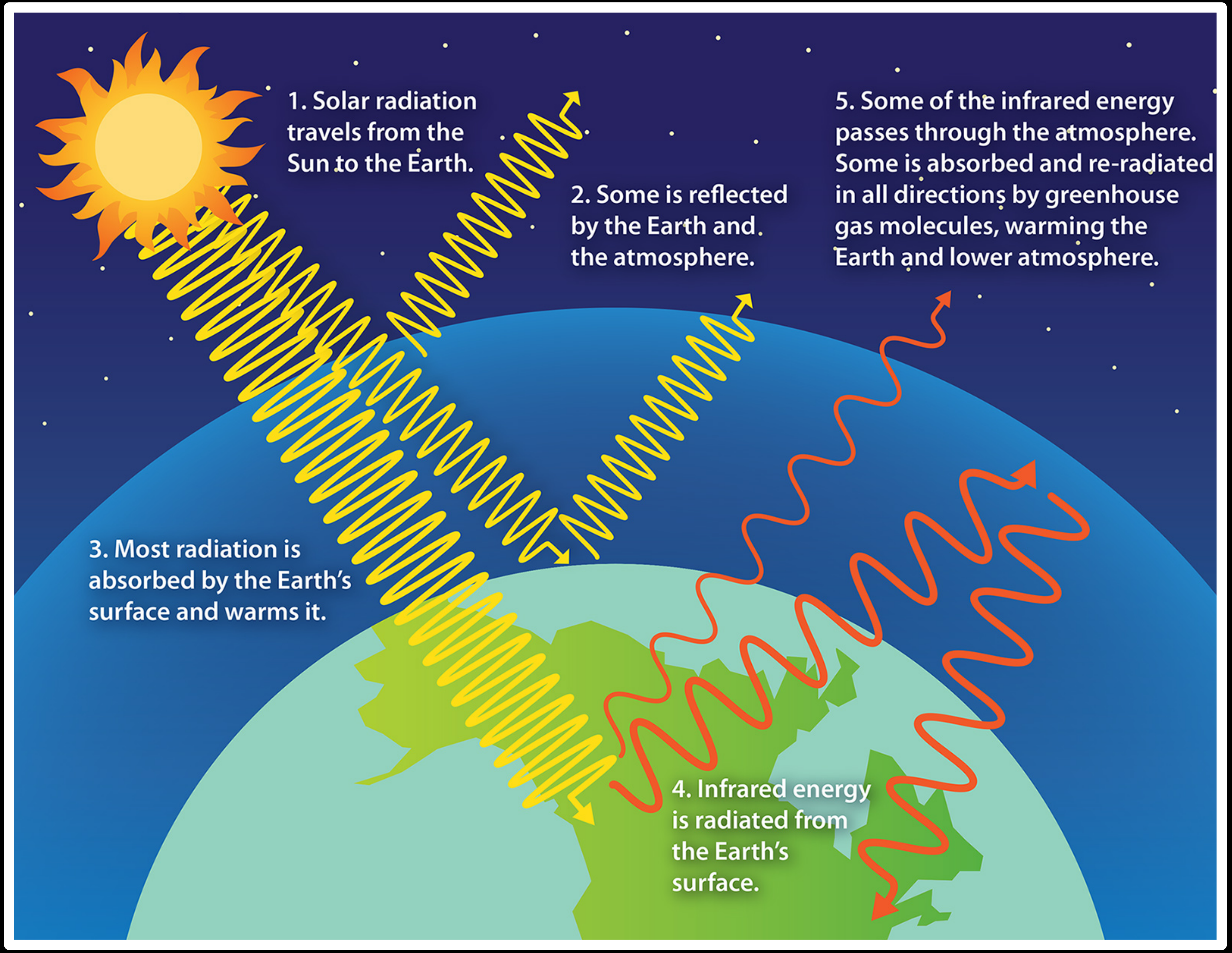
		r	Uniform T_p	Slow Rotator	
Planet	Albedo	(AU)	$T_{bb}(1 - A)^{1/4}$	$T_{ss}(1 - A)^{1/4}$	T_{obs}
Venus	0.76	0.72	230 K	325 K	740 K
Earth	~ 0.4	1	(-16 F°) 246 K	(164 F°) 347 K	(60 F°) 290 K
Neptune	0.62	30.1	40 K	57 K	59 K

Neptune is *warmer than expected* because, like all Jovian planets, it started much hotter than it is today and has not radiated away all its internal heat.

