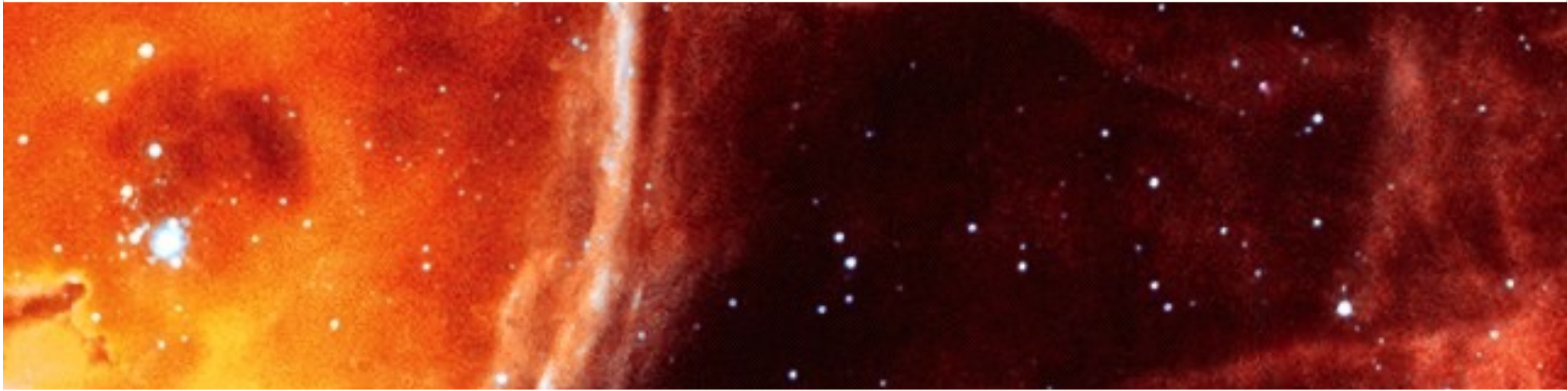
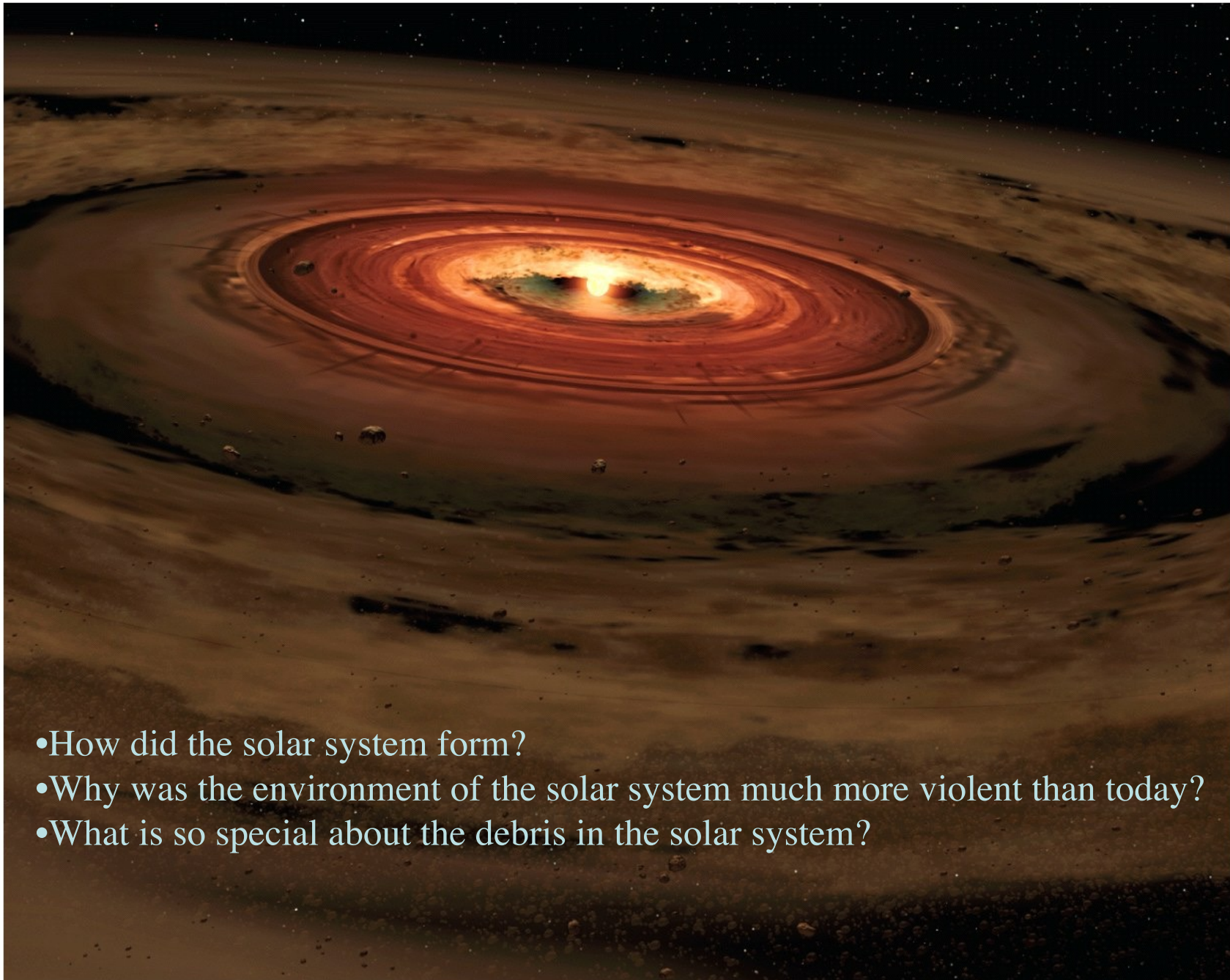


Discovering the Essential Universe



Neil F. Comins

CHAPTER 4 Formation of the Solar System



- How did the solar system form?
- Why was the environment of the solar system much more violent than today?
- What is so special about the debris in the solar system?

