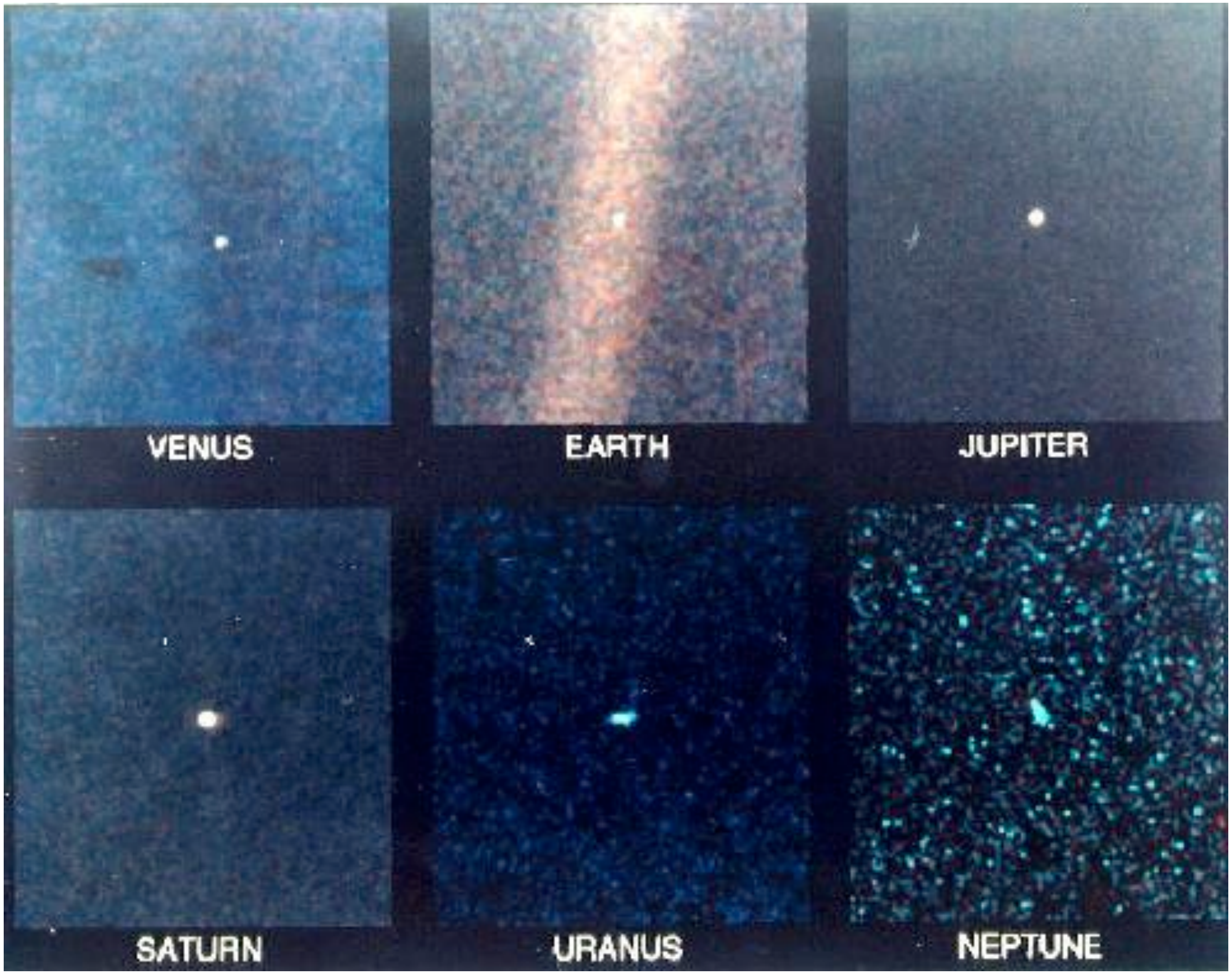
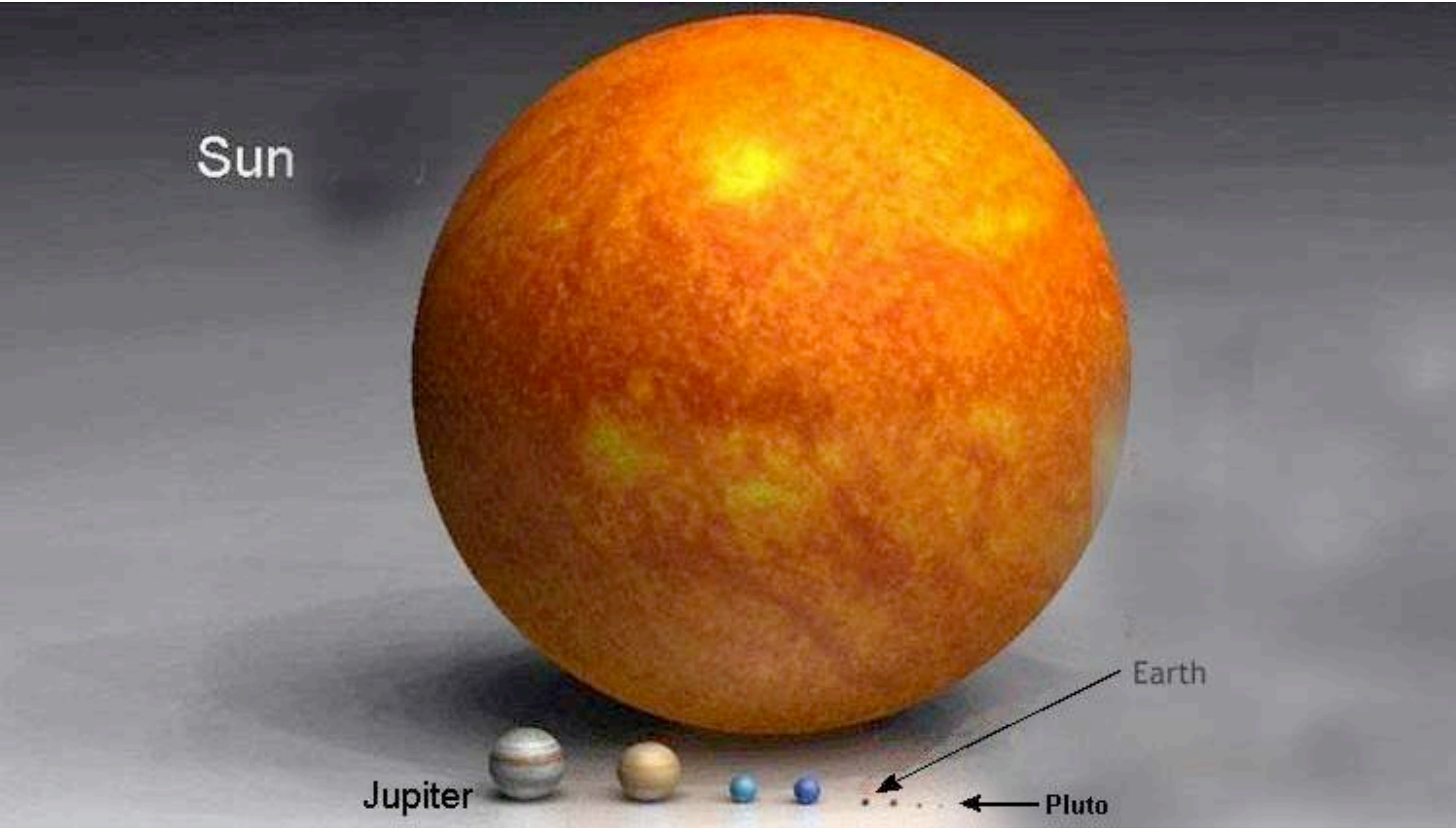
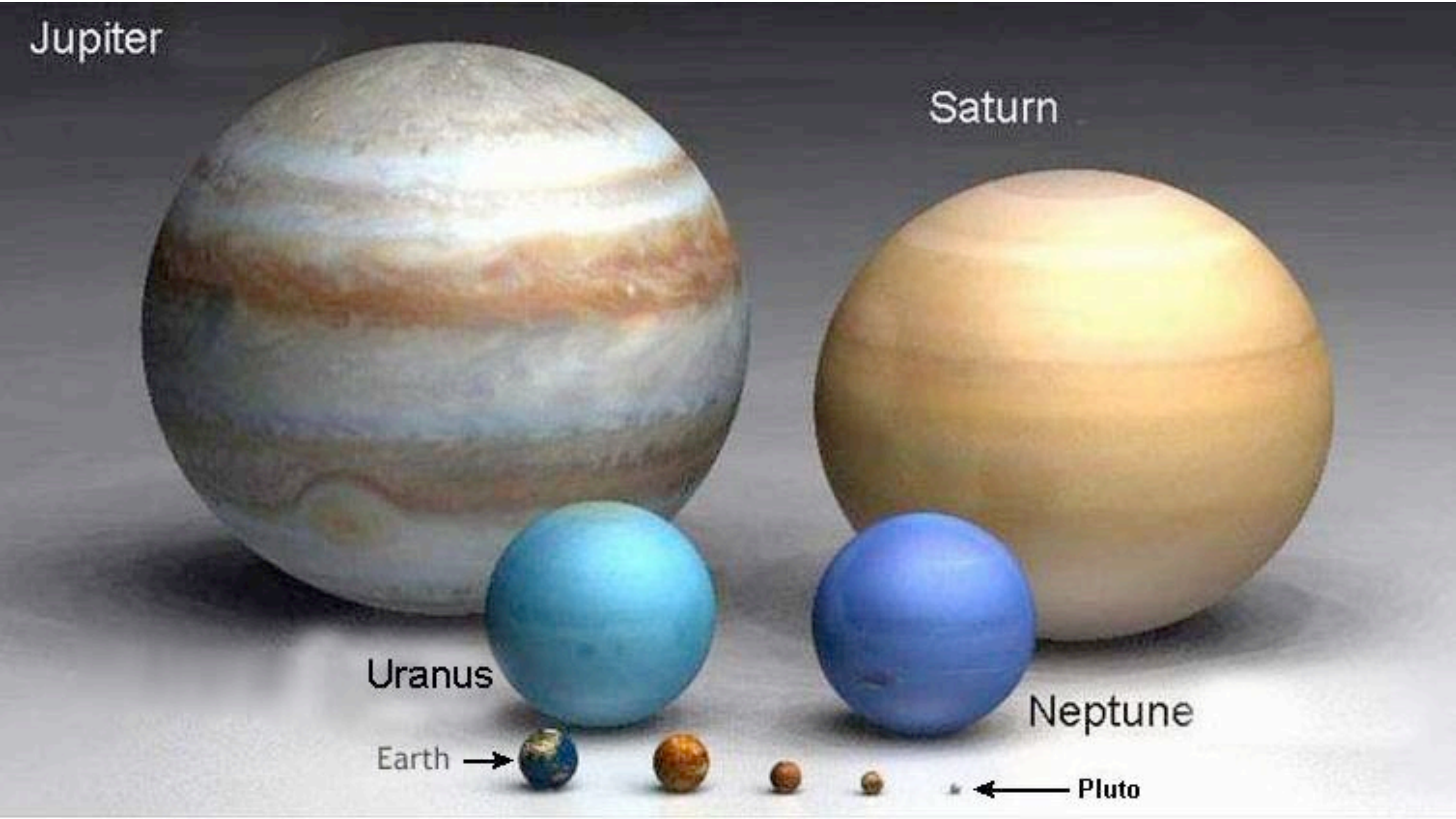
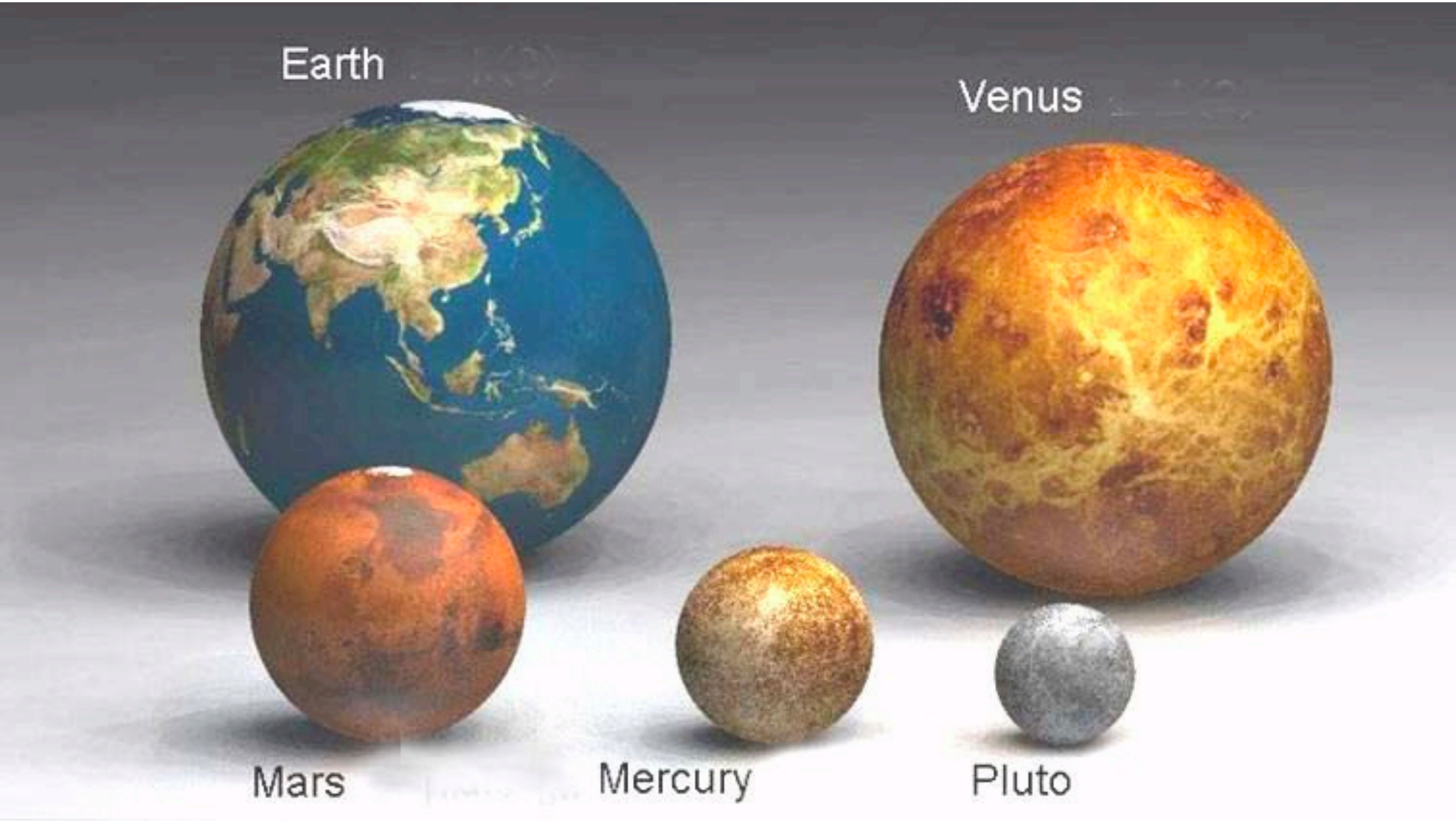
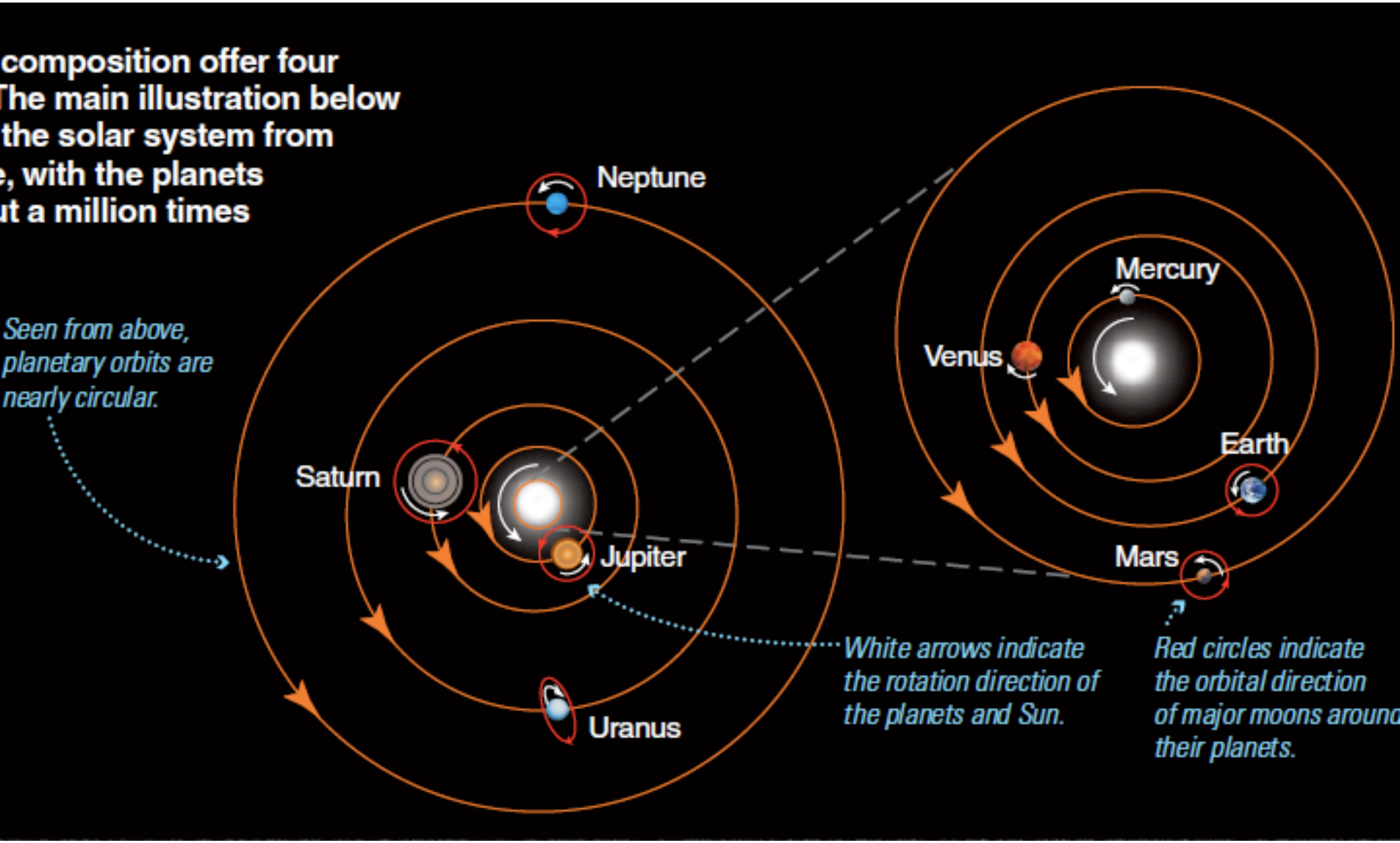
A Look Back at Our Planetary System