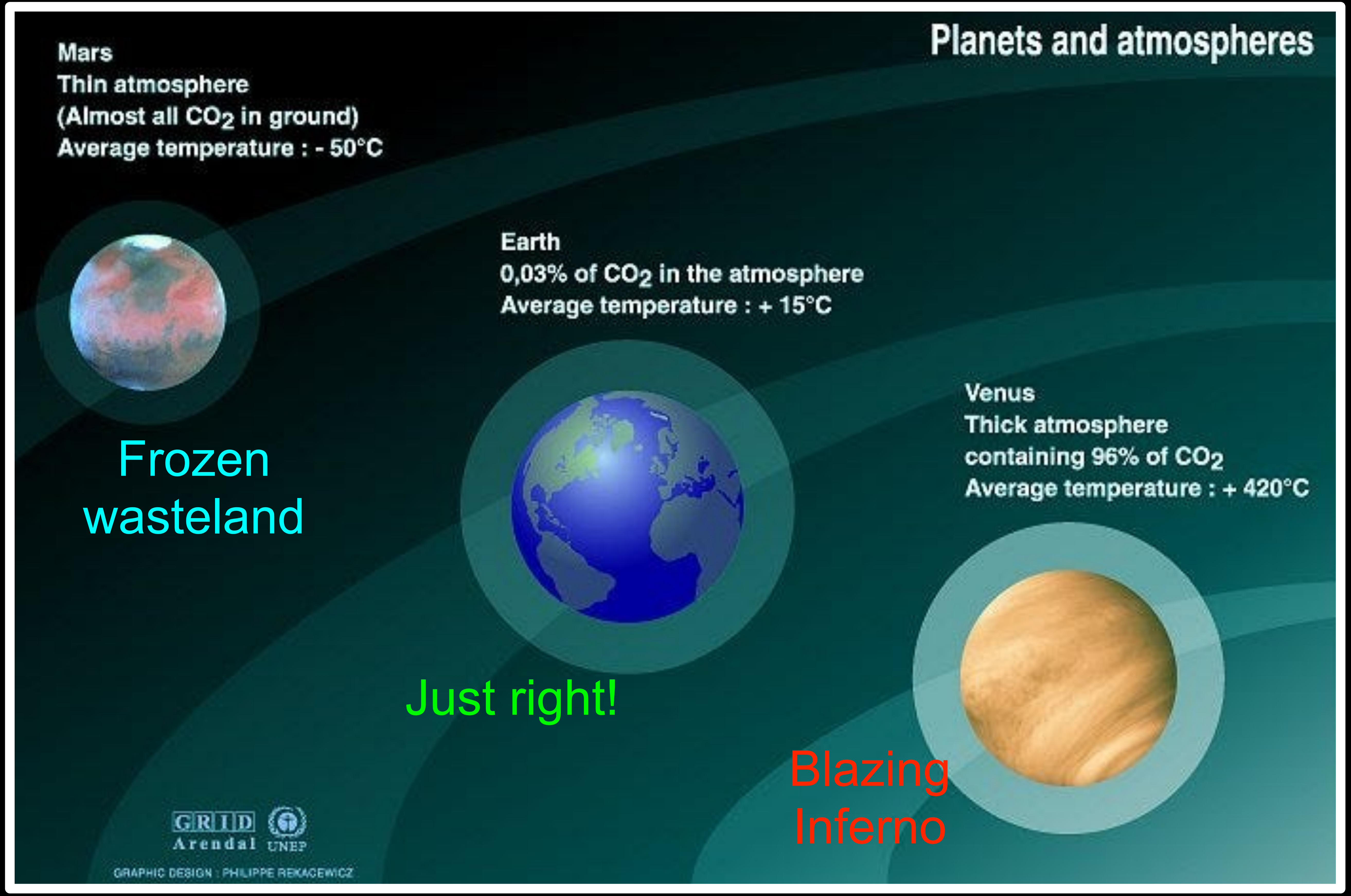
Earth and **Venus** are warmer than expected because of the **greenhouse effect.**

Greenhouse Effect

The Earth's "Insulated Blanket"