The star Antares

Mass loss at the end of the star's life

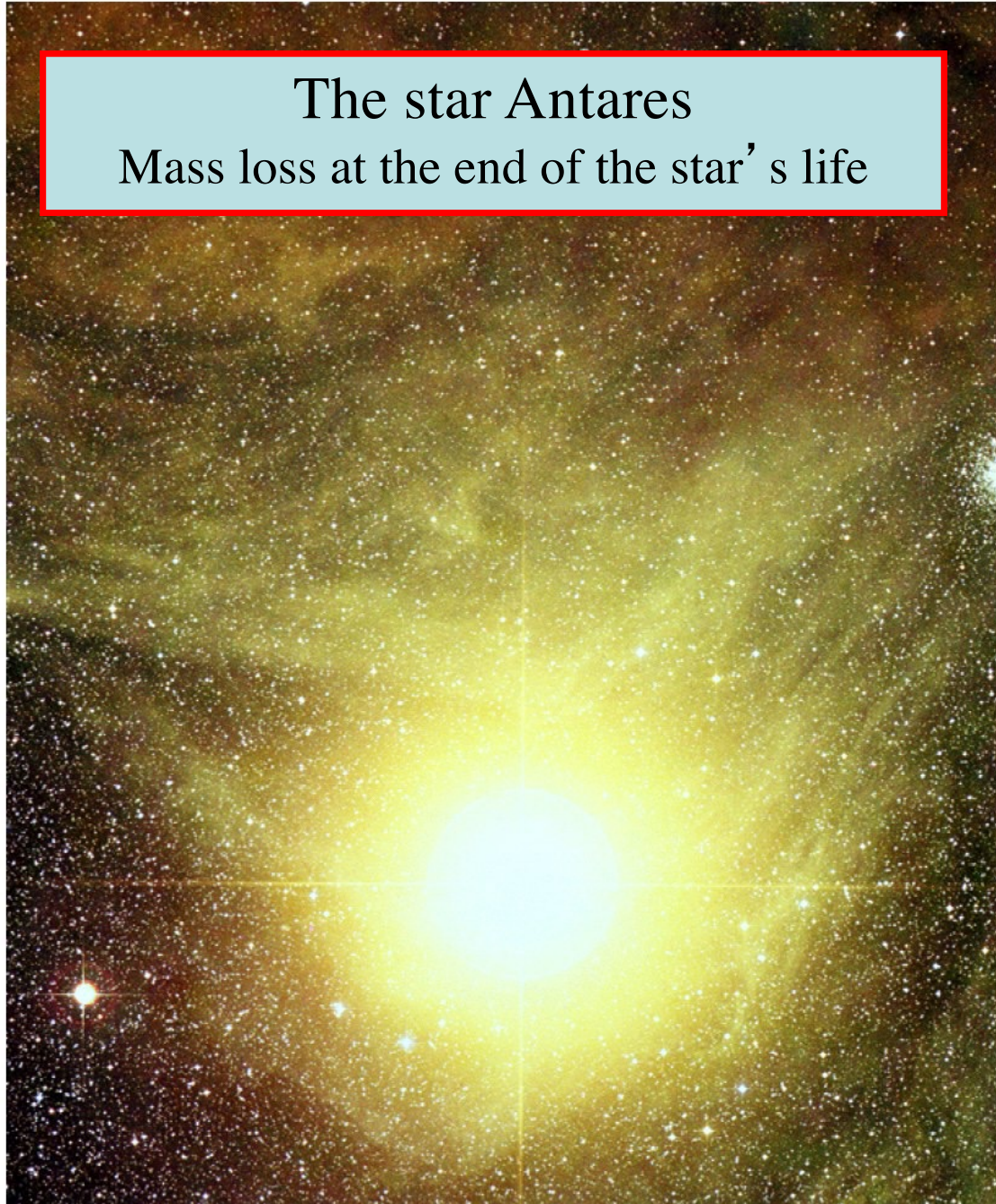
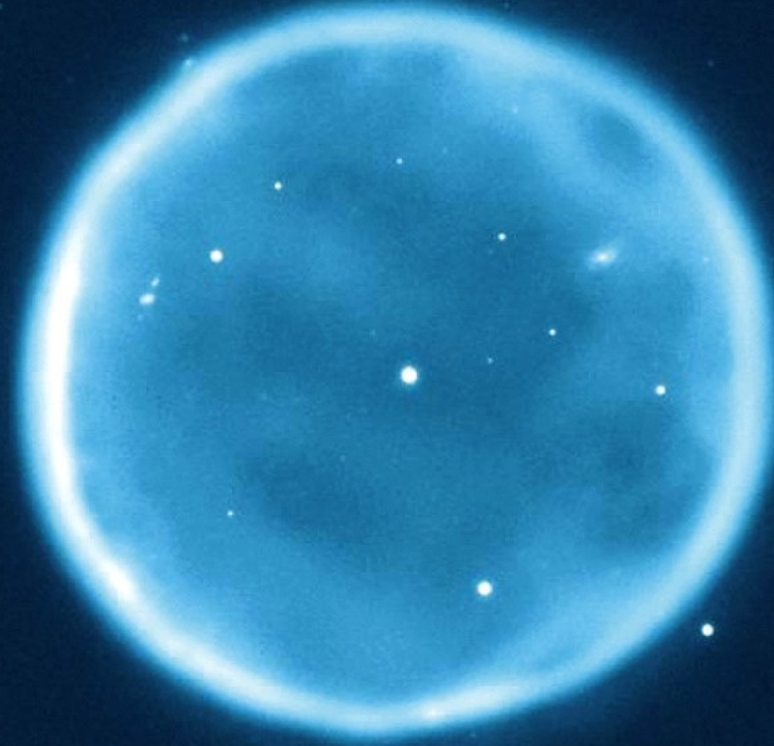


Figure 5-1a
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The planetary nebula Abell 39
Star's outer layers of gas and dust
expanding as a spherical shell



This is the fate of our sun in
another 5 Bill. years

Figure 5-1b
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The Crab Nebula

The remnant of a supernova from 1054,
the most violent form of shedding mass.

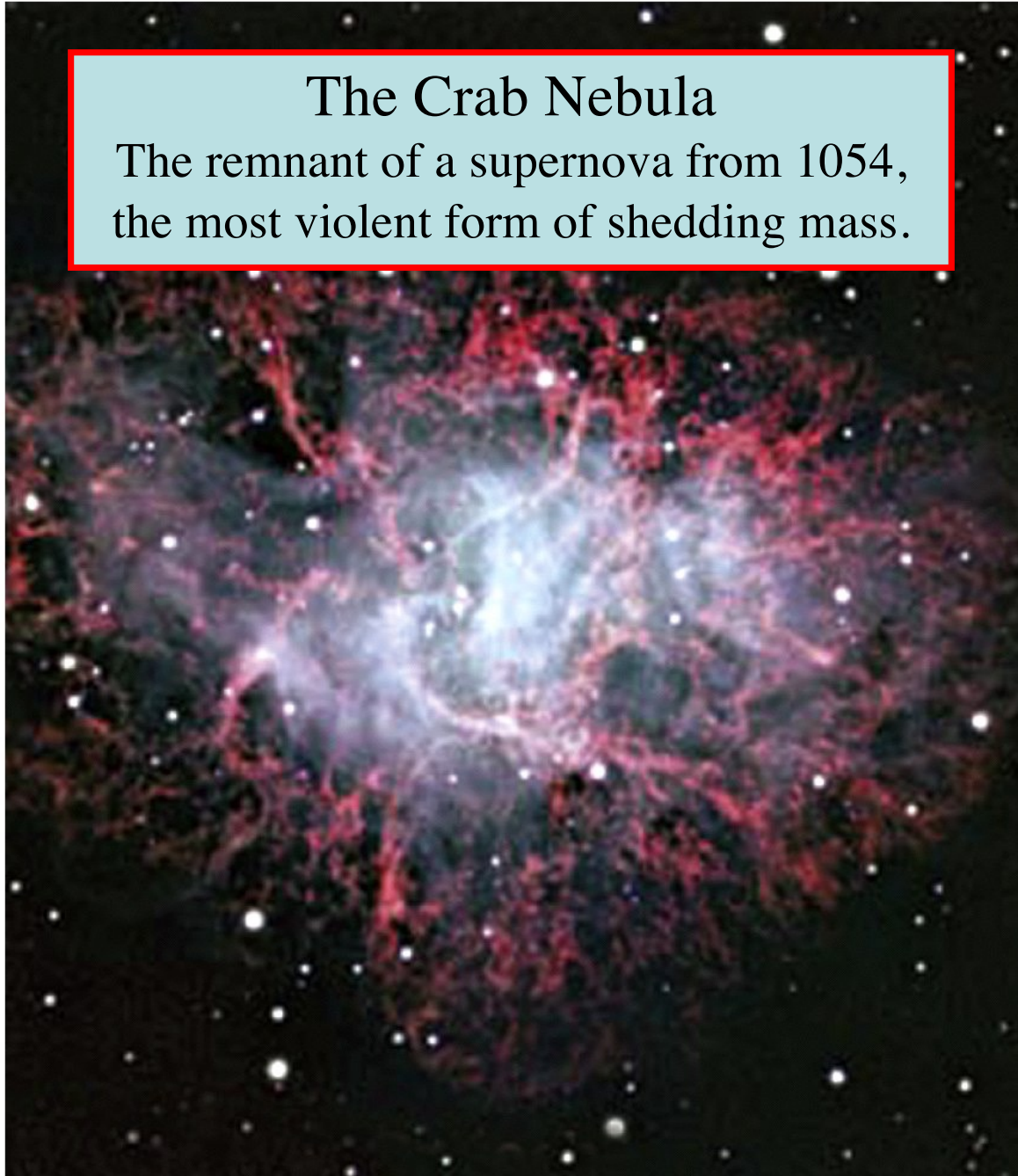


Figure 5-1c
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Dusty regions of star formation in the Cone Nebula