Sun
Earth
Jupiter
Pluto


Jupiter
Saturn
Uranus
Neptune
Earth
Pluto


Earth
Venus
Mars
Mercury
Pluto


composition offer four
The main illustration below
the solar system from
e, with the planets
ut a million times
Neptune
Seen from above, planetary orbits are nearly circular.
Saturn
Jupiter
Uranus
Mercury
Venus
Earth
Mars
White arrows indicate the rotation direction of the planets and Sun.
Red circles indicate the orbital direction of major moons around their planets.

Comparative Planetology

• Studying the similarities among and differences between the *planets*

– this includes moons, asteroids, & comets

• This approach is useful for learning about:

– the physical processes which shape the planets

– the origin and history of our Solar System

– the nature of planetary systems around other stars

The Layout of the Solar System

• What are the major patterns of motion in our solar system?

• What are the two major types of planet?

• Where do we find asteroids and comets in the solar system?

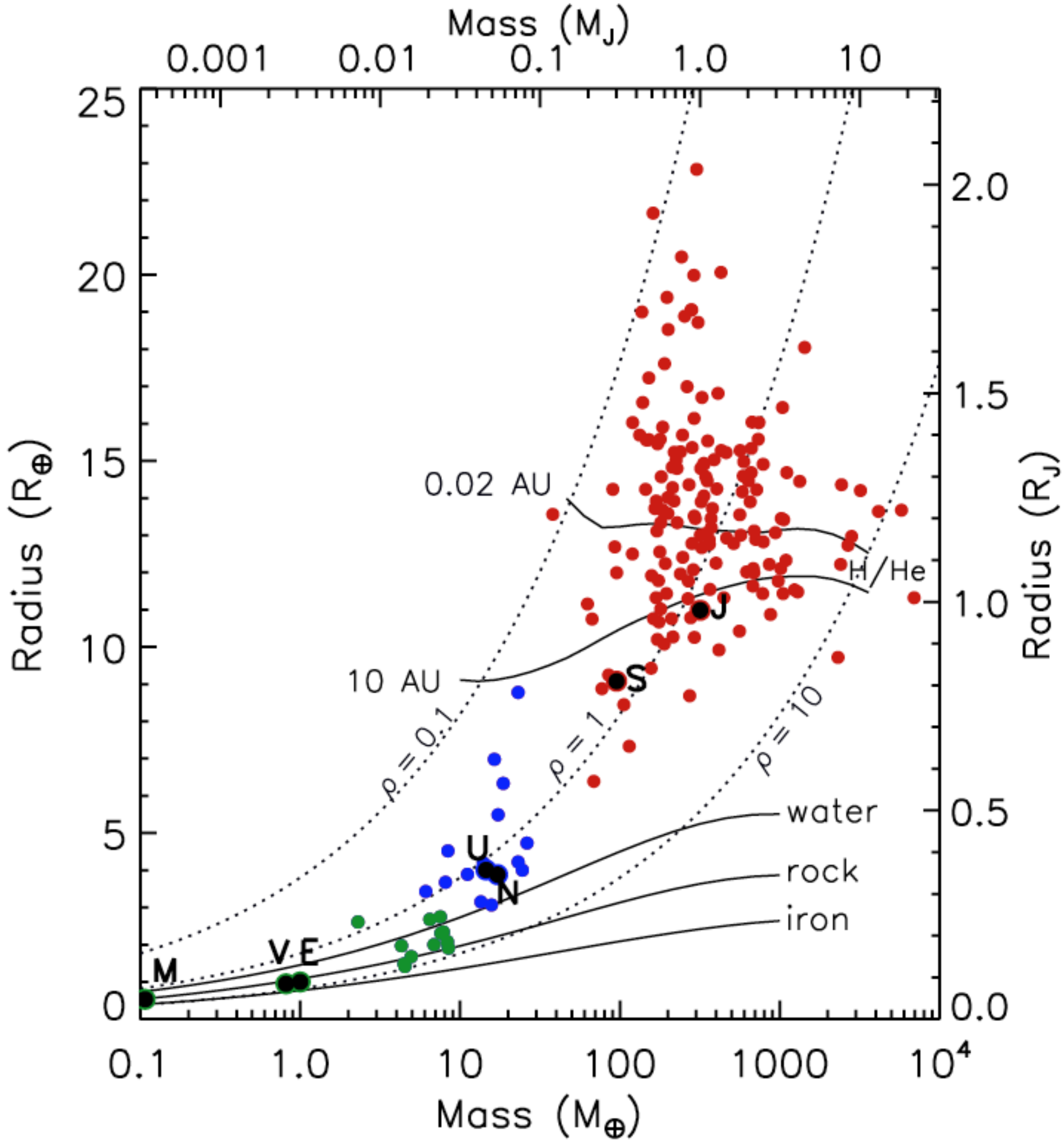
• Describe a few important exceptions to the general rules.

What is density?

density = mass/volume

typical units: [g/cm3]

Density of water is *1 g/cm³.*



Planets fall into two major categories: Small, rocky terrestrial planets and large, hydrogen-ric

terrestrial planet

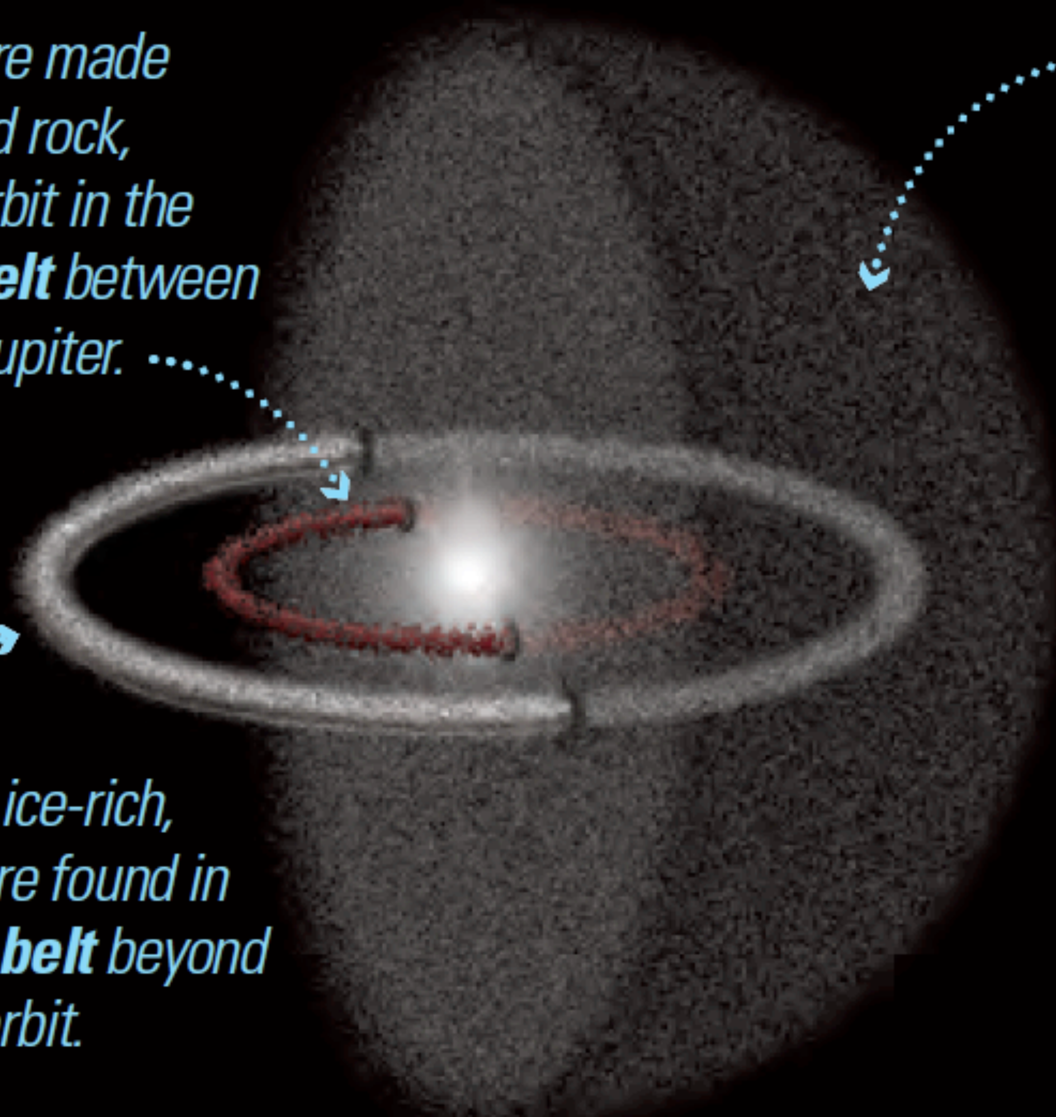
jovian planet

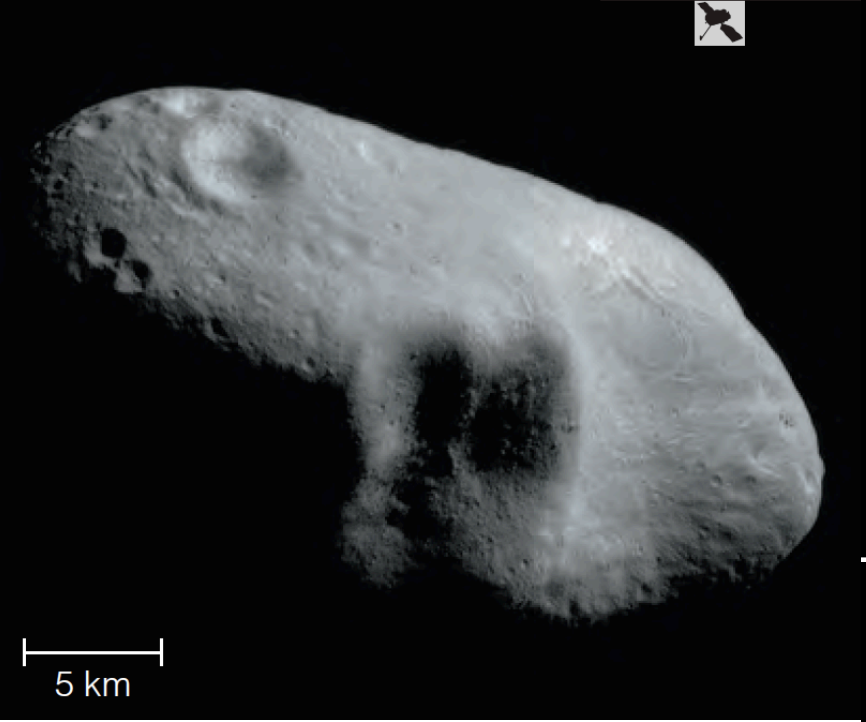
Terrestrial Planets:

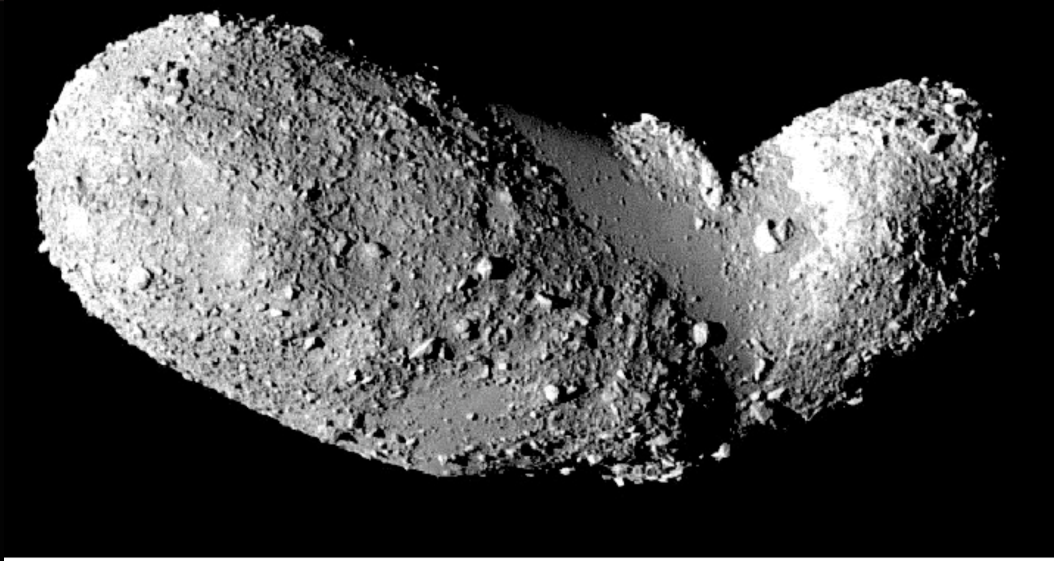
- *small in mass and size*
- *close to the Sun*
- *made of metal and rock*
- *few moons and no rings*

- *made of H, He, and hydrogen compounds*
- *rings and many moons*

Swarms of asteroids and comets populate the solar system. Vast numbers of rocky asteroids and icy comets are found throughout the solar system, but are concentrated in three distinct regions.