A Tale of Ice and Fire



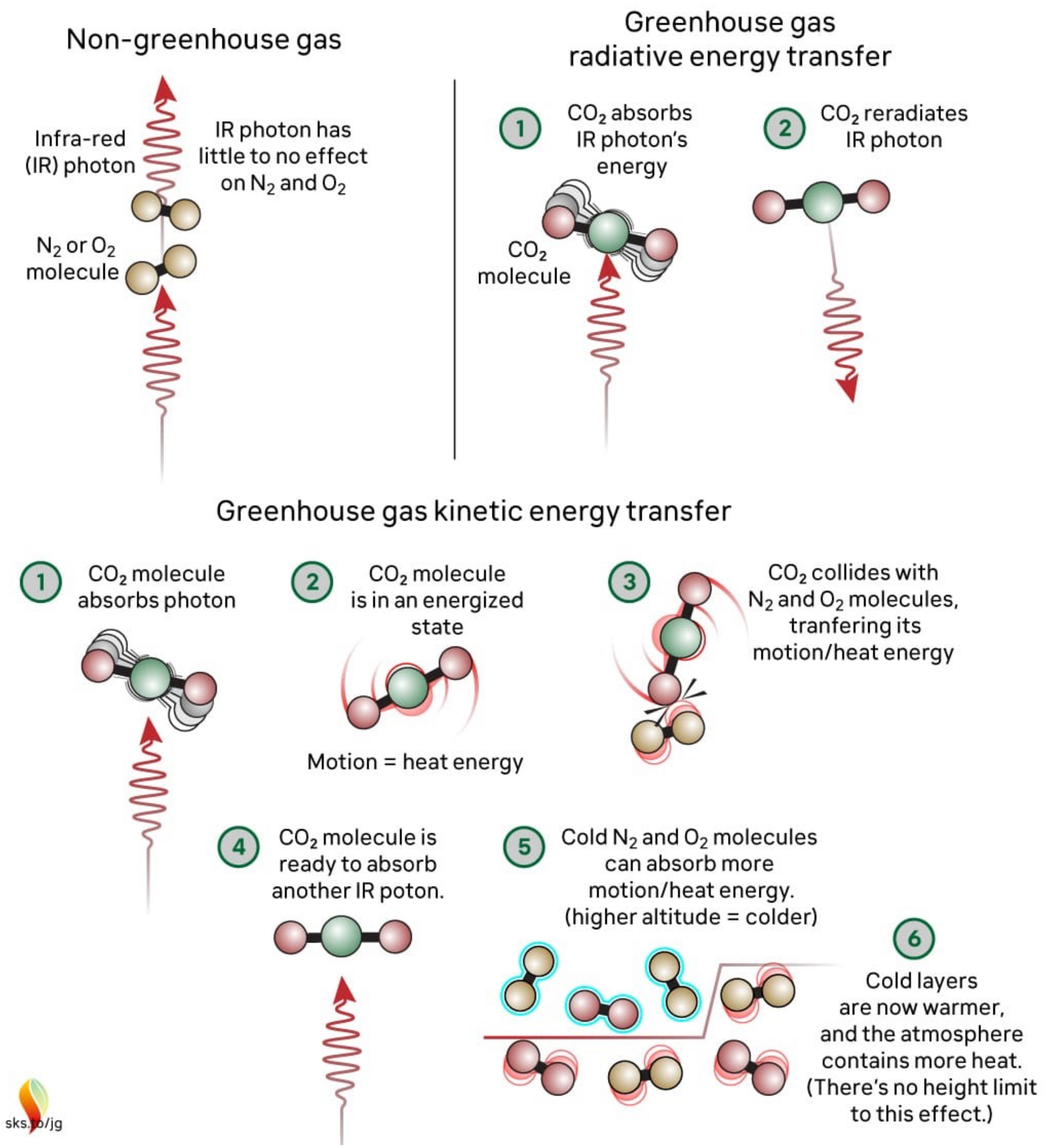
- Visible light form the Sun warms the surface of the Earth.
- This light is re-radiated at infrared wavelengths.
- Greenhouse gases *absorb* and *re-emit* some of this light, trapping it in the atmosphere and heating the planet.

- The thin Martian atmosphere hinders the greenhouse effect.
- The thick Venusian CO_2 atmosphere creates a runaway greenhouse effect.

Greenhouse Effect

Greenhouse gases **absorb** and **re-emit the light that the surface of the Earth produces.**

They also **absorb energy**, and then **transfer that energy kinetically to other molecules in the atmosphere**.

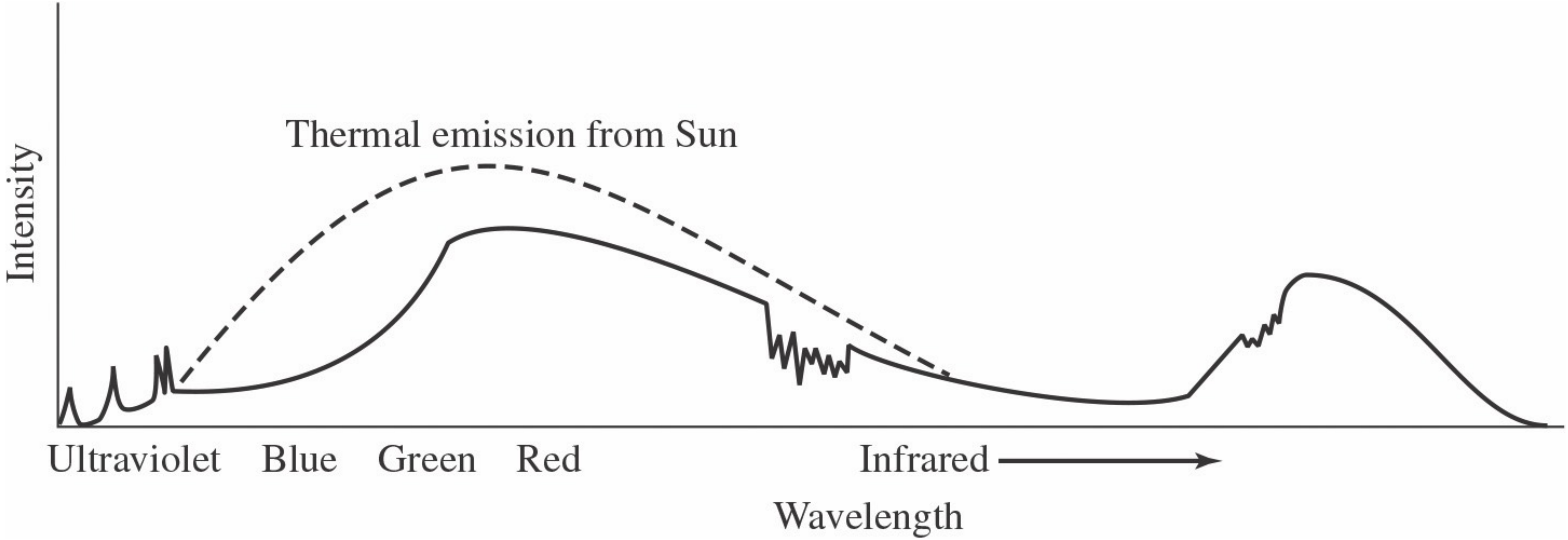


Spectrum of Mars

The spectrum of a planet is the sum of two blackbody spectra (reflected sunlight + thermal emission of the planet).