Our solar system
formed from a similar
fragment

Figure 5-2a
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Newly formed stars in the Orion Nebula

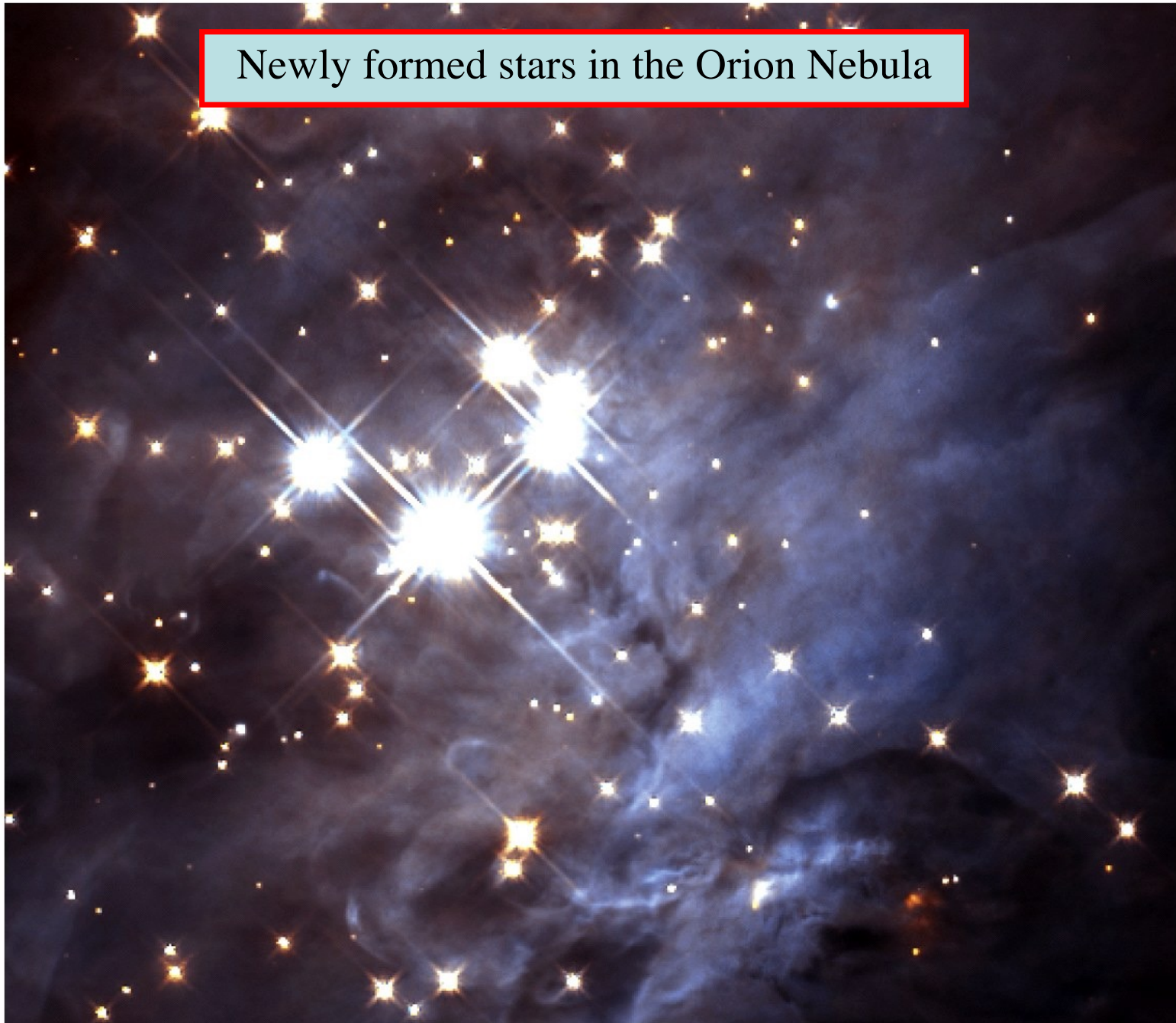


Figure 5-2b
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The formation of the solar system

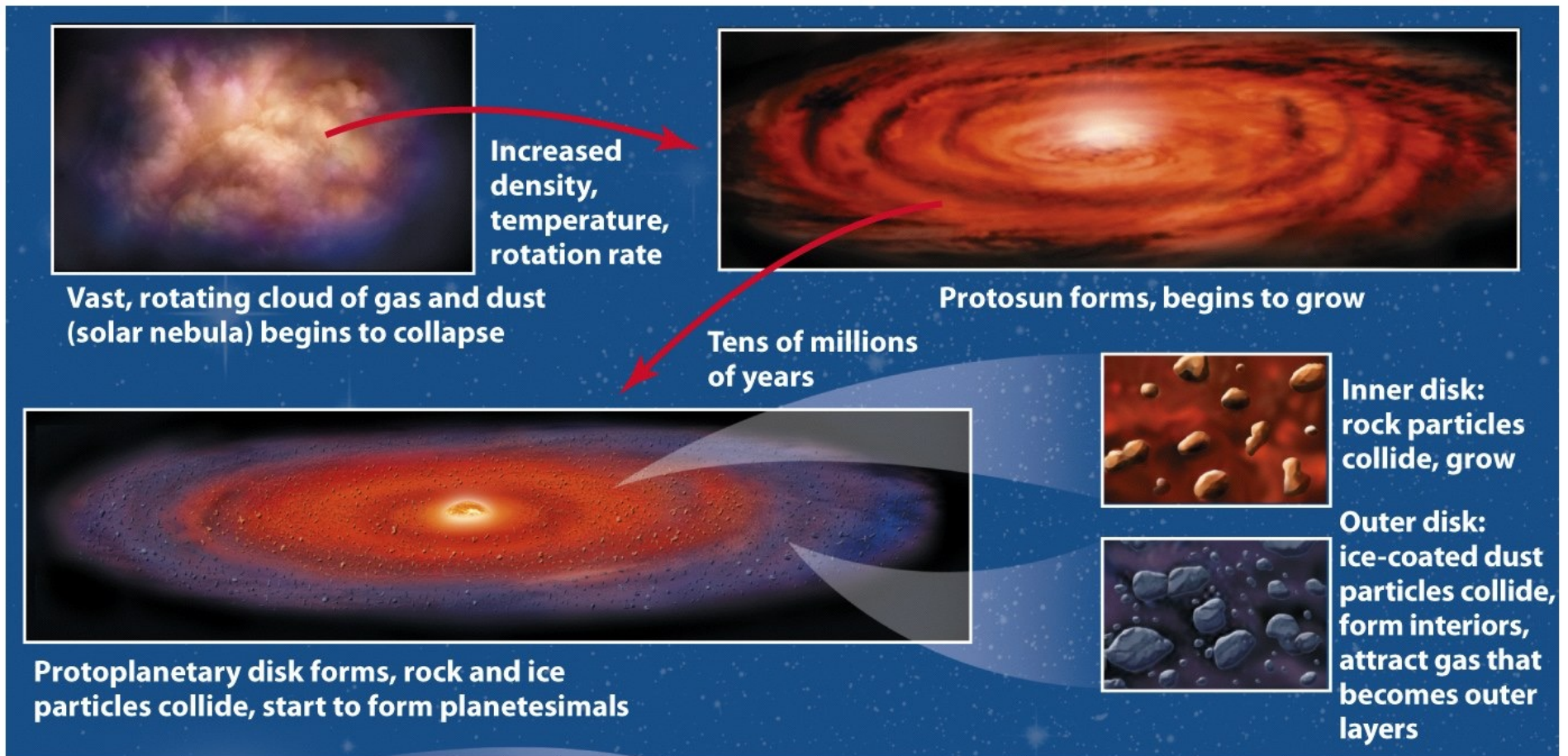
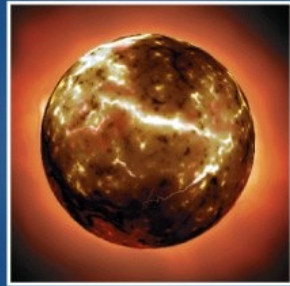