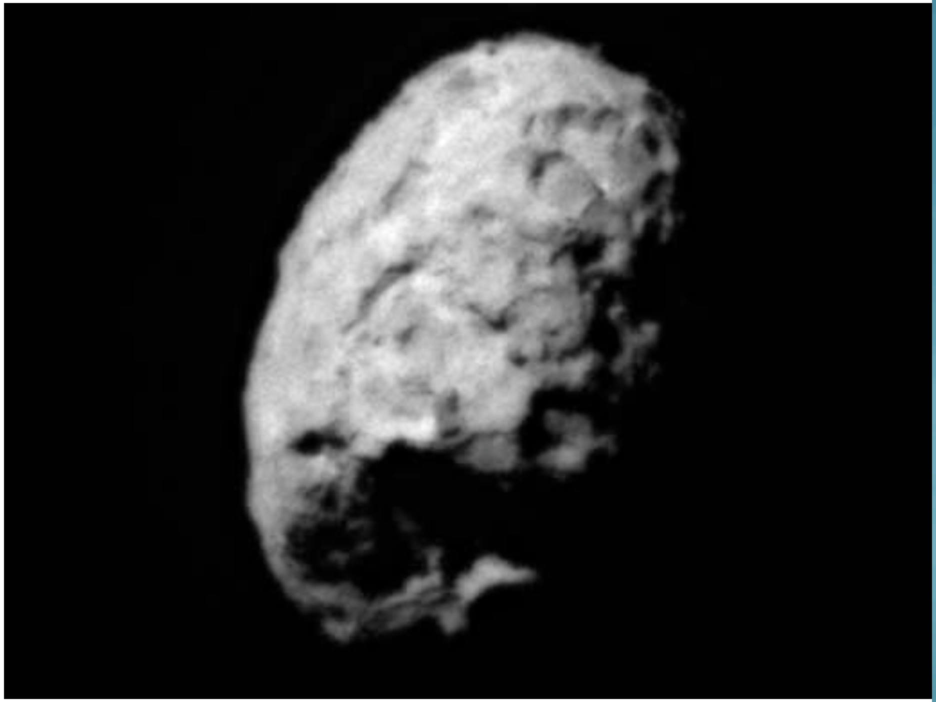


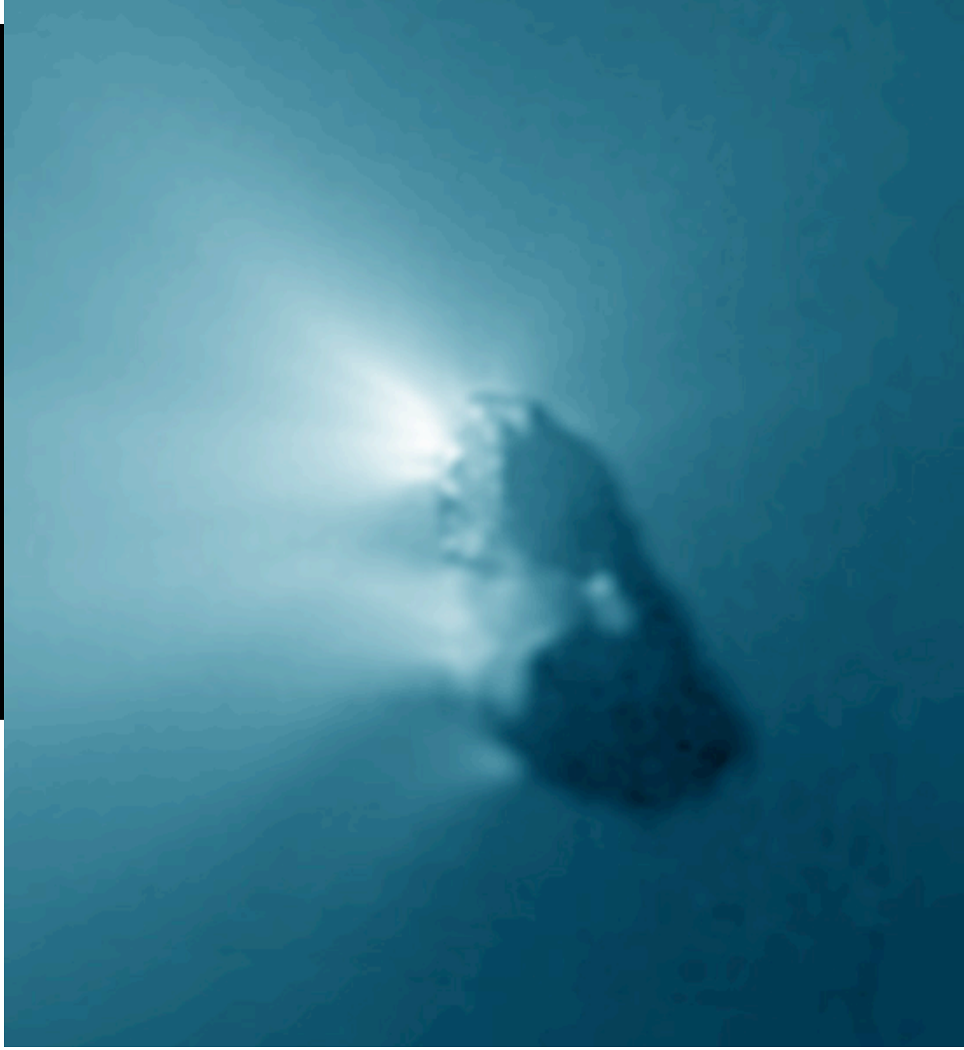
Asteroids

Small and irregularly shaped

Rock and iron

The total mass of the asteroids is 2.3×10^{21} kg, roughly 2500 times less than the mass of the Earth (about 30 times less than the mass of the Moon)





Comets

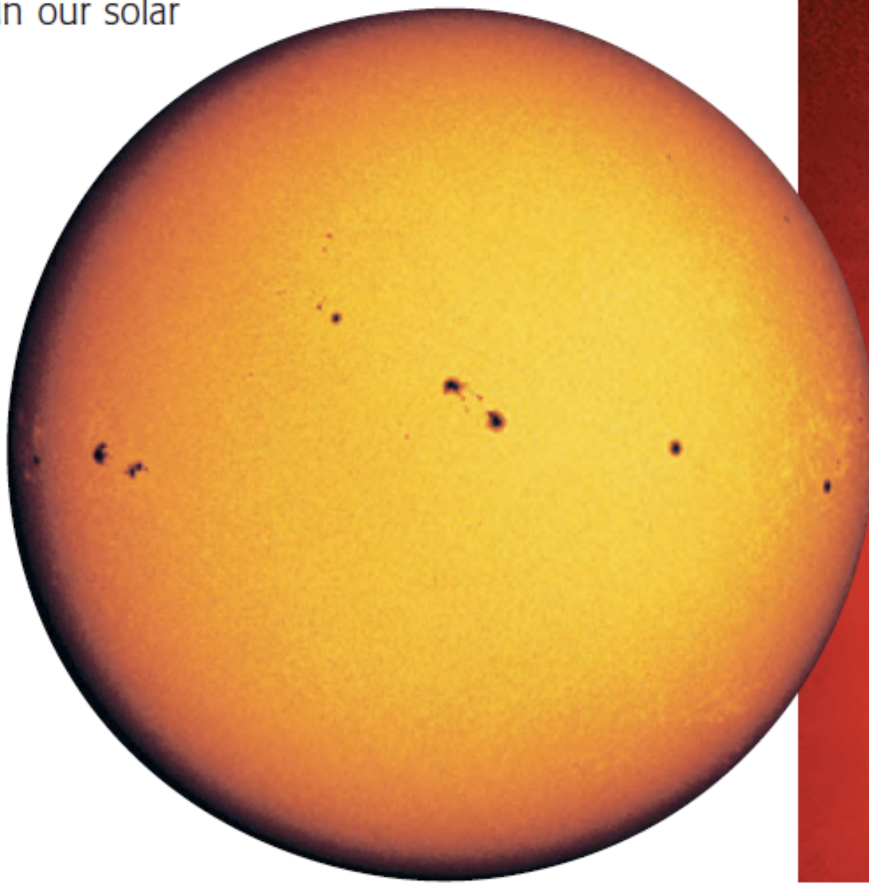
Small and irregularly shaped

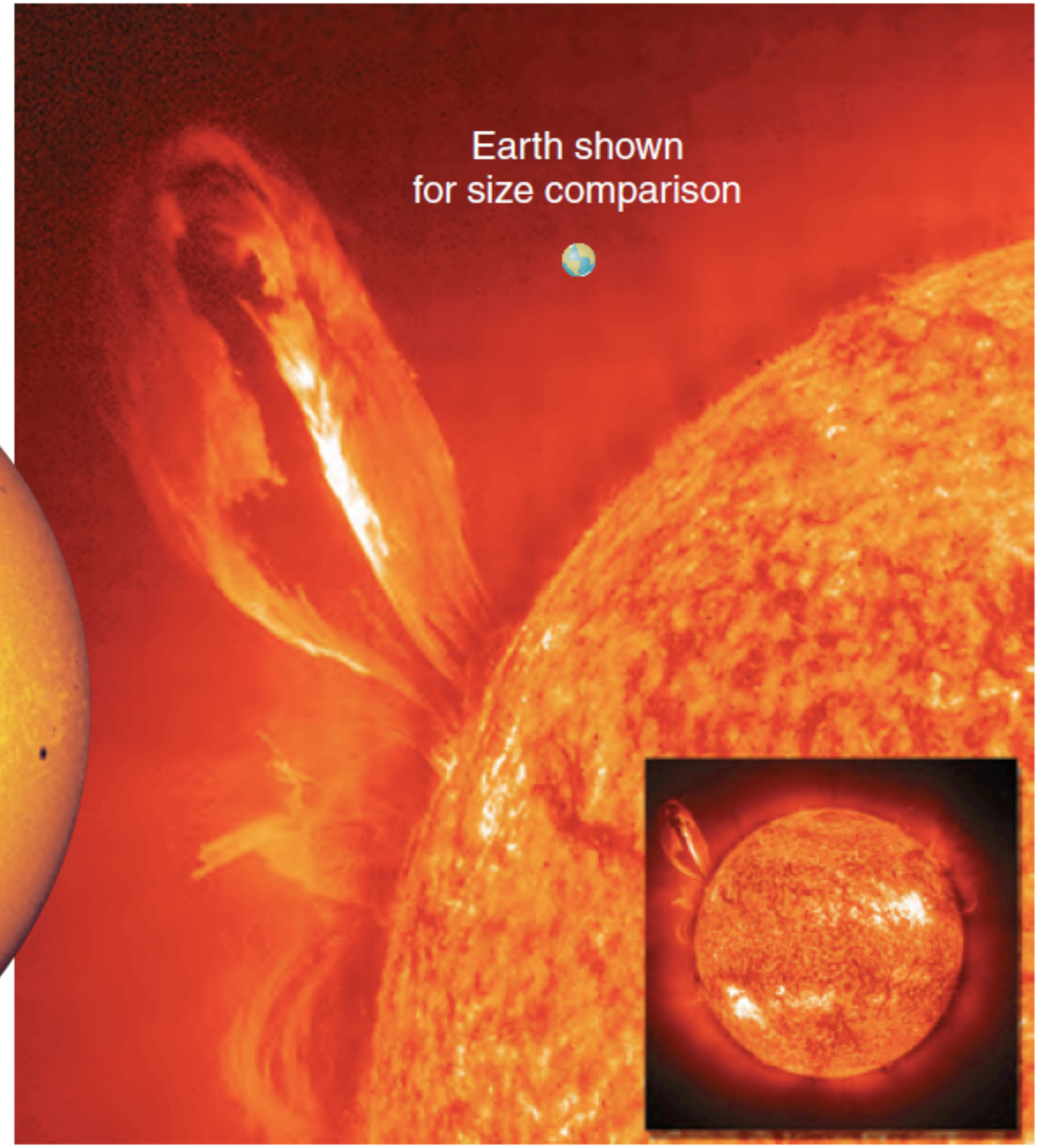
Water and rock and iron

Total mass of Oort Cloud comets is very uncertain, but probably around 10^{25} kilograms, or roughly five times the mass of the Earth

$1M_{sun}=1000\ M_{Jupiter}$

ontains more
s in our solar





a A visible-light photograph of the Sun's surface. The dark splotches are sunspots—each large enough to swallow several Earths.

b This ultraviolet photograph, from the *SOHO* spacecraft, shows a huge streamer of hot gas on the Sun. The image of Earth was added for size comparison.

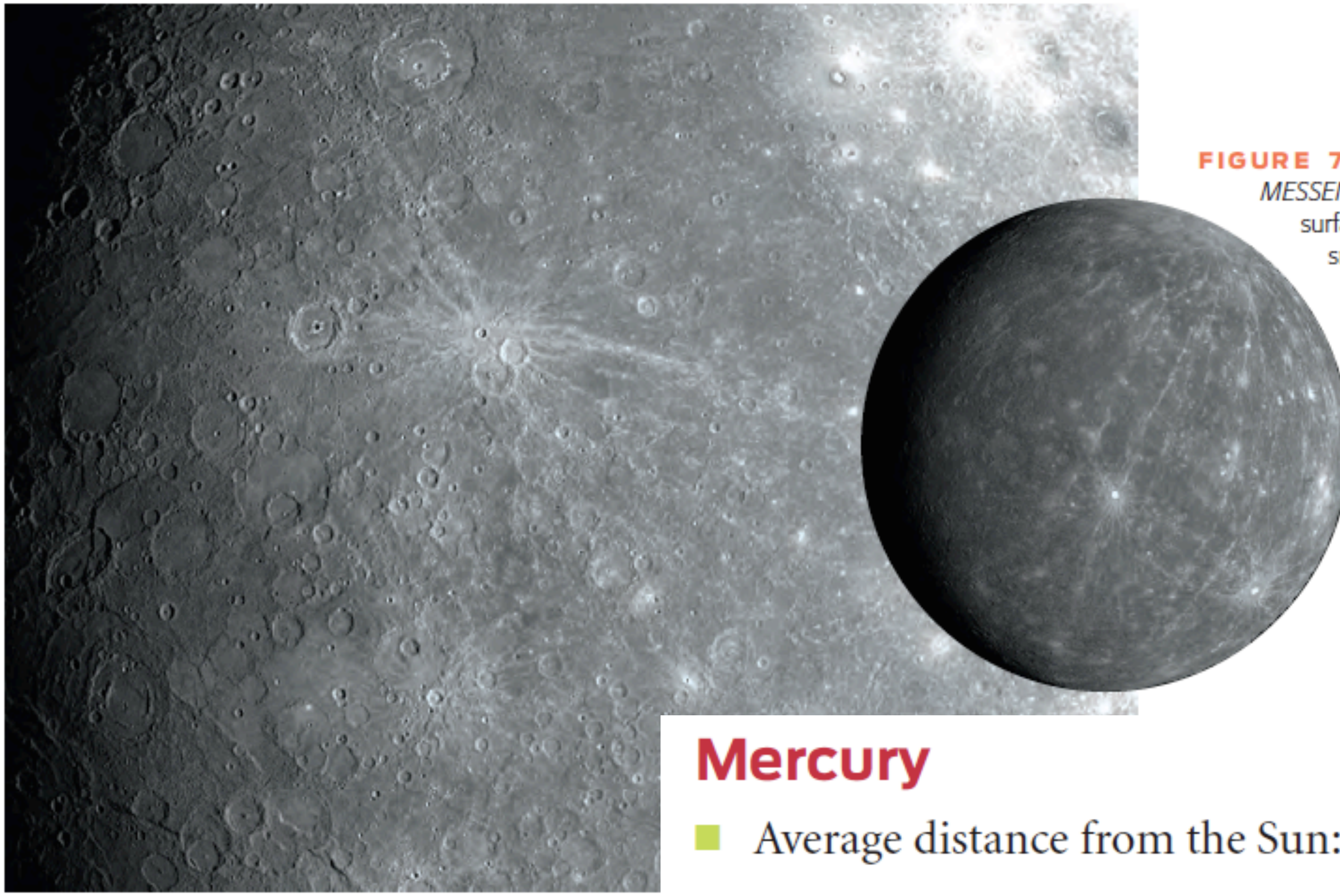


FIGURE 7.3 The main image, taken by the *MESSENGER* spacecraft, shows that Mercury's surface is heavily cratered but also has smooth volcanic plains and long, steep cliffs. The inset shows a nearly full Mercury photographed by *MESSENGER*.