The iron oxide absorbs blue light, making Mars look redder (Mars is red because it's rusty).

- Left peak is reflection of sunlight.
- Right peak is thermal emission at $T \sim 225\ \mathrm{K}$



Keeping your atmosphere

- The giant planets have compositions that closely resemble the Sun (mostly H and He).
- Terrestrial planets are deficient in H and He b**ecause they are too hot to retain such light elements.**
- Hotter planets will have more random thermal motions between individual gas particles.
- In a dense atmosphere a particle will travel only a short distance before colliding with another particle.
- This depends on *how deep* it is in the atmosphere.

Keeping your atmosphere

- If a particle is moving upwards fast enough it might escape before colliding.
- The height at which particles are more likely to escape than collide is called the “**exobase**”.
- The layer above that is called the “**exosphere**”.
- Under what conditions does a planet retain elements in its atmosphere?

Physical Properties of Planets - Atmosphere

First, we need to understand the concept of the **mean free path** (λ).

Consider a gas of n particles. The **mean free path** is the *average distance a particle will move **free** before it collides with another particle*

For example, at sea level on Earth the number density of particles is

$$n \sim 2.5 \times 10^{25} \frac{1}{m^3}$$ (Number Density at Sea Level)

The size (cross-section) for the most common particle is

$$\sigma \sim 10^{-18} m^2$$ (Interaction Cross-Section)

Physical Properties of Planets - Atmosphere

The mean free path is

$$\lambda \sim \frac{1}{n\sigma} \sim 4 \times 10^{-7}\ \mathrm{m} = 400\ \text{Å}$$

Therefore, an air molecule will travel $400\ \text{Å}$ before colliding with another molecule.

At some height in the atmosphere, the mean free path increases to the point where a gas particle moving upwards faster than the escape speed and escapes from the atmosphere before colliding with a mother particle.

This height is called the **exobase**, and the layer of the atmosphere above the exobase is called the **exosphere**.

Physical Properties of Planets - Atmosphere

Where does the **exobase** lie?

To answer this, let's start off by assuming that all gas particles have an average cross section σ and that the density is a function of height in the atmosphere, $n(z)$

At a height of (z_{ex}) the exobase is formed

$$\int_{z_{ex}}^{\infty} \sigma n(z) dz = \sigma N(z_{ex}) = 1 \quad \text{(Exobase Column Density Condition)}$$

By setting the integral equal to 1, we are defining the exobase as the height where the total number of expected collisions for a particle on its way out of the atmosphere is exactly one

Here $N(z_{\text{ex}})$ is the column density of gas particles above the exobase.

Physical Properties of Planets - Atmosphere

Therefore, the exobase is located where the column density fall to

$$N \sim \frac{1}{\sigma}$$

In the Earth's atmosphere this is $\sim 10^{-18}\ \mathrm{m}^{-2}$

Therefore, the Earth's exobase is around $\sim 500\ \mathrm{km}$ above sea level.

Physical Properties of Planets - Atmosphere

For a particle at the exobase, it will be moving with a speed defined by the temperature (v_{rms})

$$v_{rms} = \sqrt{\frac{3kT_{ex}}{m}}$$

The **escape speed** (v_{esc}) is determined by the gravitational force.

$$v_{esc} = \sqrt{\frac{2GM}{R_{ex}}}$$

Rule of Thumb: for a planet to *retain a particular gas* in its atmosphere for the age of the solar system, the particles must have $v_{rms} \lesssim v_{esc}/6$.


Questions?

Origin of Solar System

The **Nebular Theory** states that the Solar System formed from a giant, swirling cloud of gas and dust.

It's founded on two principles of physics:

1. ***Newton's Law of Gravity***
   Heating due to gravitational potential energy

2. ***Conservation of angular momentum***
   Rotational motion is conserved

The Solar Nebula

Solar Nebula – The cloud of gas from which our own Solar System formed.