Figure 5-3 part 1

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**Terrestrial planet
in molten state**

**Several hundred
million years**

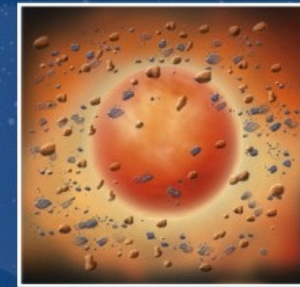


**Accretion of terrestrial planets, protosun becomes hot
enough for nuclear fusion to begin**



**Jovian planets accrete from gas in outer disk,
terrestrial planets heat up, begin chemical
differentiation**

**Several hundred
million years**

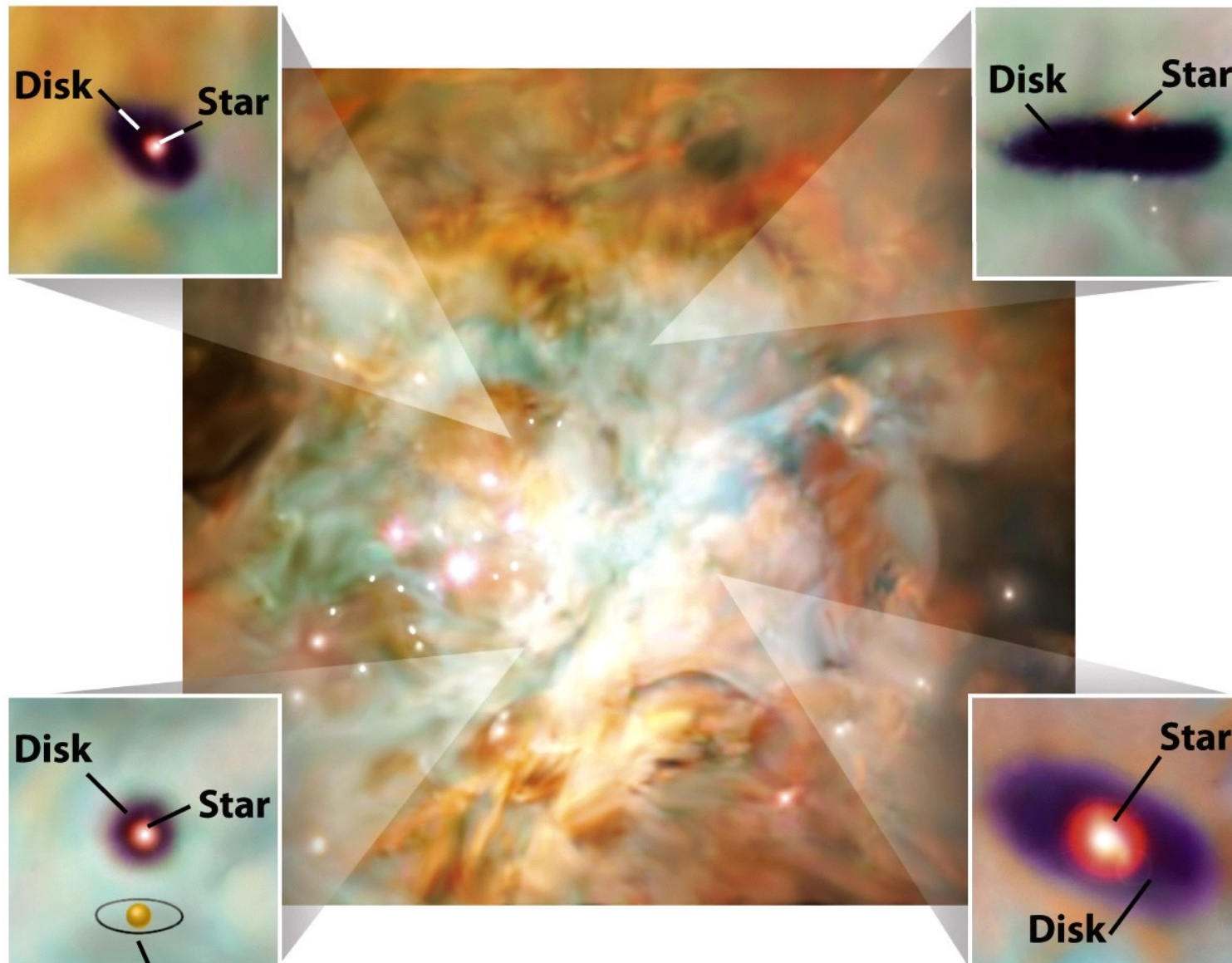


**Jovian planet with
core of rock, ices**



Wind from Sun sweeps away gas and dust, leaving planets, moons, asteroids, Kuiper belt, Oort cloud

Young circumstellar disks of matter in the heart of the Orion Nebula

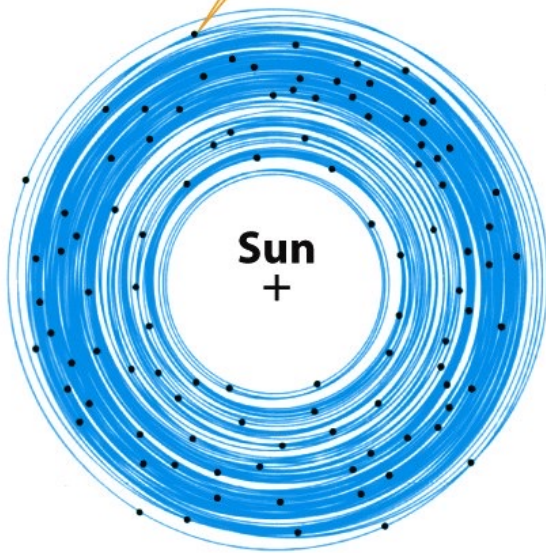


Size of our solar system

Figure 5-4
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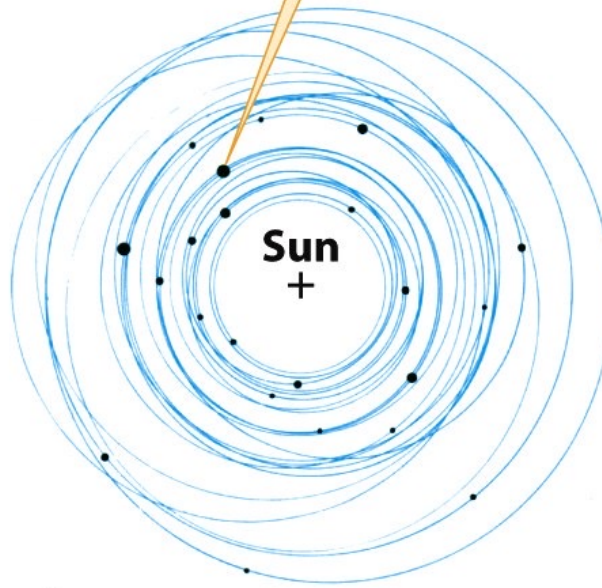
The formation of the inner planets through accretion of material

The computer simulation begins with 100 planetesimals orbiting the Sun.