Mercury

- Average distance from the Sun: 0.39 AU
- Radius: 2440 km = $0.38R_{\text{Earth}}$
- Mass: $0.055M_{\text{Earth}}$
- Average density: 5.43 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 700 K (day), 100 K (night)
- Moons: 0

Venus

- Average distance from the Sun: 0.72 AU
- Radius: 6051 km $= 0.95R_{\text{Earth}}$
- Mass: $0.82M_{\text{Earth}}$
- Average density: 5.24 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 740 K
- Moons: 0

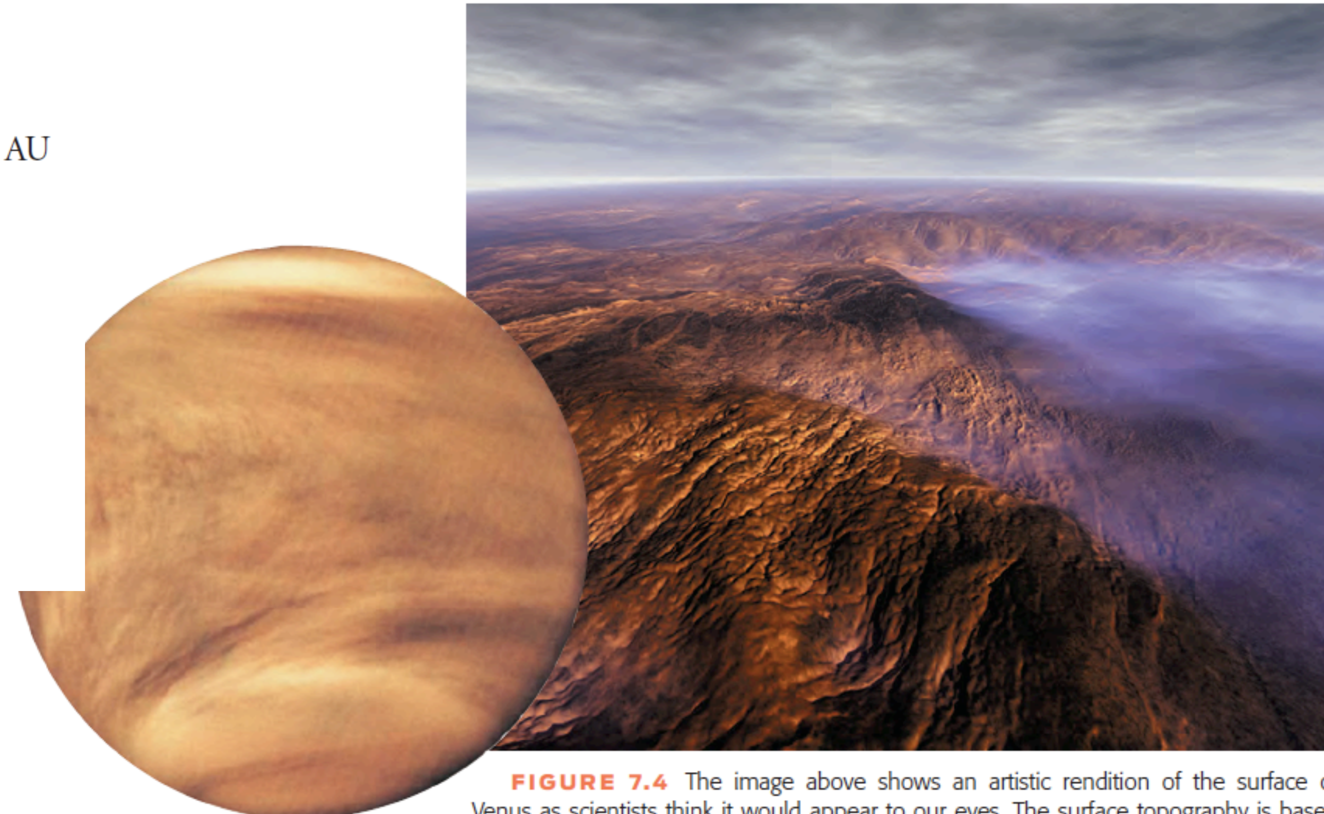
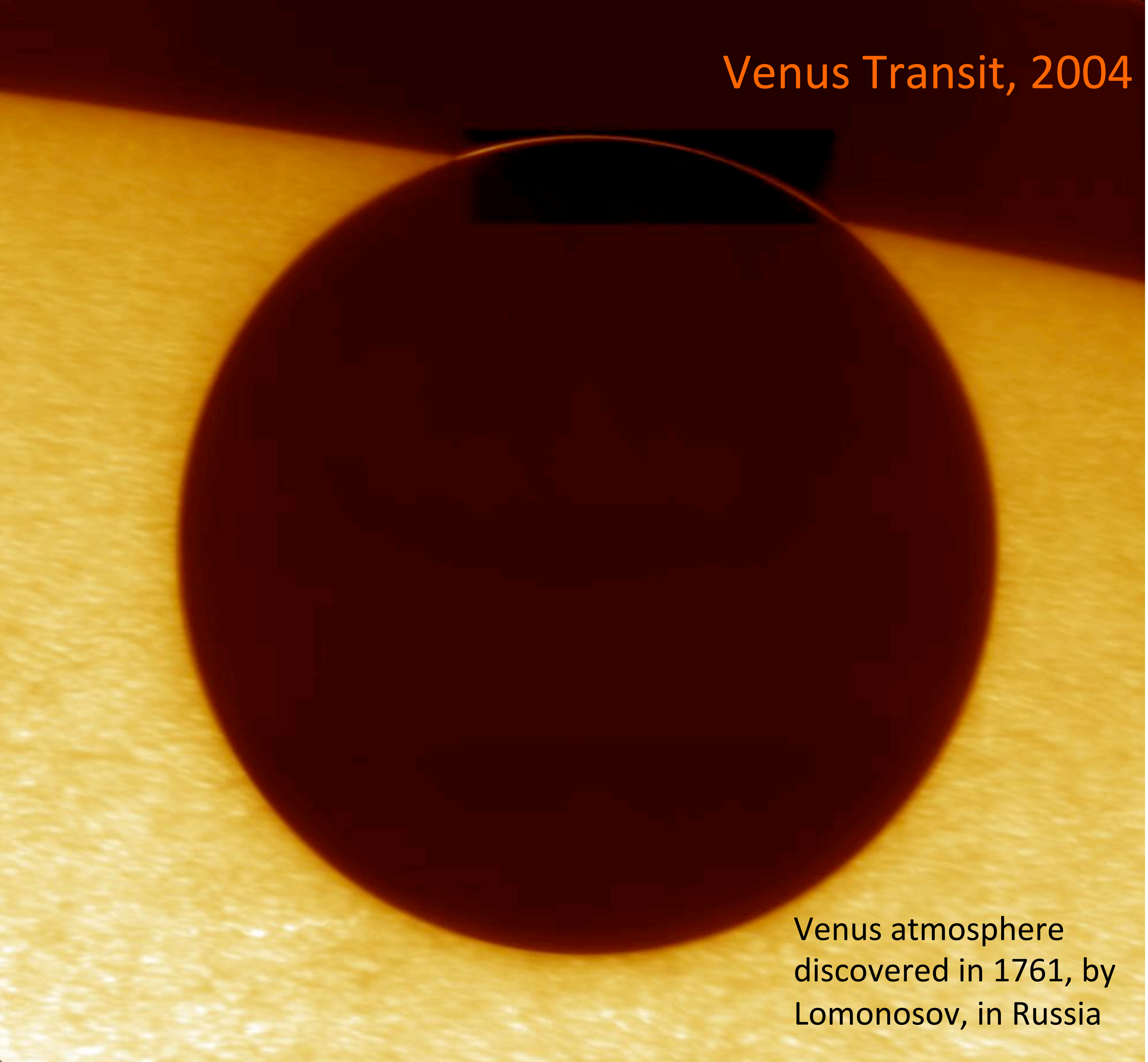
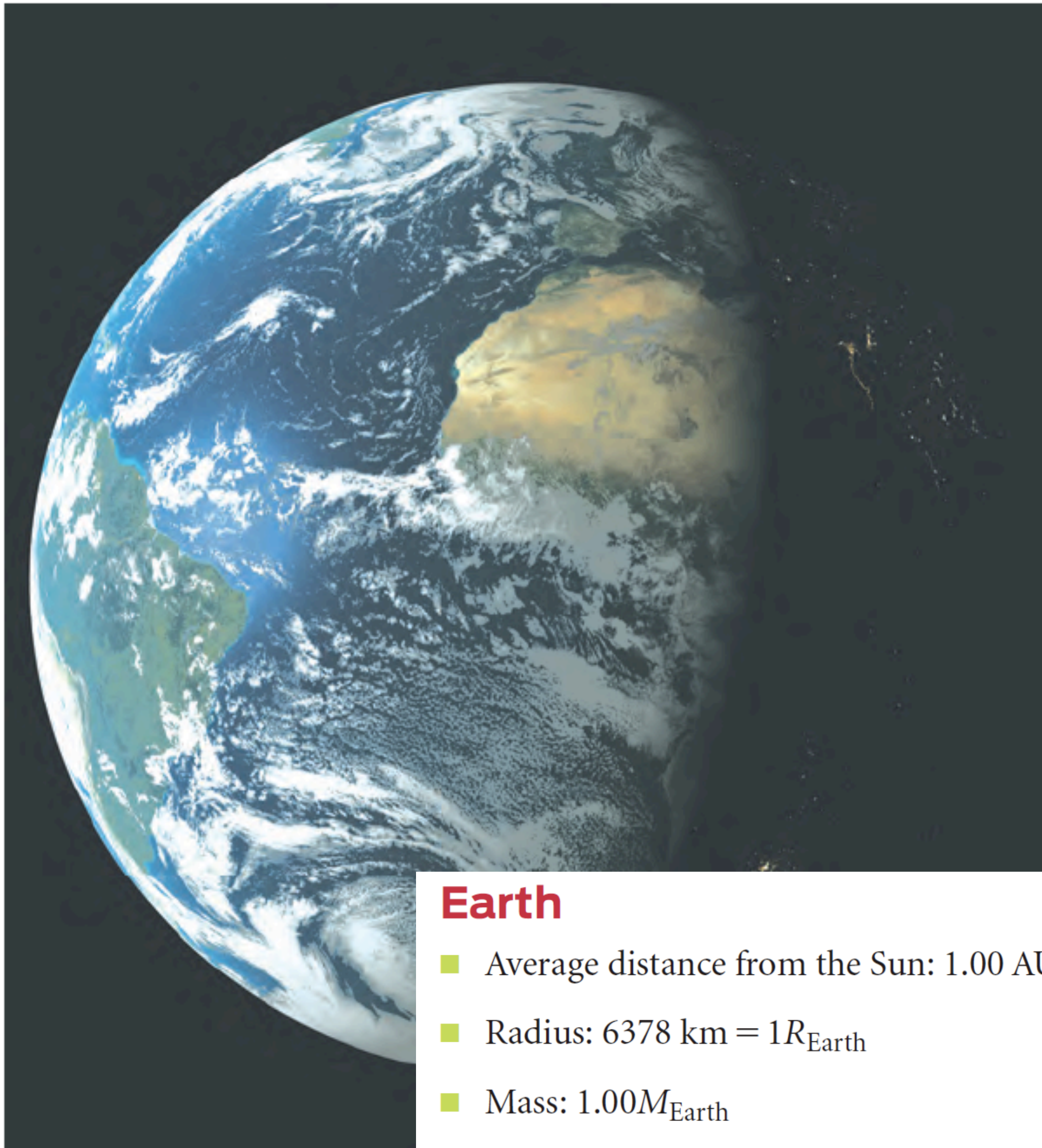


FIGURE 7.4 The image above shows an artistic rendition of the surface of Venus as scientists think it would appear to our eyes. The surface topography is based on data from NASA's *Magellan* spacecraft. The inset (left) shows the full disk of Venus photographed by NASA's *Pioneer Venus Orbiter* with cameras sensitive to ultraviolet light. With visible light, stinguished from the general haze. (Image above from the Voyage scale model the Challenger Center for Space Science Education, the Smithsonian Institution, P. Anderson, Southern Methodist University © 2001.)


Venus Transit, 2004
Venus atmosphere discovered in 1761, by Lomonosov, in Russia



a This image (left), computer generated from satellite data, shows the striking contrast between the day and night hemispheres of Earth. The day side reveals little evidence of human presence, but at night our presence is revealed by the lights of human activity. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

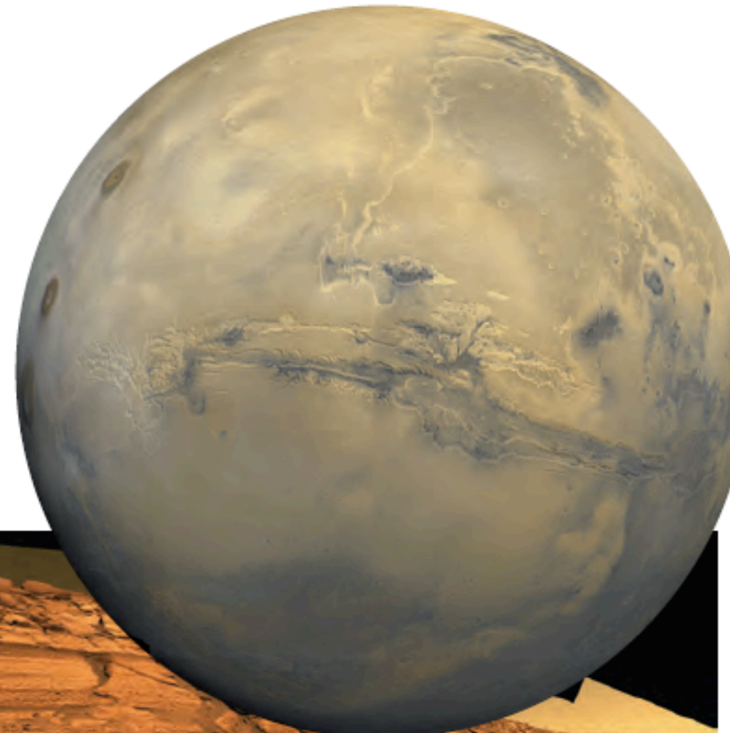
Earth

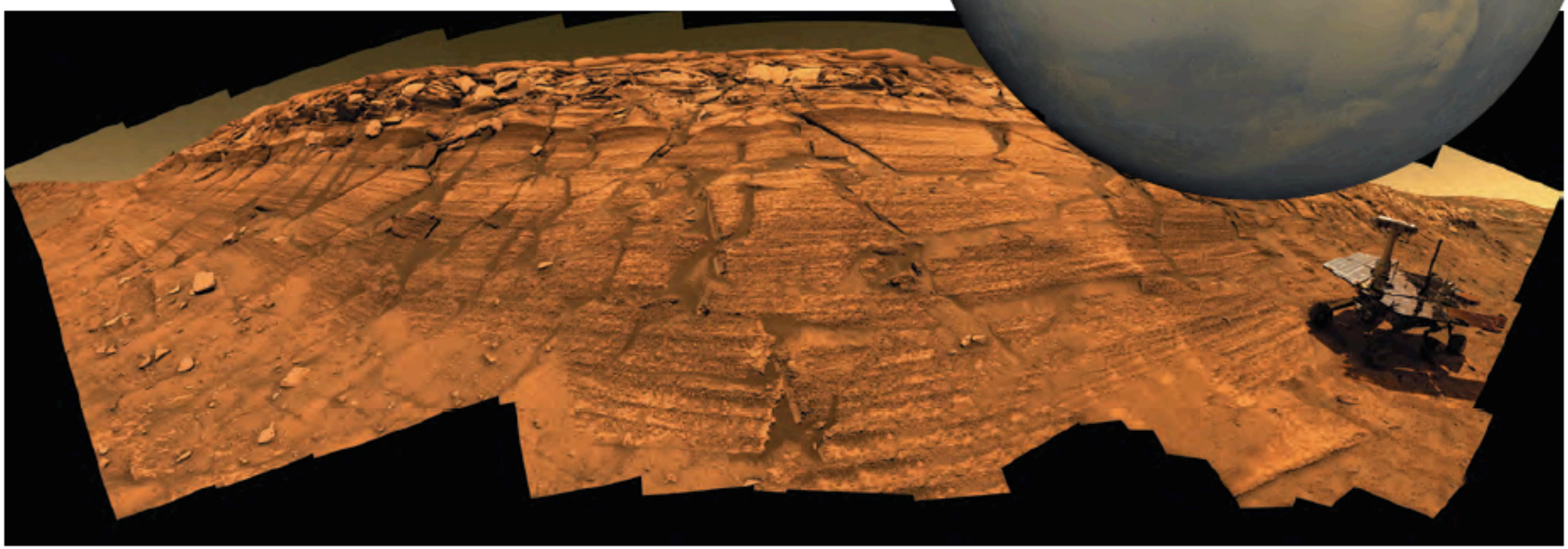
- Average distance from the Sun: 1.00 AU
- Radius: 6378 km $= 1R_{\text{Earth}}$
- Mass: $1.00M_{\text{Earth}}$
- Average density: 5.52 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 290 K
- Moons: 1

b Earth and the Moon, shown to scale. The Moon is about 1/4 as large as Earth in diameter, while its mass is about 1/80 of Earth's mass. To show the distance between Earth and Moon on the same scale, you'd need to hold these two photographs about 1 meter (3 feet) apart.