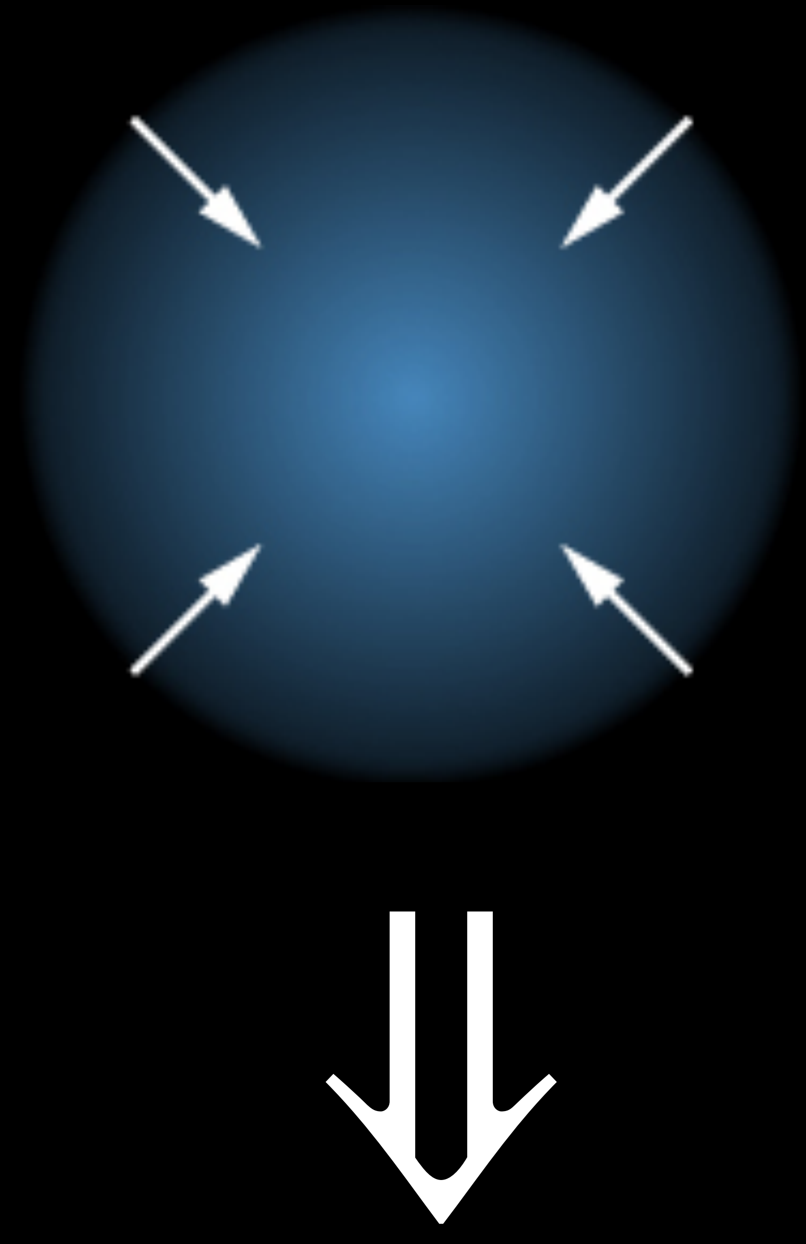
The nebular theory states that our Solar System formed out of a nebula which collapsed under self-gravity.

- **Observational Evidence**
  - We observe stars in the process of forming today.
  - We always find them within interstellar clouds of gas.

Newly born stars in the Omega Nebula

Gravitational Collapse: A Scenario

1. **The solar nebular was initially somewhat spherical and a few light years in diameter.**
   - It was relatively cold.
   - It was slightly rotating.
2. **Some outside force gave it a push.**
   - This could have been a “shock wave” from a nearby exploding star.
3. **As the nebula shrank, the force of gravity increased, causing collapse.**
4. **As the nebula “falls” inward, gravitational potential energy is converted to heat.**
   - *Conservation of energy.*
5. **As the nebula’s radius decreases, it rotates faster**
   - *Conservation of angular momentum.*



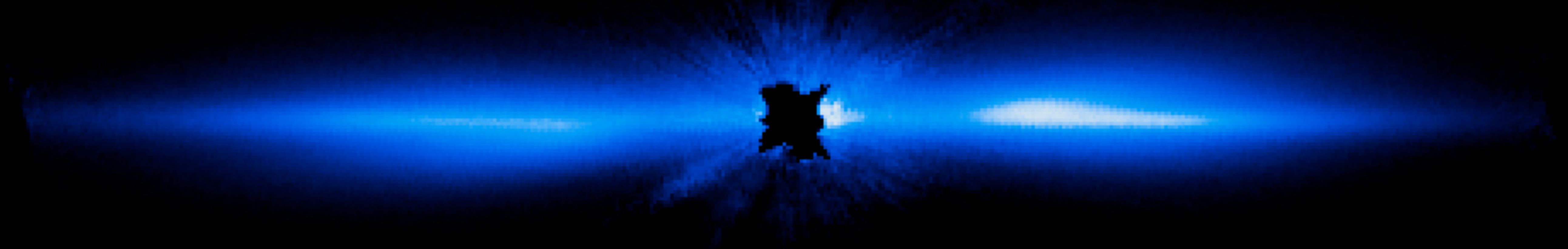
Flattening the Solar Nebula

1. As the nebula collapses, clumps of gas collide & merge.
2. Flattening is a natural consequence of collisions between particles and the spinning cloud.
3. Therefore, their random velocities average out into the nebula’s direction of of rotation ⇒ Orderly motion.
4. The spinning nebula assumes the shape of a disk.
5. As the nebula continue to collapse, it heats up, spins faster, and flattens.