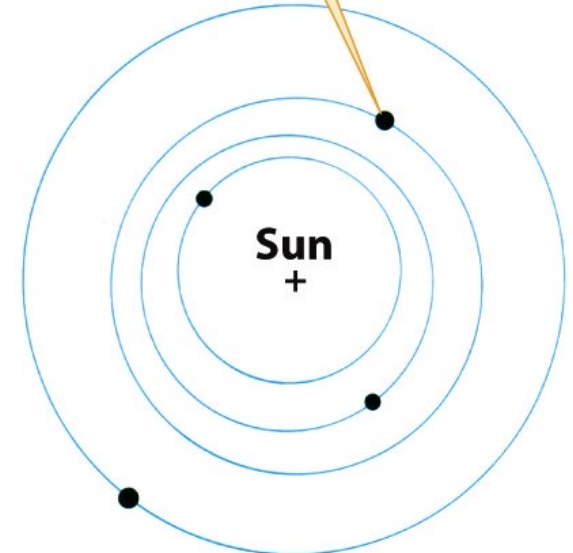
a

After 30 million years, the 100 have coalesced into 22 planetesimals...



b

...and after a total elapsed time of 441 million years, four planets remain.

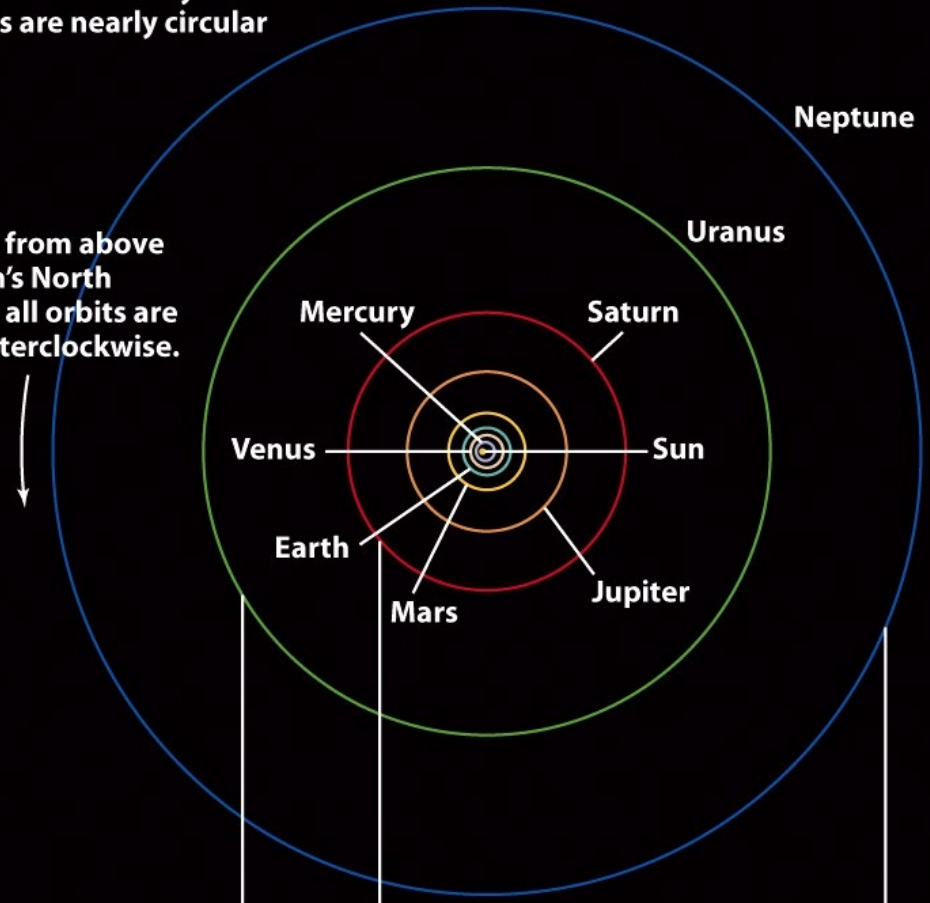


c

Figure 5-5
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**View of the solar system from above:
orbits are nearly circular**

Seen from above
Earth's North
Pole, all orbits are
counterclockwise.