Mars

- Average distance from the Sun: 1.52 AU
- Radius: 3397 km = $0.53R_{Earth}$
- Mass: $0.11M_{Earth}$
- Average density: 3.93 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 220 K
- Moons: 2 (very small)





Clicker: How do comets differ from asteroids?

A. They are mostly ices, not rock.
B. Their orbits are usually much farther from the Sun.
C. They are leftover pieces of a smashed planet.
D. all of the above
E. A and B

Clicker: How do comets differ from asteroids?

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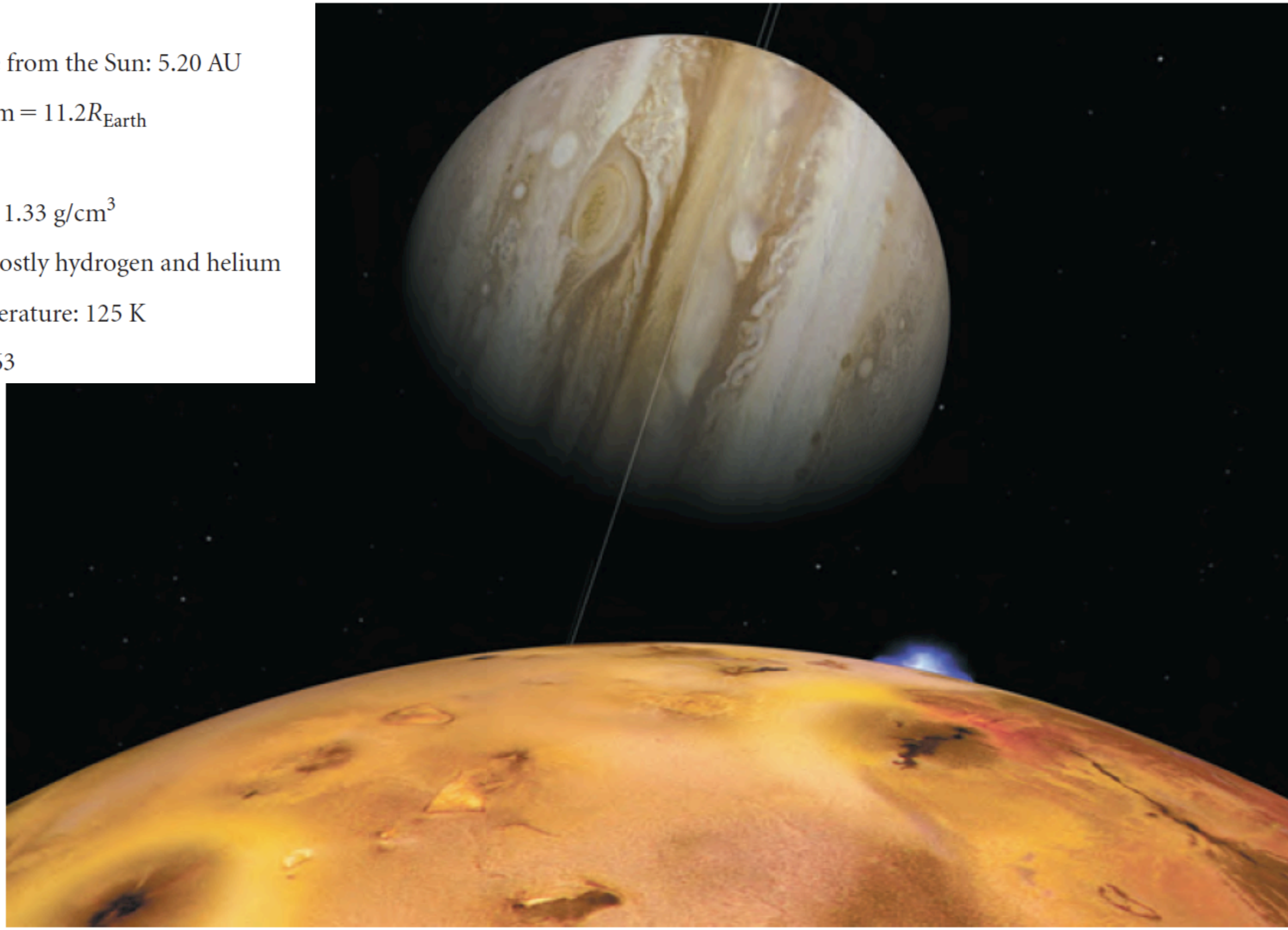
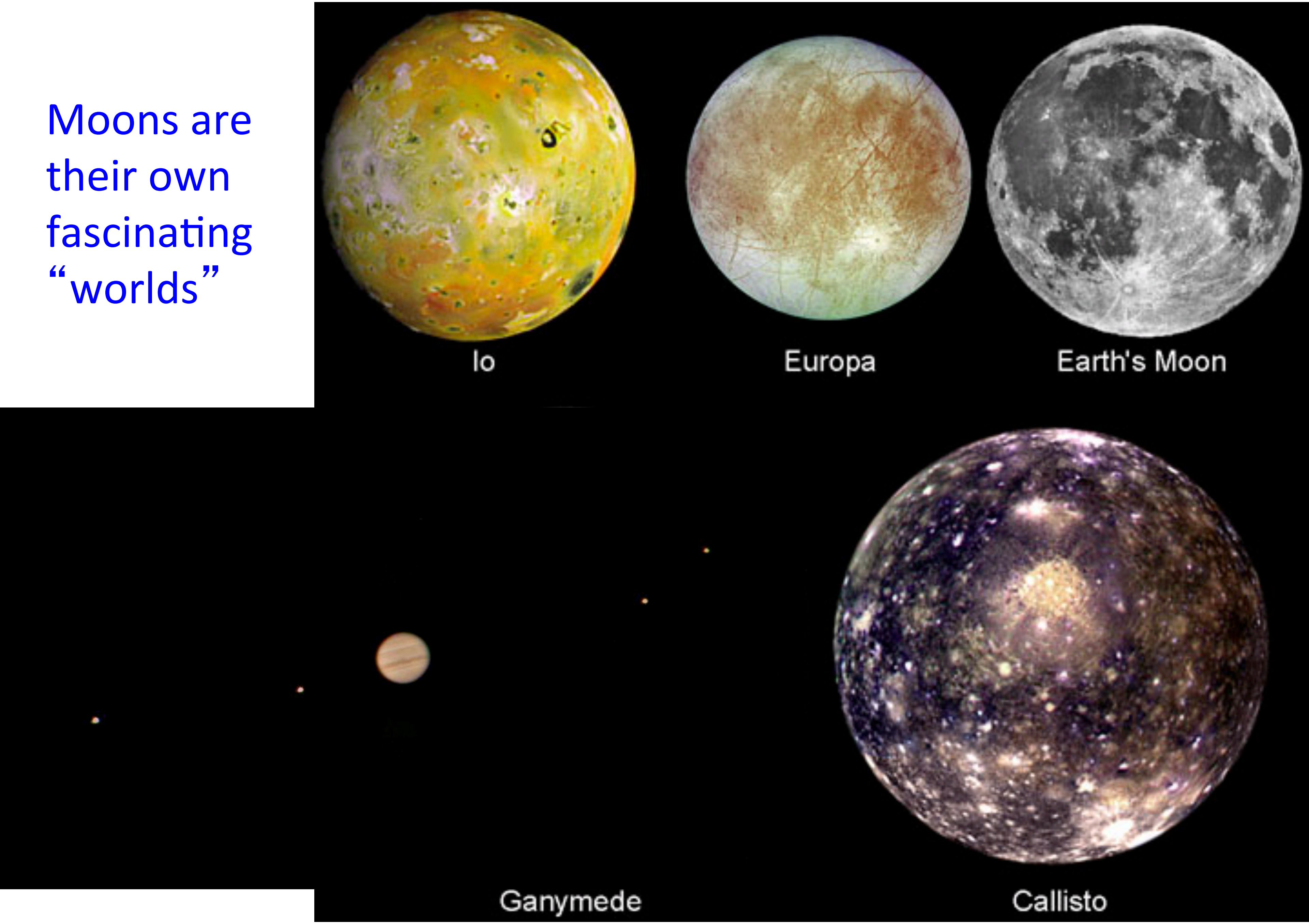
C. They are leftover pieces of a smashed planet.
D. all of the above
E. A and B

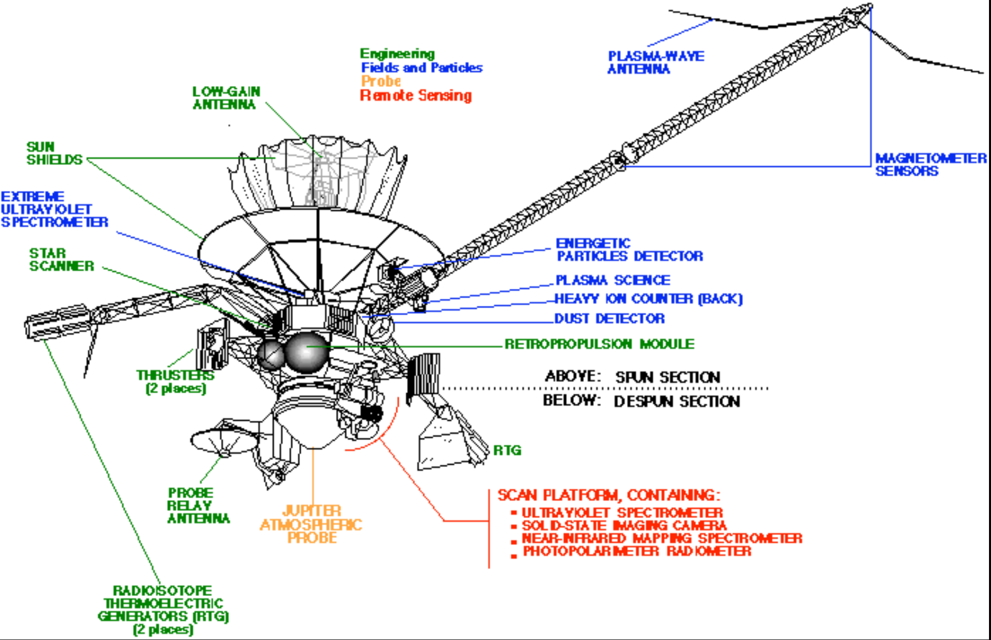
Jupiter

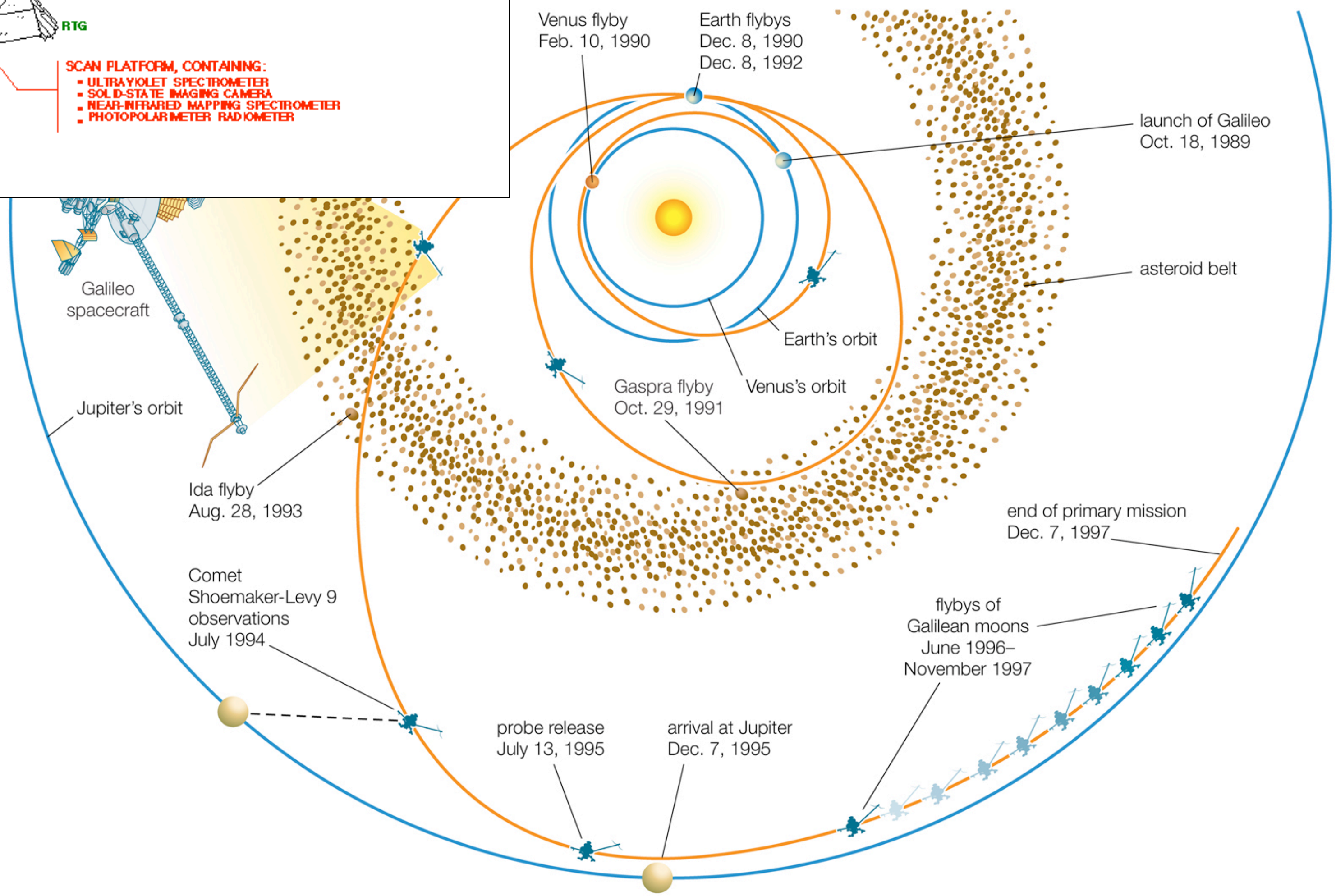
- Average distance from the Sun: 5.20 AU
- Radius 71,492 km = $11.2R_{\text{Earth}}$
- Mass: $318M_{\text{Earth}}$
- Average density: 1.33 g/cm^3
- Composition: mostly hydrogen and helium
- Cloud-top temperature: 125 K
- Moons: at least 63