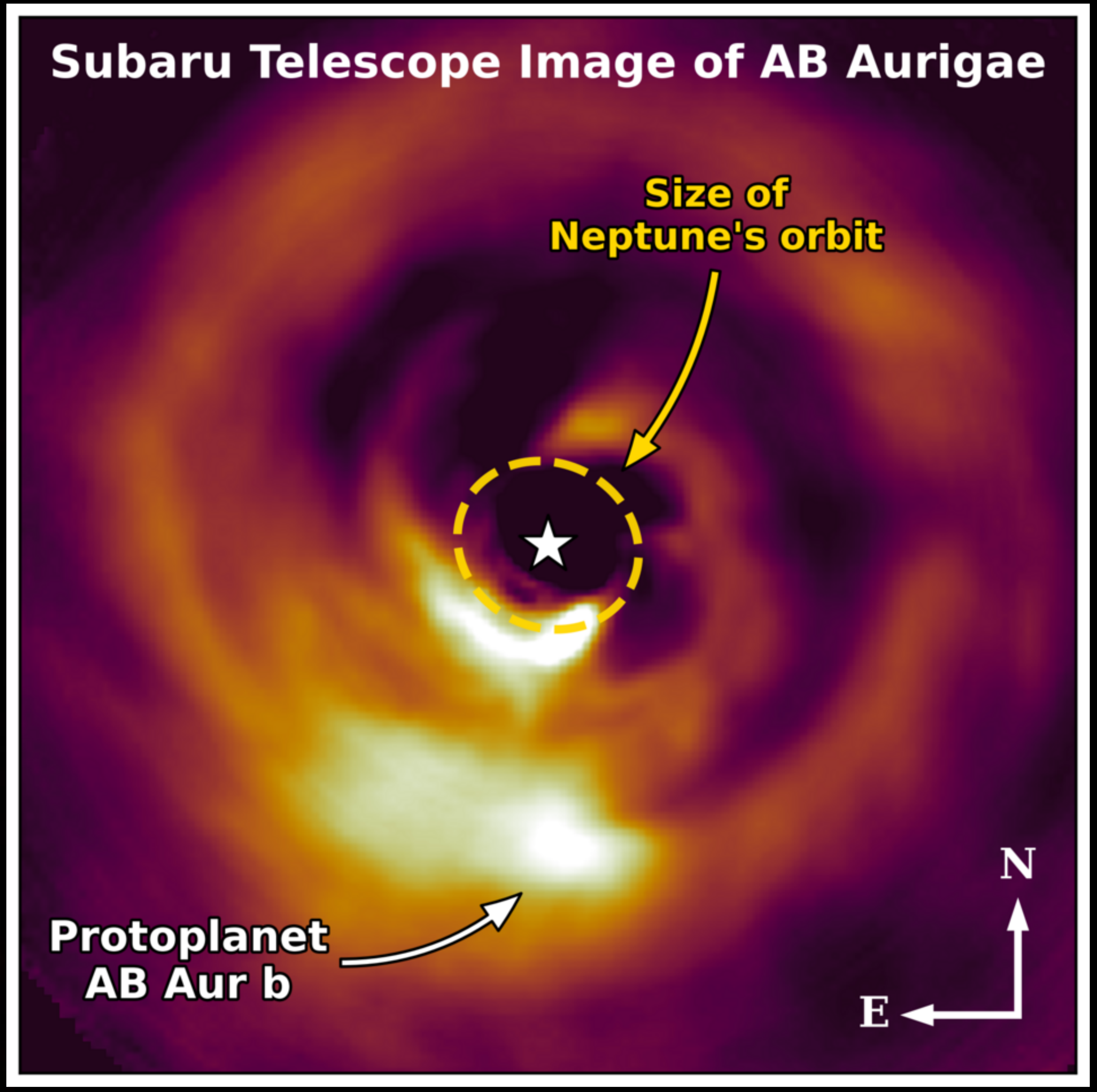
More Support for the Nebular Theory

1. We have observed disks around other stars!!!
2. These could be new planetary systems in formation.

Beta Pictoris Disk — first disk discovered



ALMA image of disk around the star HD 163296 as seen in dusk.



Building the Planets – Condensation

- Elements & compounds began to condense (i.e. solidify) out of the nebula, and this depends on temperature!
- Heavier elements (metals and rocks) have much higher condensation temperatures.
- Meaning that they can stay solid closer to the star, providing material for terrestrial planets.