**View of the solar system from the side:
orbits are all in nearly the same plane**

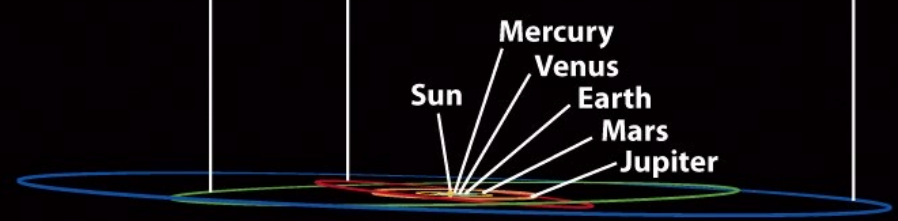


Figure 5-6
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Our moon

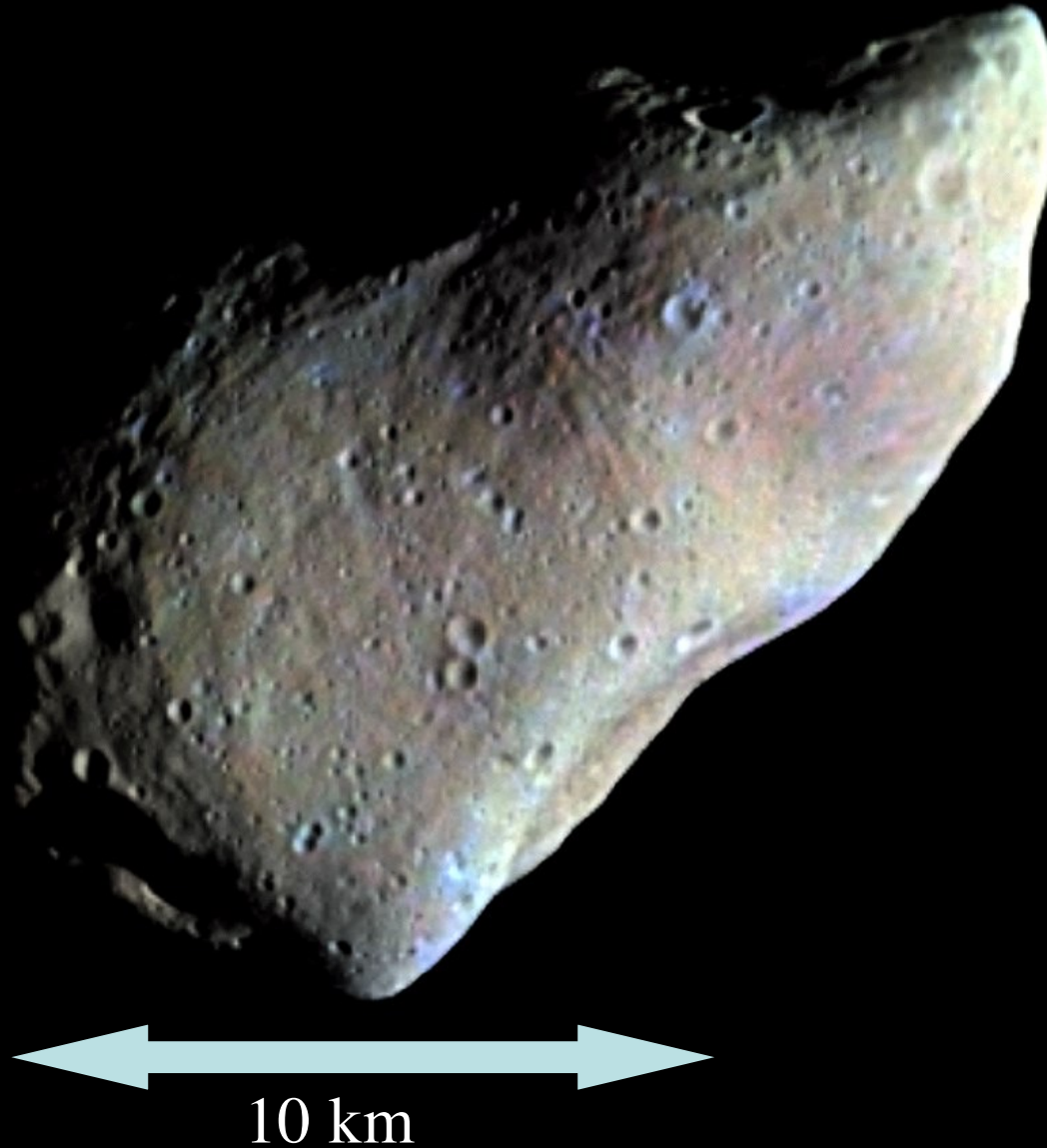


Most craters are impacts from leftover rocky debris from the formation of the solar system.

Age-dating reveals an age of 4.5 Bill years.

Figure 5-7
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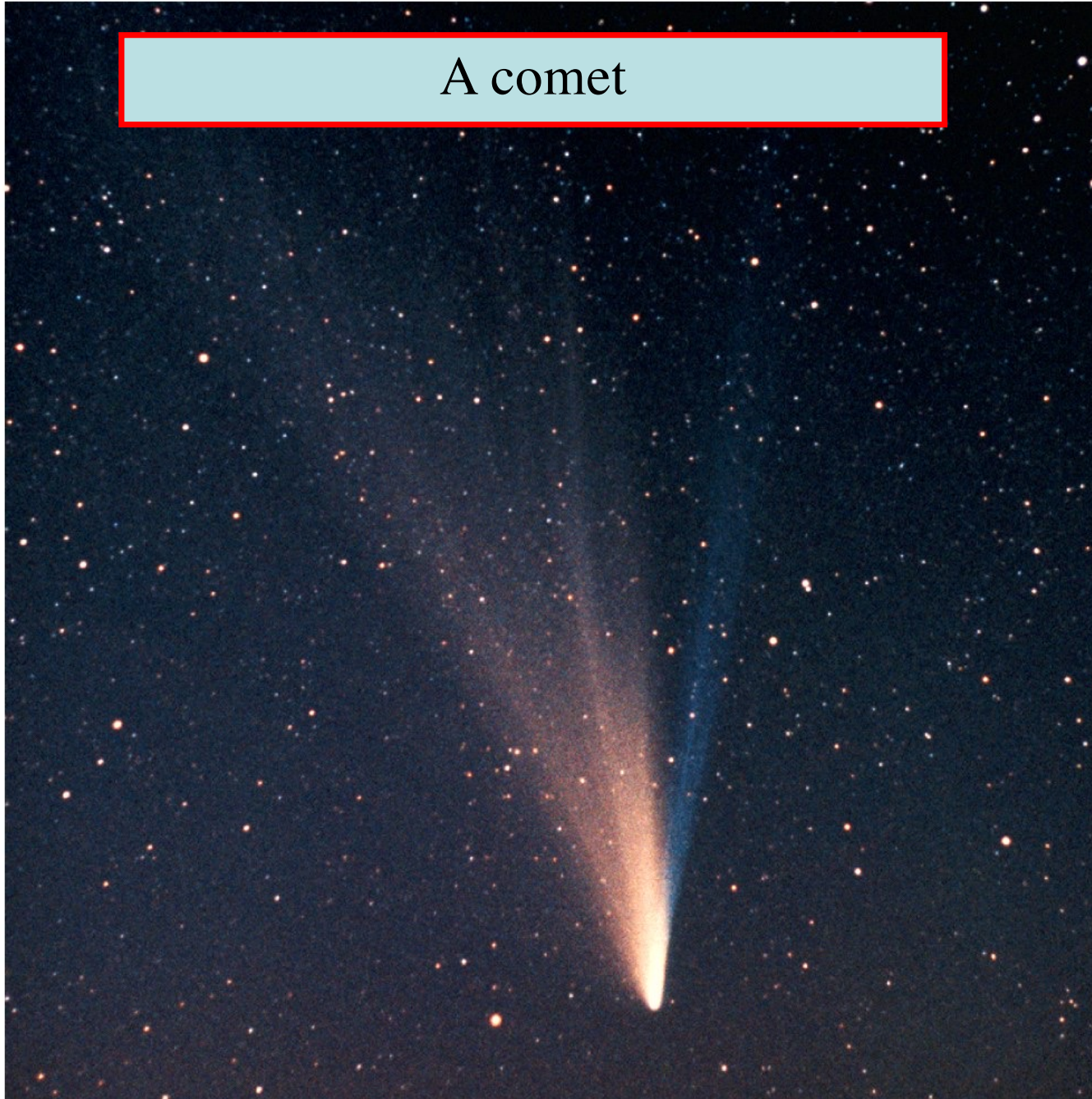
The asteroid Gaspra



More than 100,000 asteroids have been observed in the asteroid belt.

Figure 5-8
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A comet



This is another example of leftover debris from the formation of the solar system.

The comet nucleus is typically 10 km in size.

TABLE 5-1 Orbital Characteristics of the Planets

| | Average distance from Sun | | Orbital period |
|----------------|----------------------------------|----------------------------|-----------------------|
| | (AU) | (10⁶ km) | (year) |
| Mercury | 0.39 | 58 | 0.24 |
| Venus | 0.72 | 108 | 0.62 |
| Earth | 1.00 | 150 | 1.00 |
| Mars | 1.52 | 228 | 1.88 |
| Jupiter | 5.20 | 778 | 11.86 |
| Saturn | 9.54 | 1427 | 29.46 |
| Uranus | 19.19 | 2871 | 84.01 |
| Neptune | 30.06 | 4497 | 164.79 |