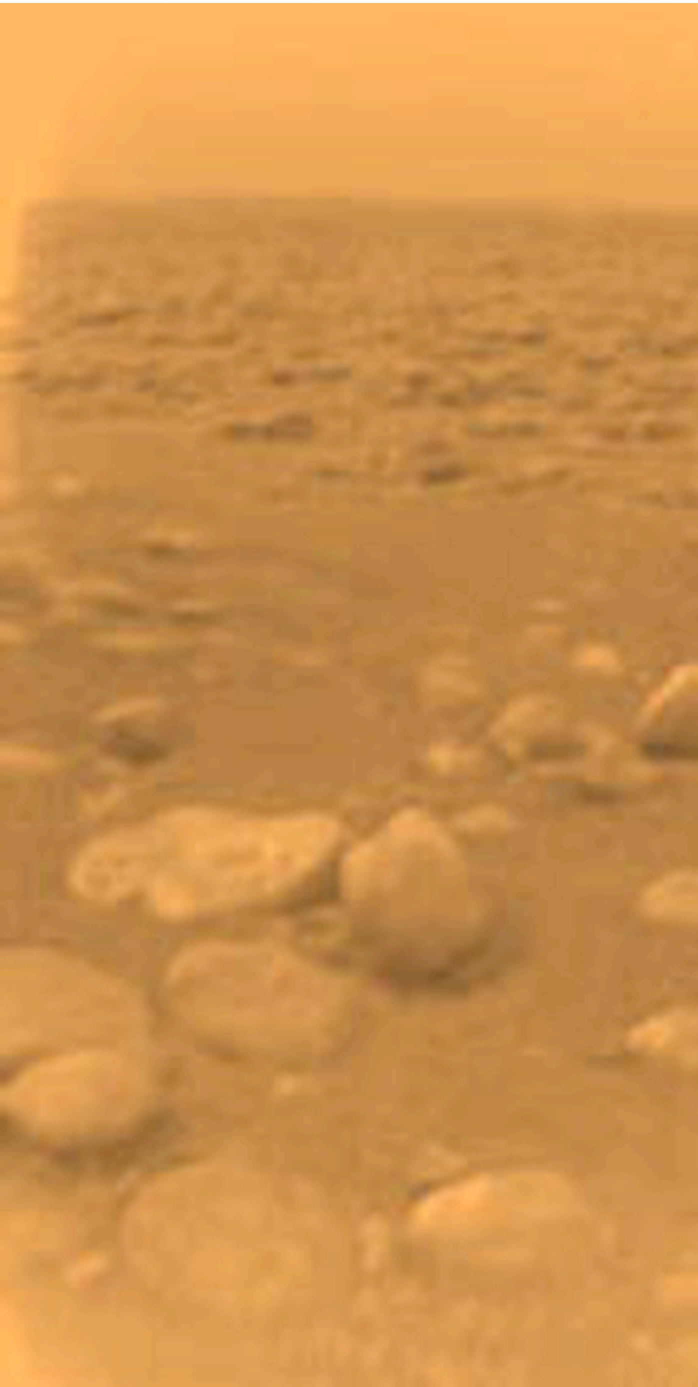
Moons are their own fascinating "worlds"

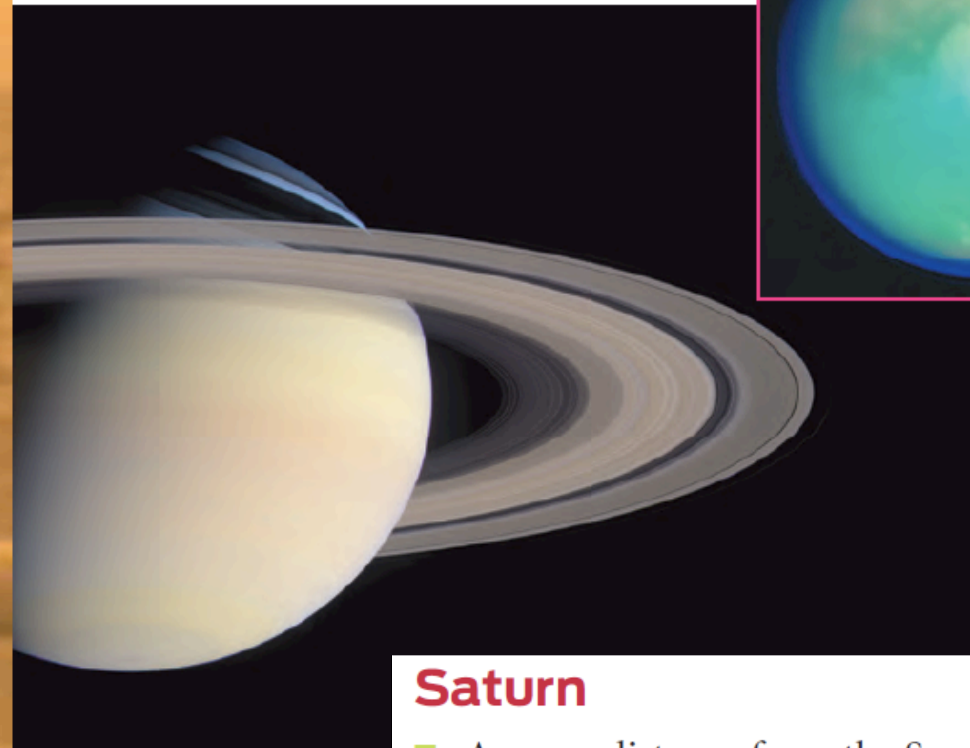


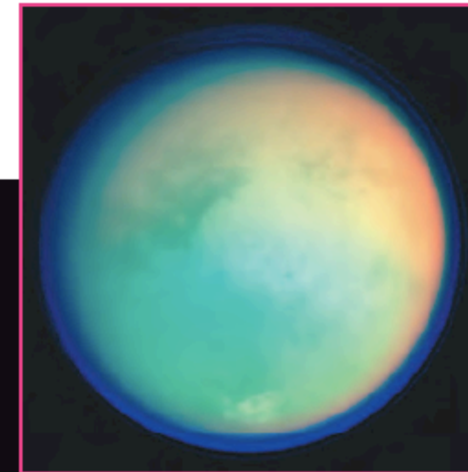

Engineering
Fields and Particles
Probe
Remote Sensing
LOW-GAIN ANTENNA
SUN SHIELDS
EXTREME ULTRAVIOLET SPECTROMETER
STAR SCANNER
THRUSTERS (2 places)
PROBE RELAY ANTENNA
RADIOISOTOPE THERMOELECTRIC GENERATORS (RTG) (2 places)
JUPITER ATMOSPHERIC PROBE
PLASMA-WAVE ANTENNA
MAGNETOMETER SENSORS
ENERGETIC PARTICLES DETECTOR
PLASMA SCIENCE
HEAVY ION COUNTER (BACK)
DUST DETECTOR
RETROPROPULSION MODULE
ABOVE: SPUN SECTION
BELOW: DESPUN SECTION
RTG
SCAN PLATFORM, CONTAINING:
ULTRAVIOLET SPECTROMETER
SOLID-STATE IMAGING CAMERA
NEAR-INFRARED MAPPING SPECTROMETER
PHOTOPOLARIMETER RADIOMETER


Venus flyby
Feb. 10, 1990
Earth flybys
Dec. 8, 1990
Dec. 8, 1992
launch of Galileo
Oct. 18, 1989
asteroid belt
Earth's orbit
Venus's orbit
Gaspra flyby
Oct. 29, 1991
Galileo spacecraft
Jupiter's orbit
Ida flyby
Aug. 28, 1993
Comet Shoemaker-Levy 9 observations July 1994
probe release
July 13, 1995
arrival at Jupiter
Dec. 7, 1995
end of primary mission
Dec. 7, 1997
flybys of Galilean moons
June 1996–November 1997

1995, Galileo Entry Probe:
in situ measurements of a gas giant planet



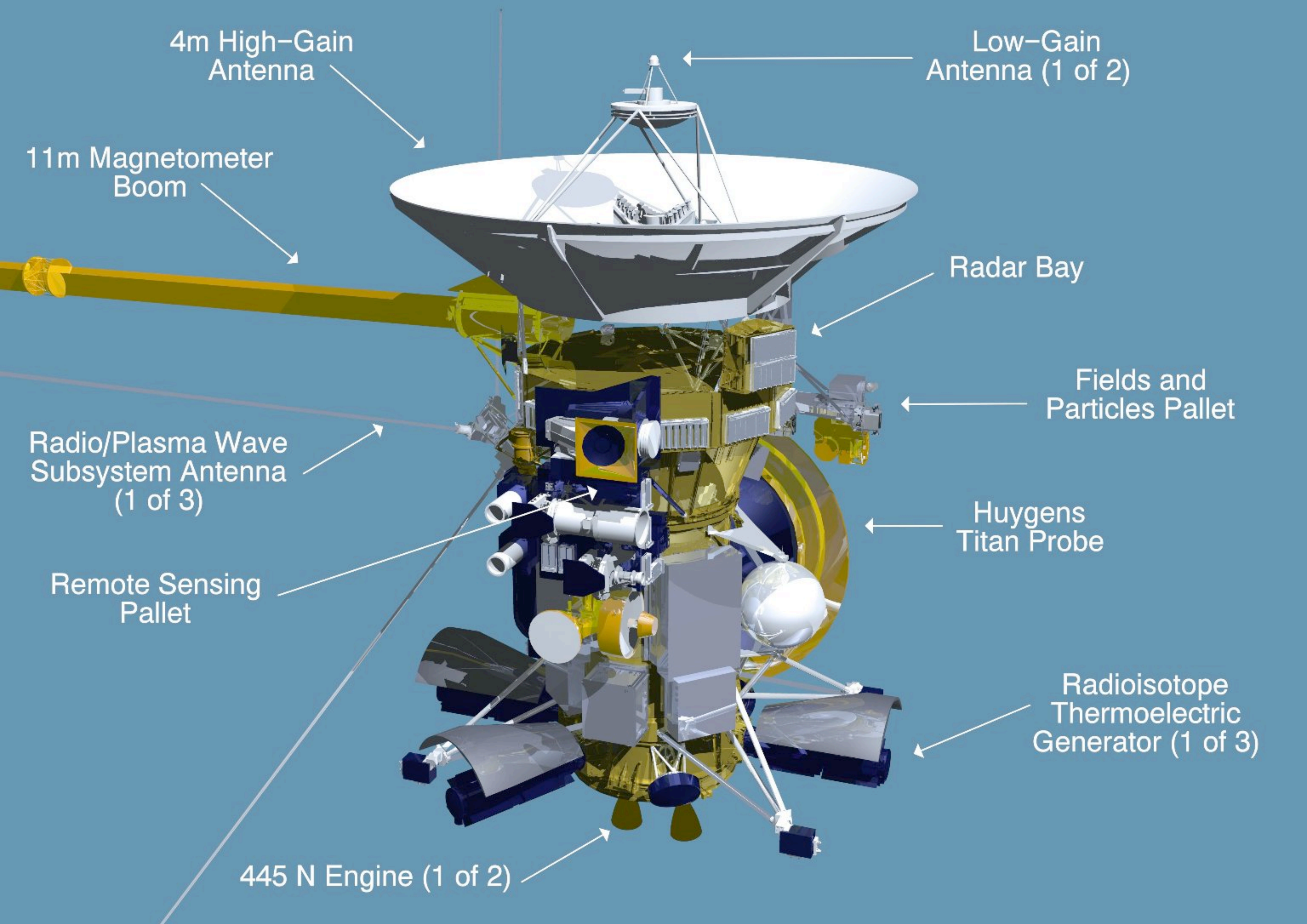


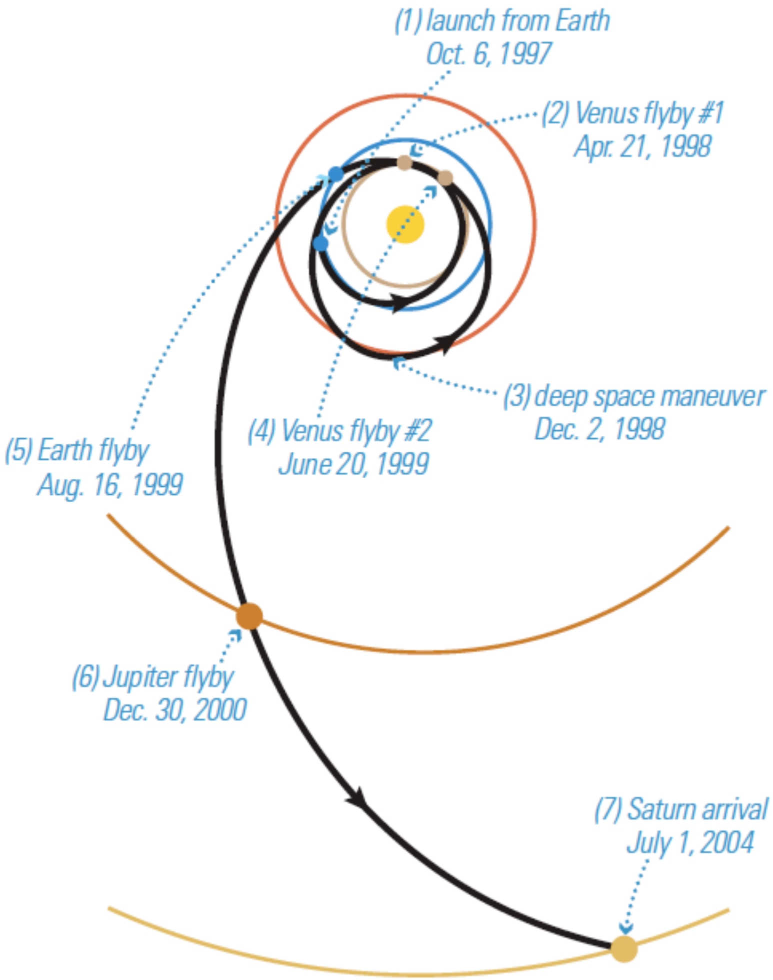


Saturn

- Average distance from the Sun: 9.54 AU
- Radius: 60,268 km = $9.4R_{\text{Earth}}$
- Mass: $95.2M_{\text{Earth}}$
- Average density: 0.70 g/cm^3
- Composition: mostly hydrogen and helium
- Cloud-top temperature: 95 K
- Moons: at least 60