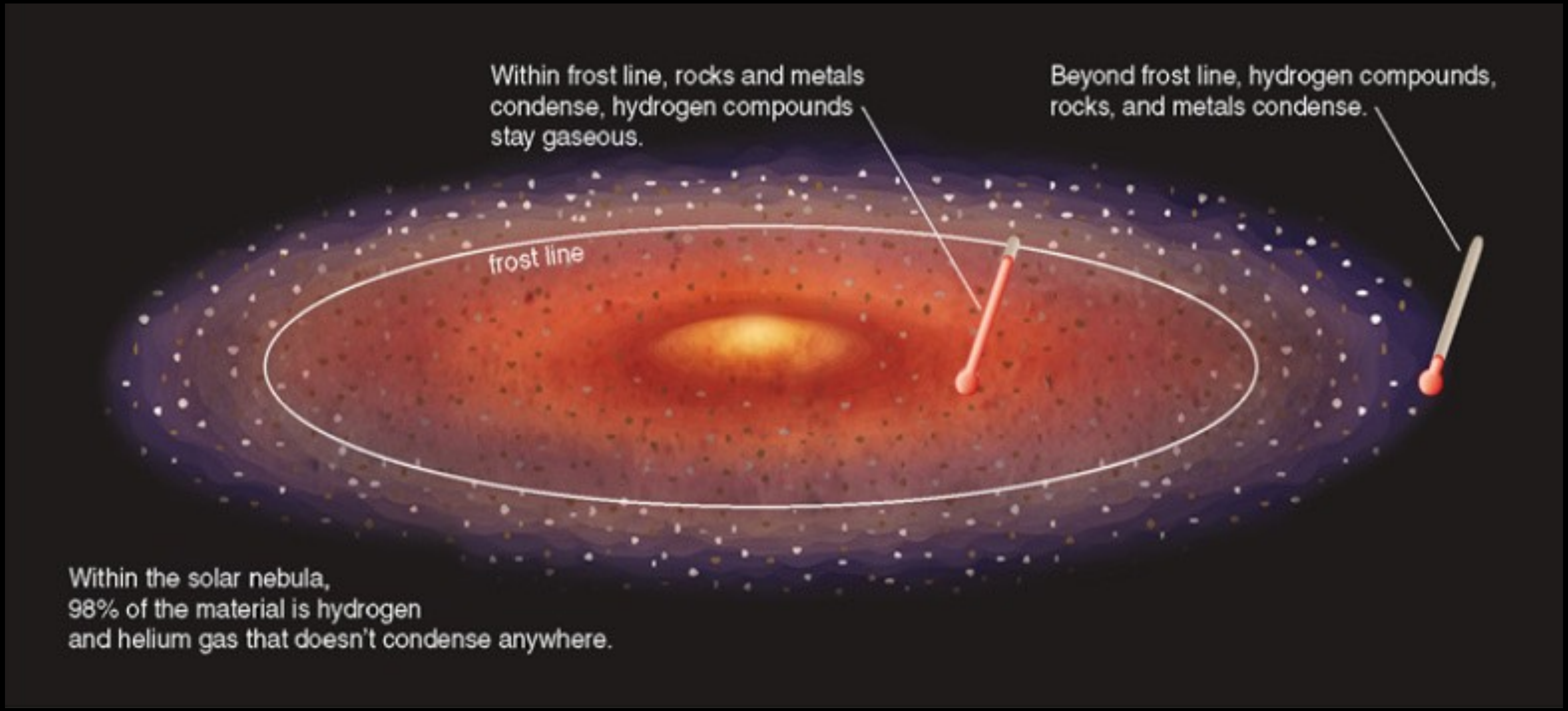
Materials in the Solar Nebula

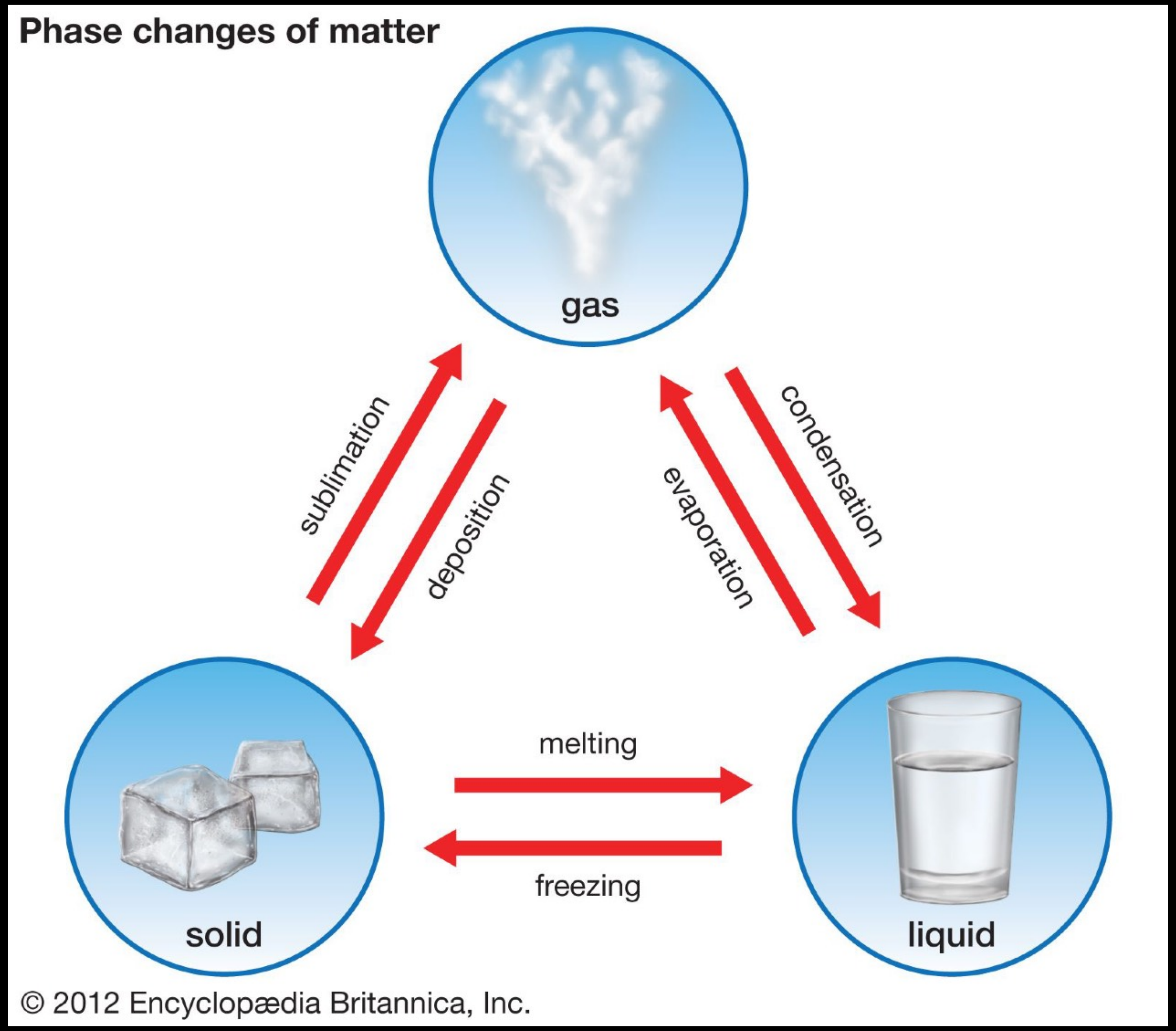
	Metals	Rocks	Hydrogen Compounds	Light Gases
				