The sun and the eight planets drawn to size scale

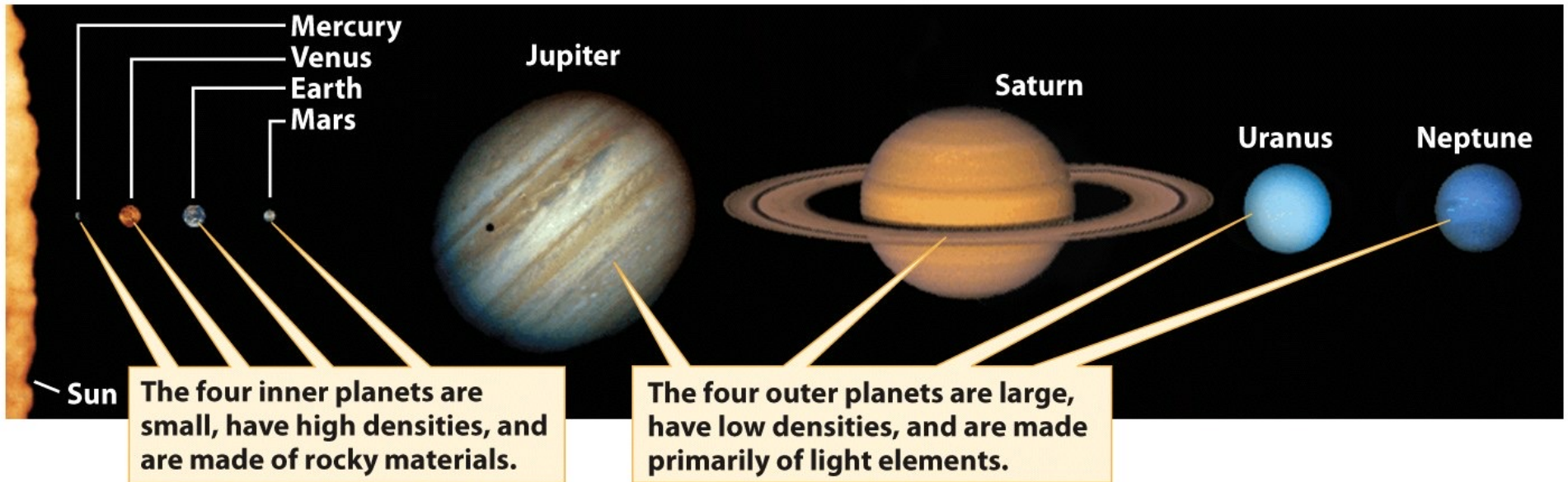


Figure 5-10

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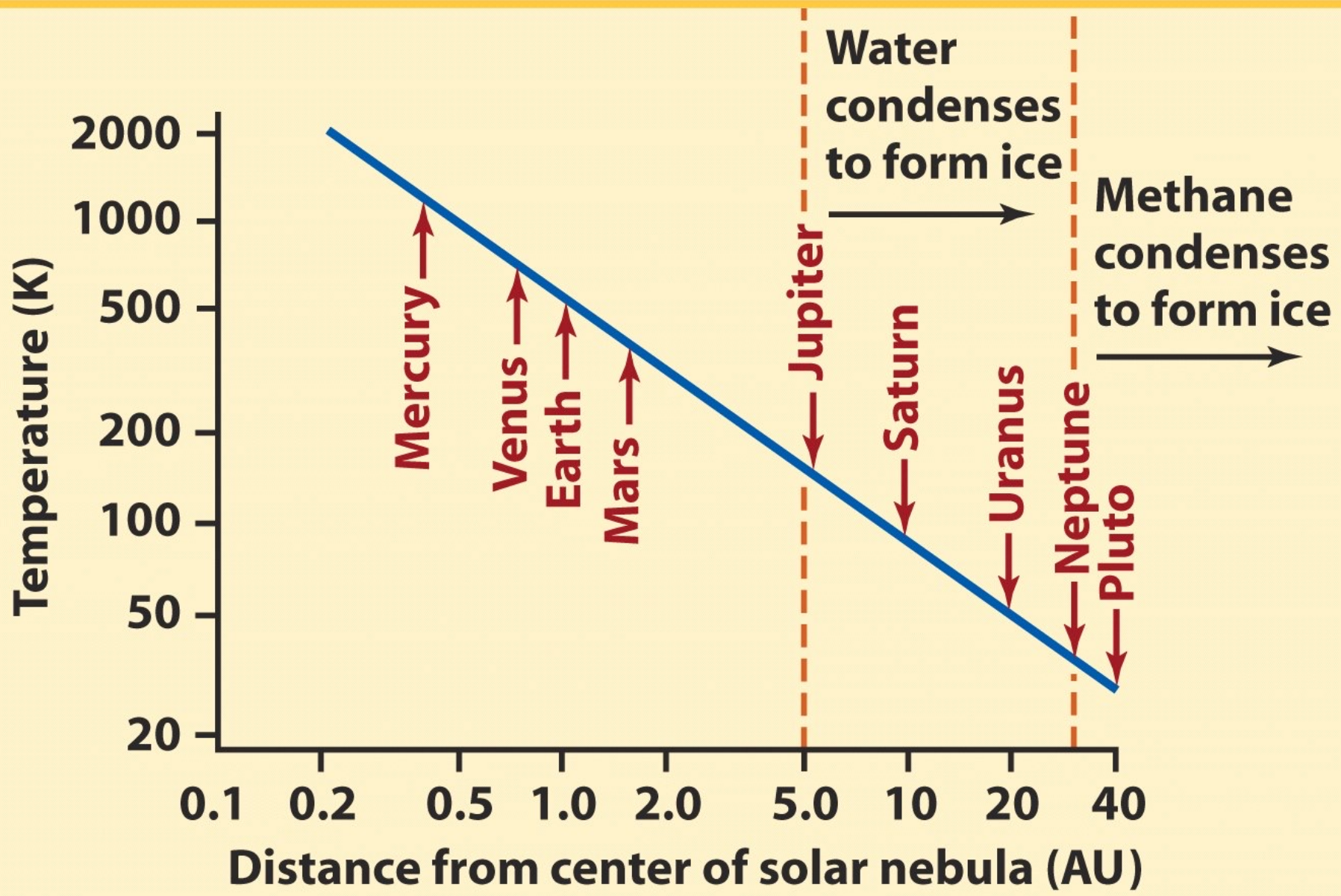
•The average density, D , of any substance depends in part on its composition

$$D = \frac{m}{V}$$

•An object sinks in a fluid if its average density is greater than that of the fluid, but rises if its average density is less than that of the fluid

•The terrestrial (inner) planets are made of rocky materials and have dense iron cores, which gives these planets high average densities

•The Jovian (outer) planets are composed primarily of light elements such as hydrogen and helium, which gives these planets low average densities



Why do some gases remain in an atmosphere and not others?

Kinetic energy, E_k , of a gas atom (or molecule)

$$E_k = \frac{1}{2} m v^2 = \frac{3}{2} k T$$

m = atom mass (kg)

T = temperature (K)

v = atom velocity (m/s)

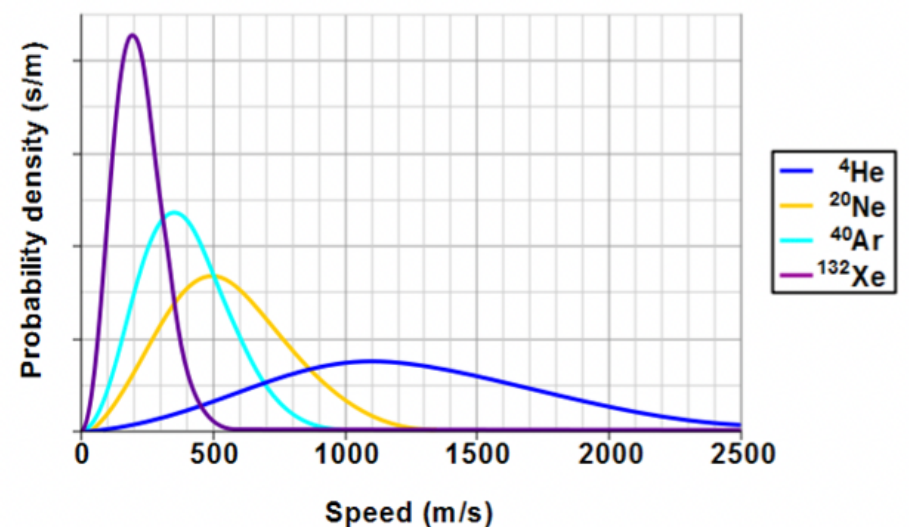
k = Boltzmann's constant

$$1.38 \cdot 10^{-23} \text{ J/K}$$

$$\Rightarrow v_{\text{rms}} = \text{SQRT} (3 kT / m)$$

If $6v_{\text{rms}} > v_{\text{esc}}$, then, over time, gas escapes the planet's gravity.