CASSINI SPACECRAFT



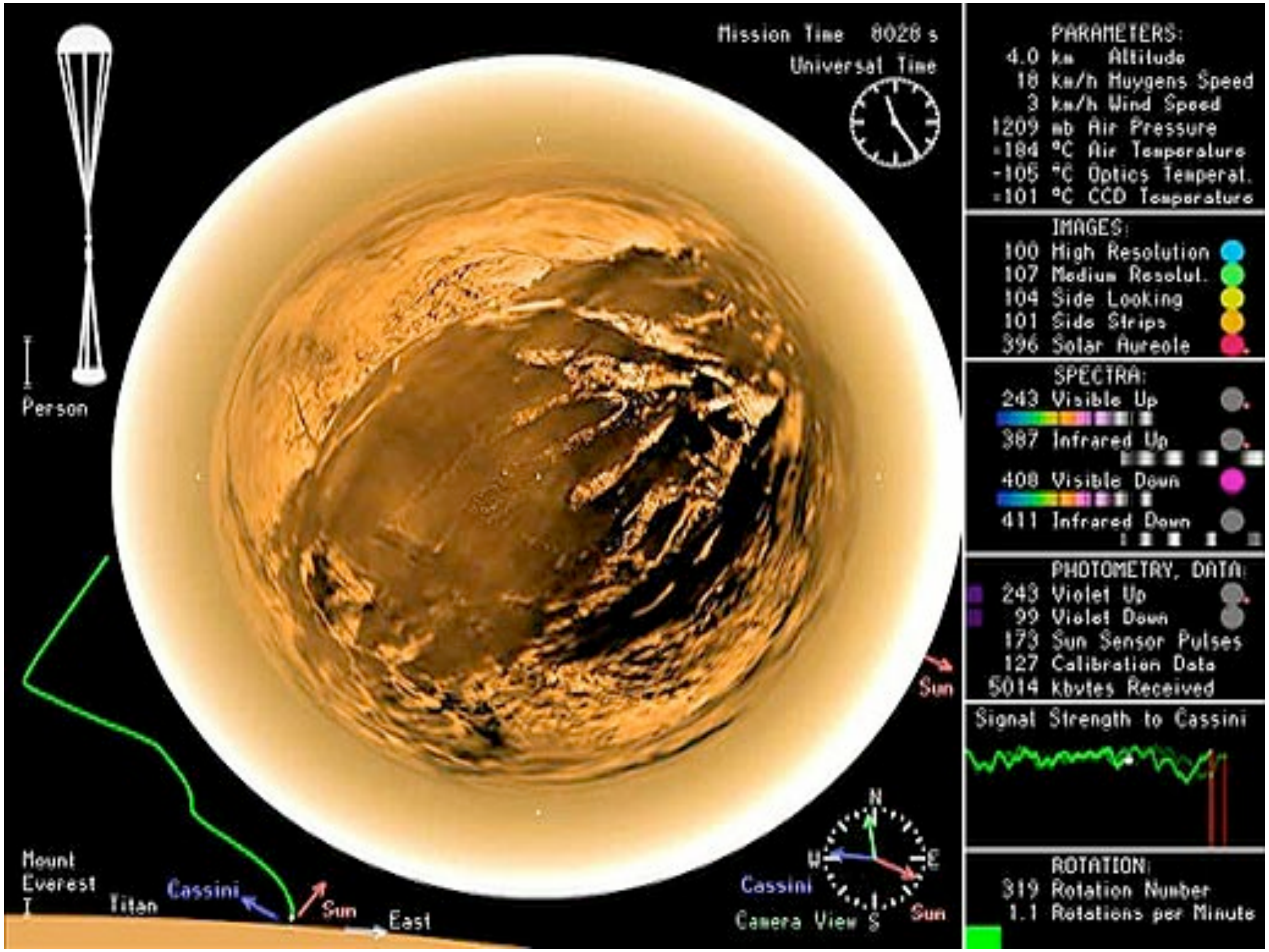


a The trajectory of *Cassini* to Saturn

b Artist's conception of the *Huygens* probe landing on Titan. From upper right to lower left: As the *Cassini* mothership passes in the distance, the probe enters the atmosphere, parachutes down, and finally lands on the surface. *Huygens* landed in January 2005, collecting data and transmitting images for several hours before its batteries ran out. (See Figure 11.27 for actual images of Titan taken by the *Huygens* probe.)

A close-up view of the Huygens probe highlighting large and unexpected parachute movements, a scale bar for comparison to human height.

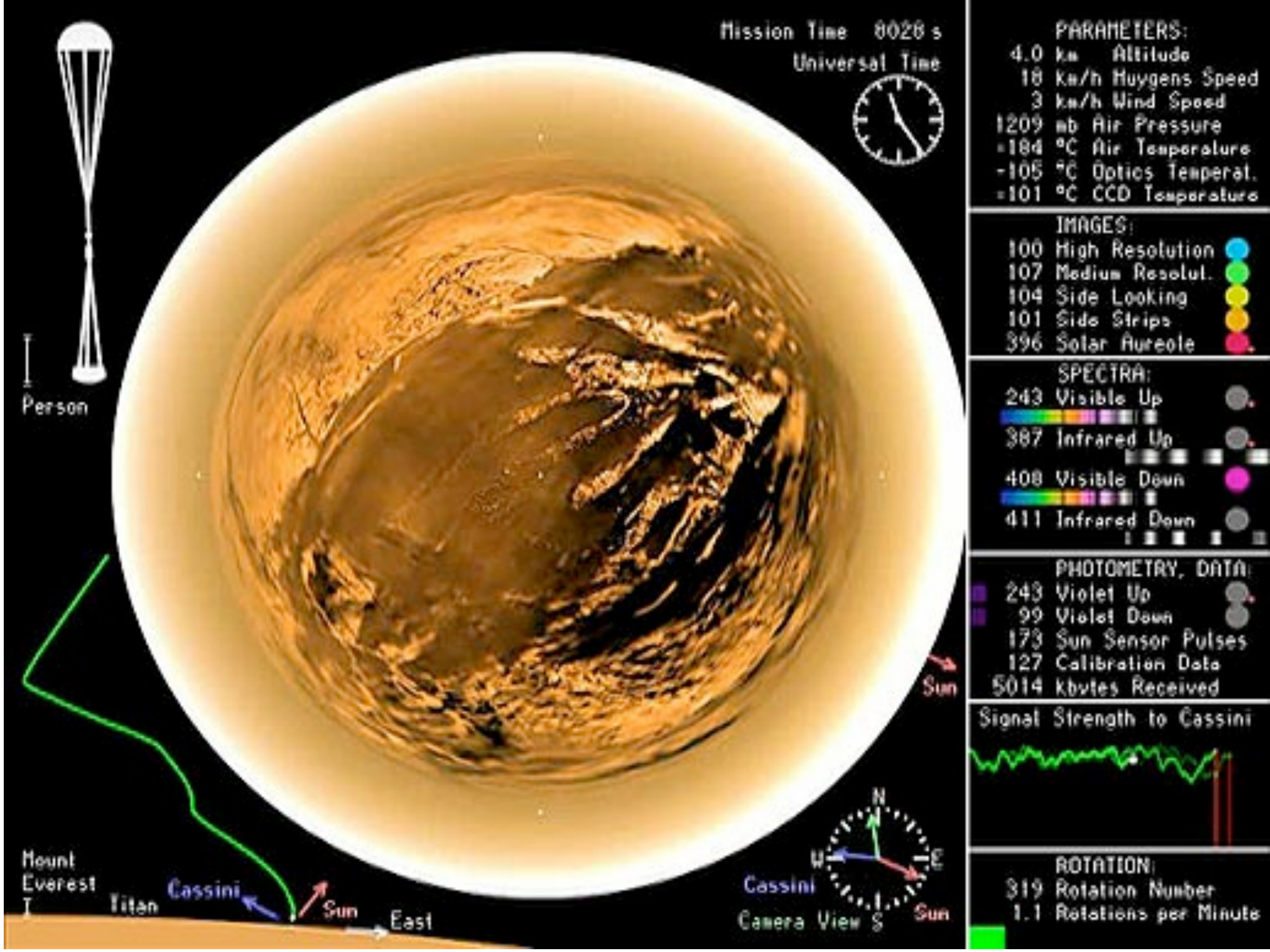
A clock that shows Universal Time for Jan. 14, 2005. Above the clock, events are listed in mission time, which starts with the deployment of the first of the three parachutes.



Huygens' trajectory views from the south, a scale bar for comparison to the height of Mount Everest, colored arrows that point to the sun and to the Cassini orbiter.

A compass that shows the changing direction of view as Huygens rotates, along with the relative positions of the sun and Cassini.

Sounds from a left speaker trace Huygens' motion, with tones changing with rotational speed and the tilt of the parachute. There also are clicks that clock the rotational counter, as well as sounds for the probe's heat shield hitting Titan's atmosphere, parachute deployments, heat shield release, jettison of the camera cover and touchdown.



Sounds from a right speaker go with the Descent Imager/Spectral Radiometer activity. There's a continuous tone that represents the strength of Huygens' signal to Cassini. Then there are 13 different chimes - one for each of instrument's 13 different science parts - that keep time with flashing-white-dot exposure counters. During its descent, the Descent Imager/Spectral Radiometer took 3,500 exposures.

Uranus

- Average distance from the Sun: 19.2 AU
- Radius: 25,559 km = $4.0R_{Earth}$
- Mass: $14.5M_{Earth}$
- Average density: 1.32 g/cm^3
- Composition: hydrogen, helium, hydrogen compounds
- Cloud-top temperature: 60 K
- Moons: at least 27

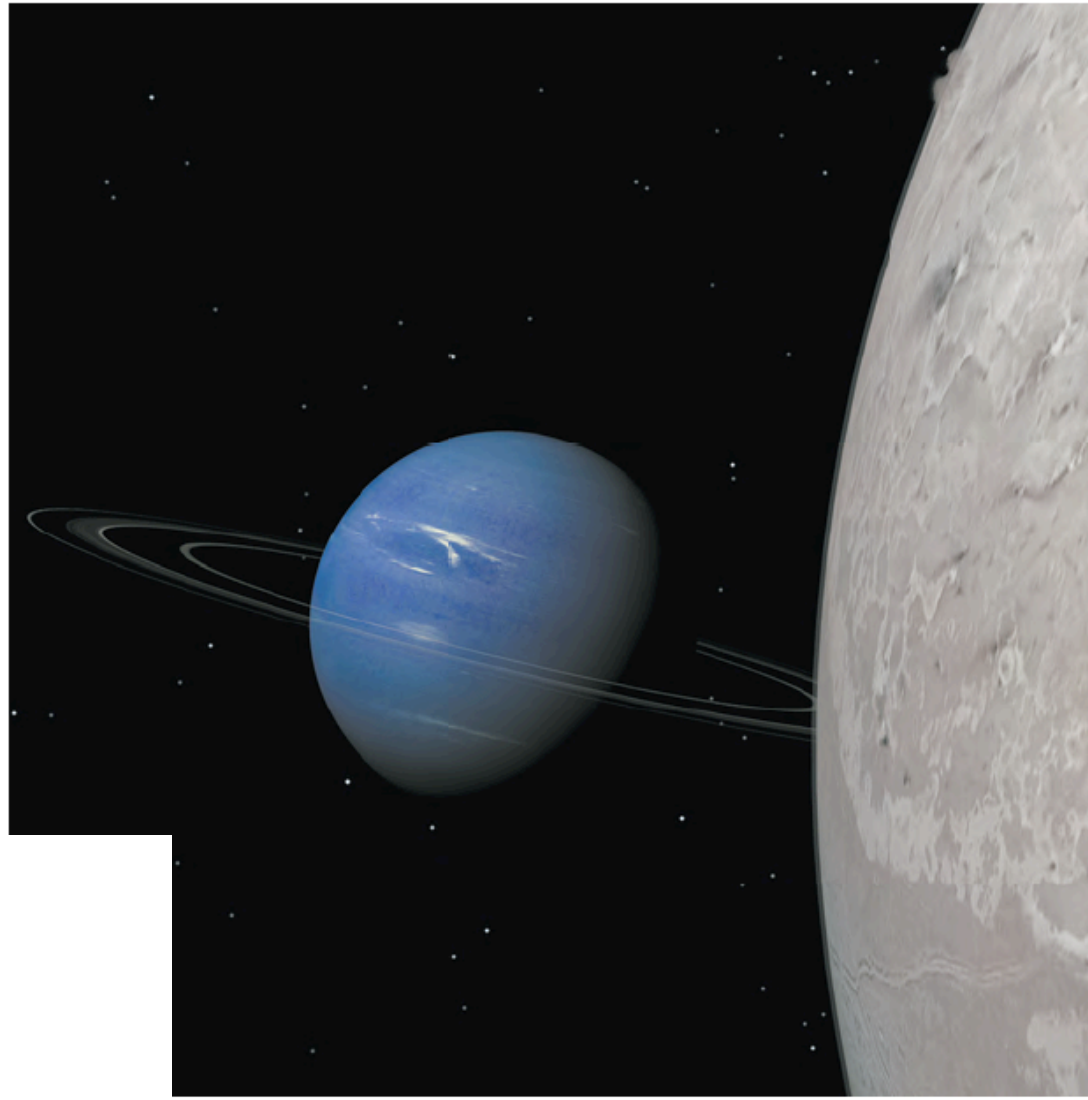


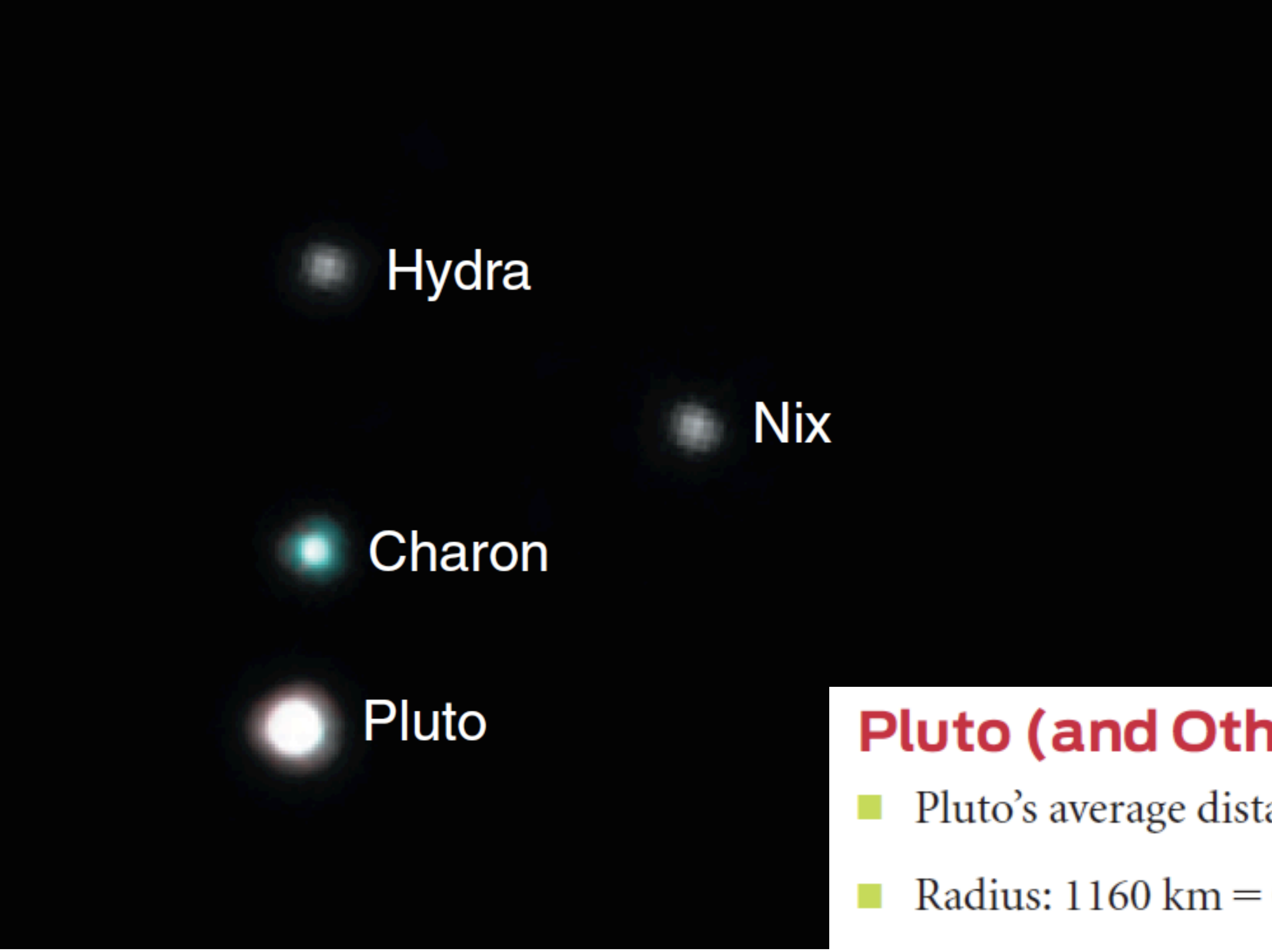
FIGURE 7.10 This image shows what it would look like to be orbiting Neptune's moon Triton as Neptune itself comes into view. The dark rings are exaggerated to make them visible in this computer simulation using data from NASA's *Voyager 2* mission. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