Examples	iron, nickel, aluminum	silicates	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	(do not condense in nebula)
Relative Abundance (by mass)	(0.2%)	(0.4%)	(1.4%)	(98%)

Hotter → Colder

Building the Planets – Frost Line

Only rocks and metals condensed within 3.5 AU from the Sun, the defines the **frost line**.





Hydrogen compounds (ices) condensed beyond the frost line.


How did our solar system come to be?
It all began about 4.6 billion years ago in a wispy cloud of gas and dust.
At some point, part of the cloud collapsed in on itself—possibly because the shockwave of a nearby supernova explosion caused it to compress.
ALMA
ALMA
SPHERE/VLT
MUSE/VLT
PDS 70 c
PDS 70 b
10 au
credit: A. Isella, M. Benisty, M. Keppler, S. Y. Haffert
The result: a flat spinning disk of dust and gas.
4.6 Billion Years Ago
Energy
Hydrogen
Helium
Fusion
Hydrogen
Energy
When enough material collected at this disk's center, nuclear fusion began. Our sun was born. It gobbled up 99.8% of all the material.
Credit: Gemini Observatory/AURA
These clumps became planets, dwarf planets, asteroids, comets, and moons.
Nuclear fusion occurs when hydrogen atoms fuse into helium.
This cloud was a small part of a much bigger cloud.
The material left behind by the sun clumped together into bigger and bigger pieces.
Rings
Gaps
HL Tauri
Present
Only rocky things could survive close to the sun, so gaseous and icy material collected further away. That's how our solar system came to be the place it is today!
Comets and asteroids are the left over remains of the solar system's formation.


Questions?

Evaluating Learning Objectives

By the end of today's lecture you will be able to:

- Calculate the mass and density of a planet.
- Describe the different classes of solar system objects — i.e., Jovian, Terrestrial, and dwarf planets, Trans-Neptunian Objects, and Kuiper-belt objects.
- Explain how albedo and the luminosity of the Sun impact Earth's equilibrium temperature.
- Explain why the Greenhouse Effect keeps the Earth warm.
- Describe the formation of the Solar System.

Astrophysics Research Panel

October 30th @ 6PM at the Qualcomm Conference Center

Panelists:

- Adam Burgasser - Director of UCSD Cool Star Lab, specializes in oldest stars, brown dwarfs, and exoplanets, MS + Ph.D. in Physics @ Caltech
- Brian Keating - Host of the Into the Impossible Podcast, specializes in CMB + cosmology, Ph.D. in Physics @ Brown
- Ethan Nadler - Assistant Prof. + Postdoc scholar mentor, specializes in galaxy formation, dark matter, and cosmology, Ph.D. in Physics @ Stanford
- Julie Inglis - Postdoctoral Fellow, specializes in giant planet and substellar atmospheres, Ph.D. in Planetary Sciences @ Caltech

Ask for advice, undergraduate experiences, research concentrations and more!
Audience Q&A + Free Food (Mendocino Farms) + Touch a meteorite!

SASE
SOCIETY OF ASIAN SCIENTISTS & ENGINEERS
AS
ASSOCIATED STUDENTS
UC SAN DIEGO
STUDENT ORGANIZATIONS

Reminders

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- **Complete the anonymous student feedback survey before Sunday, 11/02 by 11:59pm to <u>receive extra credit.</u>**

- Log into canvas and submit your answer to the discussion question <u>by the end of the day</u> to receive participation credit.