Maxwell-Boltzmann Molecular Speed Distribution for Noble Gases



Example:

H atom

$$m = 1.66 \times 10^{-27} \text{ kg}$$

$$T = 300 \text{ K}$$

$$v_{\text{esc}} = 11,185 \text{ m s}^{-1}$$

$$v_{\text{rms}} = \text{SQRT}(3 \times 1.38 \times 10^{-23} \times 300 / 1.66 \times 10^{-27})$$

Example:

H atom

$$m = 1.66 \times 10^{-27} \text{ kg}$$

$$T = 300 \text{ K}$$

$$v_{\text{esc}} = 11,185 \text{ m s}^{-1}$$

$$\begin{aligned} v_{\text{rms}} &= \text{SQRT}(3 \times 1.38 \times 10^{-23} \times 300 / 1.66 \times 10^{-27}) \\ &= 2735 \text{ m s}^{-1} \end{aligned}$$

Example:

H atom

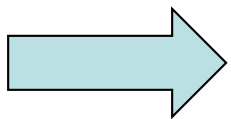
$$m = 1.66 \times 10^{-27} \text{ kg}$$

$$T = 300 \text{ K}$$

$$v_{\text{esc}} = 11,185 \text{ m s}^{-1}$$

$$v_{\text{rms}} = \text{SQRT}(3 \times 1.38 \times 10^{-23} \times 300 / 1.66 \times 10^{-27}) \\ = 2735 \text{ m s}^{-1}$$

$$6v_{\text{rms}} = 16410 \text{ m s}^{-1}$$



$$6v_{\text{rms}} > v_{\text{esc}}$$

H escapes Earth

TABLE 5-2 Physical Characteristics of the Planets

| | Diameter | | Mass | | Average density |
|---------|----------|-------------|----------------------|-------------|----------------------|
| | (km) | (Earth = 1) | (kg) | (Earth = 1) | (kg/m ³) |
| Mercury | 4878 | 0.38 | 3.3×10^{23} | 0.06 | 5430 |
| Venus | 12,100 | 0.95 | 4.9×10^{24} | 0.81 | 5250 |
| Earth | 12,756 | 1.00 | 6.0×10^{24} | 1.00 | 5520 |
| Mars | 6786 | 0.53 | 6.4×10^{23} | 0.11 | 3950 |
| Jupiter | 142,984 | 11.21 | 1.9×10^{27} | 317.94 | 1330 |
| Saturn | 120,536 | 9.45 | 5.7×10^{26} | 95.18 | 690 |
| Uranus | 51,118 | 4.01 | 8.7×10^{25} | 14.53 | 1290 |
| Neptune | 49,528 | 3.88 | 1.0×10^{26} | 17.14 | 1640 |

Table 5-2
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The diversity of the solar system is a result of its origin and evolution

| table 7-3 Comparing Terrestrial and Jovian Planets | | |
|---|--|----------------------------|
| | Terrestrial Planets | Jovian Planets |
| Distance from the Sun | Less than 2 AU | More than 5 AU |
| Size | Small | Large |
| Composition | Mostly rocky materials containing iron, oxygen, silicon, magnesium, nickel, and sulfur | Mostly hydrogen and helium |
| Density | High | Low |

The planets, satellites, comets, asteroids, and the Sun itself formed from the same cloud of interstellar gas and dust

The composition of this cloud was shaped by cosmic processes, including nuclear reactions that took place within stars that died long before our solar system was formed

Different planets formed in different environments depending on their distance from the Sun and these environmental variations gave rise to the planets and satellites of our present-day solar system

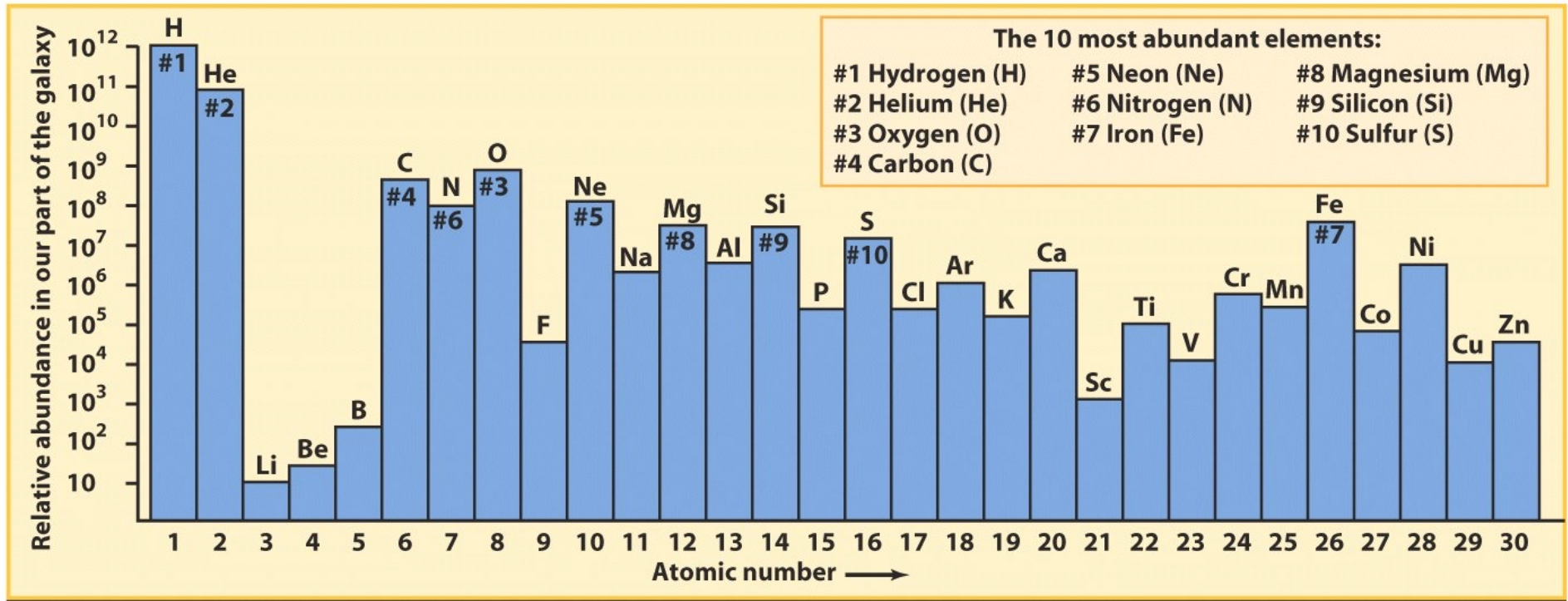
Any model of solar system origins must explain the present-day Sun and planets

The terrestrial planets, which are composed primarily of rocky substances, are relatively small, while the Jovian planets, which are composed primarily of hydrogen and helium, are relatively large.

All of the planets orbit the Sun in the same direction, and all of their orbits are in nearly the same plane.

The terrestrial planets orbit close to the Sun, while the Jovian planets orbit far from the Sun.

The abundances of the chemical elements are the result of cosmic processes



The vast majority of the atoms in the universe are hydrogen and helium atoms produced in the Big Bang