Neptune

- Average distance from the Sun: 30.1 AU
- Radius 24,764 km = $3.9R_{Earth}$
- Mass: $17.1M_{Earth}$
- Average density: 1.64 g/cm^3
- Composition: hydrogen, helium, hydrogen compounds
- Cloud-top temperature: 60 K
- Moons: at least 13

No current missions to Uranus and Neptune Planned

- They would launch in 2023, at the earliest and arrive in 2035, at the earliest.
- If you would hard on a mission, you decide to make that the centerpiece of your whole career



Pluto (and Other Dwarf Planets)

- Pluto's average distance from the Sun: 39.5 AU
- Radius: 1160 km = $0.18R_{\text{Earth}}$
- Mass: $0.0022M_{\text{Earth}}$
- Average density: 2.0 g/cm^3
- Composition: ices, rock
- Average surface temperature: 40 K
- Moons: 3


NASA, New Horizons
July 14, 2015
Launched January, 2006

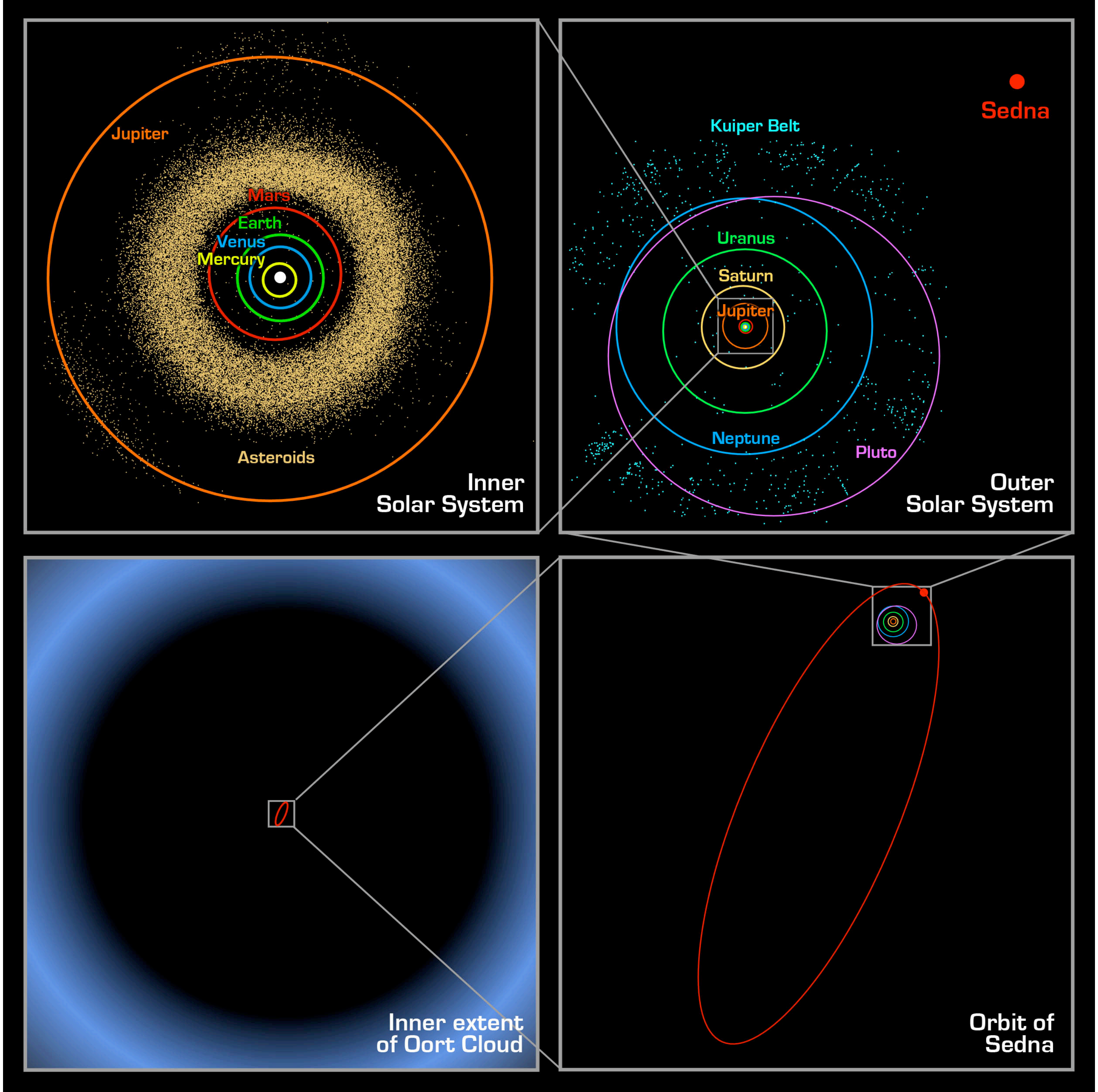
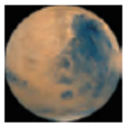
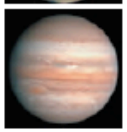
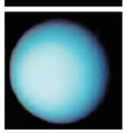
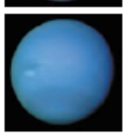
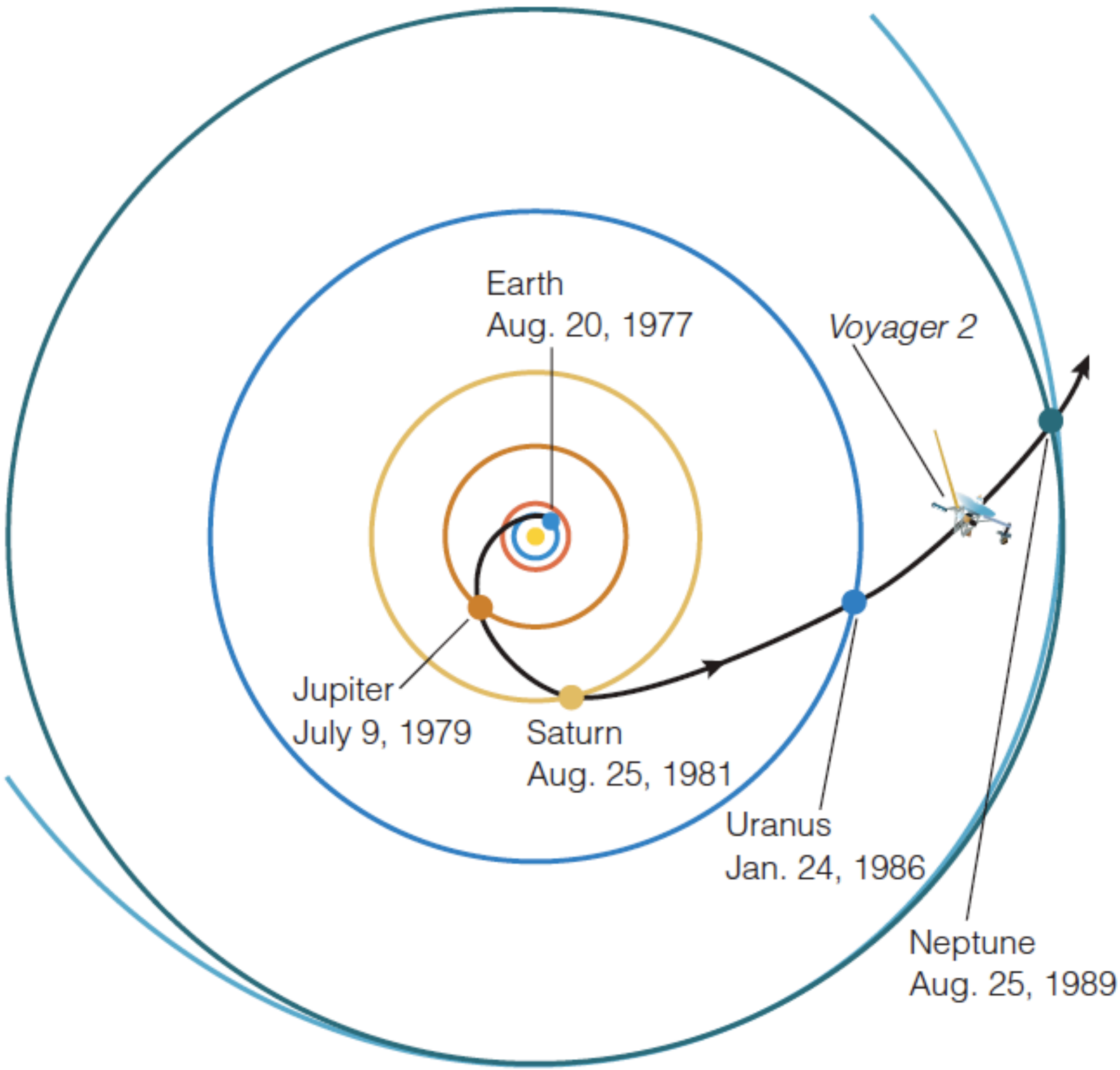

Jupiter
Mars
Earth
Venus
Mercury
Asteroids
Inner
Solar System
Sedna
Kuiper Belt
Uranus
Saturn
Jupiter
Neptune
Pluto
Outer
Solar System
Inner extent
of Oort Cloud
Orbit of
Sedna

Photo	Planet	Relative Size	Average Distance from Sun (AU)	Average Equatorial Radius (km)	Mass (Earth = 1)	Average Density (g/cm^3)	Orbital Period	Rotation Period	Axis Tilt	Averge Surface (or Cloud-Top) Temperature[†]	Composition	Known Moons (2009)	Rings?
	Mercury		0.387	2440	0.055	5.43	87.9 days	58.6 days	0.0°	700 K (day) 100 K (night)	Rocks, metals	0	No
	Venus		0.723	6051	0.82	5.24	225 days	243 days	177.3°	740 K	Rocks, metals	0	No
	Earth		1.00	6378	1.00	5.52	1.00 year	23.93 hours	23.5°	290 K	Rocks, metals	1	No
	Mars		1.52	3397	0.11	3.93	1.88 years	24.6 hours	25.2°	220 K	Rocks, metals	2	No
	Jupiter		5.20	71,492	318	1.33	11.9 years	9.93 hours	3.1°	125 K	H, He, hydrogen compounds[§]	63	Yes
	Saturn		9.54	60,268	95.2	0.70	29.4 years	10.6 hours	26.7°	95 K	H, He, hydrogen compounds[§]	60	Yes
	Uranus		19.2	25,559	14.5	1.32	83.8 years	17.2 hours	97.9°	60 K	H, He, hydrogen compounds[§]	27	Yes
	Neptune		30.1	24,764	17.1	1.64	165 years	16.1 hours	29.6°	60 K	H, He, hydrogen compounds[§]	13	Yes
	Pluto		39.5	1160	0.0022	2.0	248 years	6.39 days	112.5°	40 K	Ices, rock	3	No
	Eris		67.7	1200	0.0028	2.3	557 years	?	?	?	Ices, rock	1	?


Earth
Aug. 20, 1977
Voyager 2
Jupiter
July 9, 1979
Saturn
Aug. 25, 1981
Uranus
Jan. 24, 1986
Neptune
Aug. 25, 1989

Major Categories of Spacecraft Mission

1. Flyby – spacecraft "flies by" a world just once
2. Orbiter – spacecraft orbits the world it studies
   – longer-term study is allowed
3. Lander/Probe – spacecraft lands on the surface of the world or plunges through its atmosphere
4. Sample Return – spacecraft returns to Earth with a sample of the world it has studied

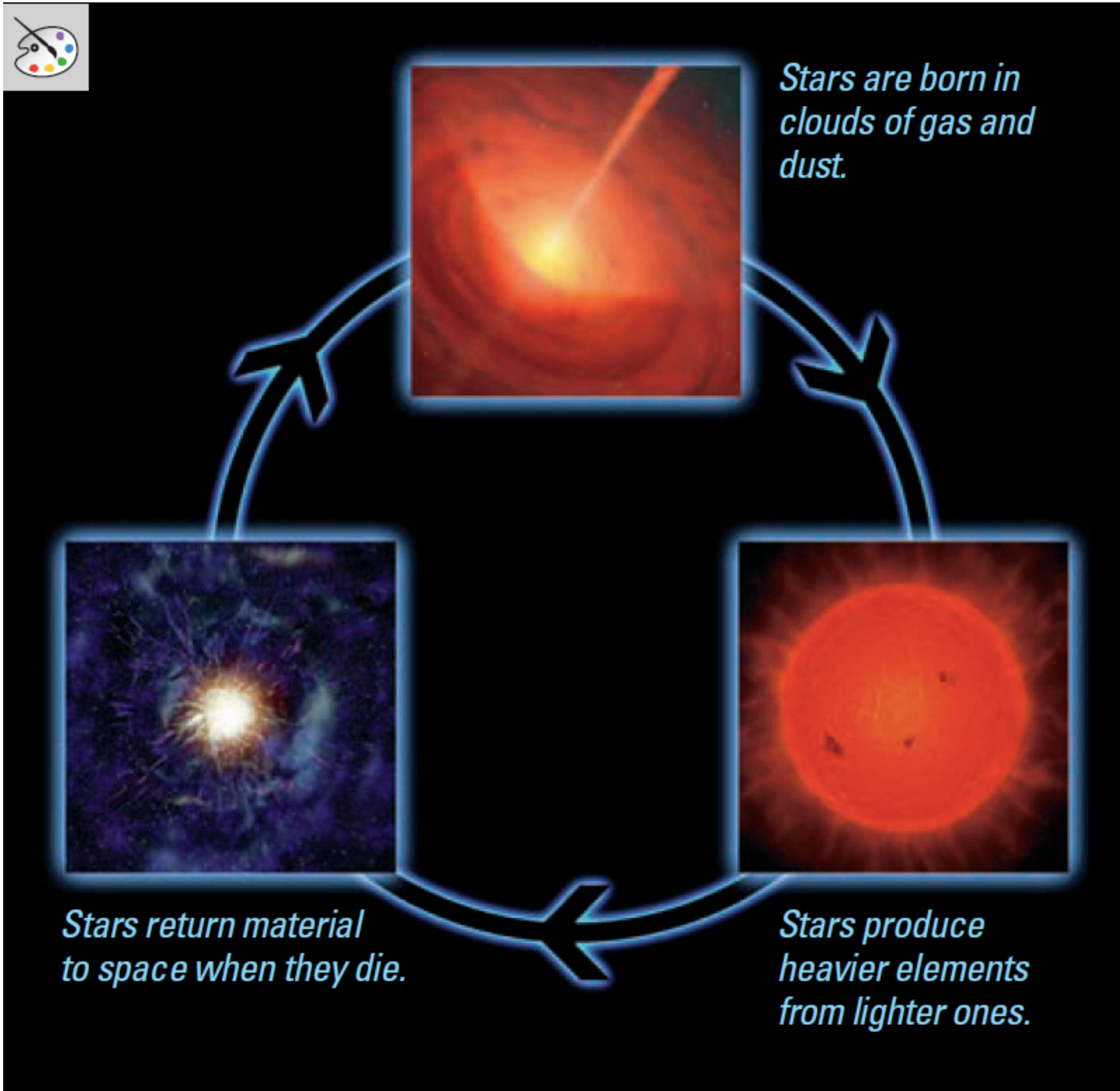
These types of mission are listed in order of increasing cost.

TABLE 7.3 Selected Robotic Missions to Other Worlds

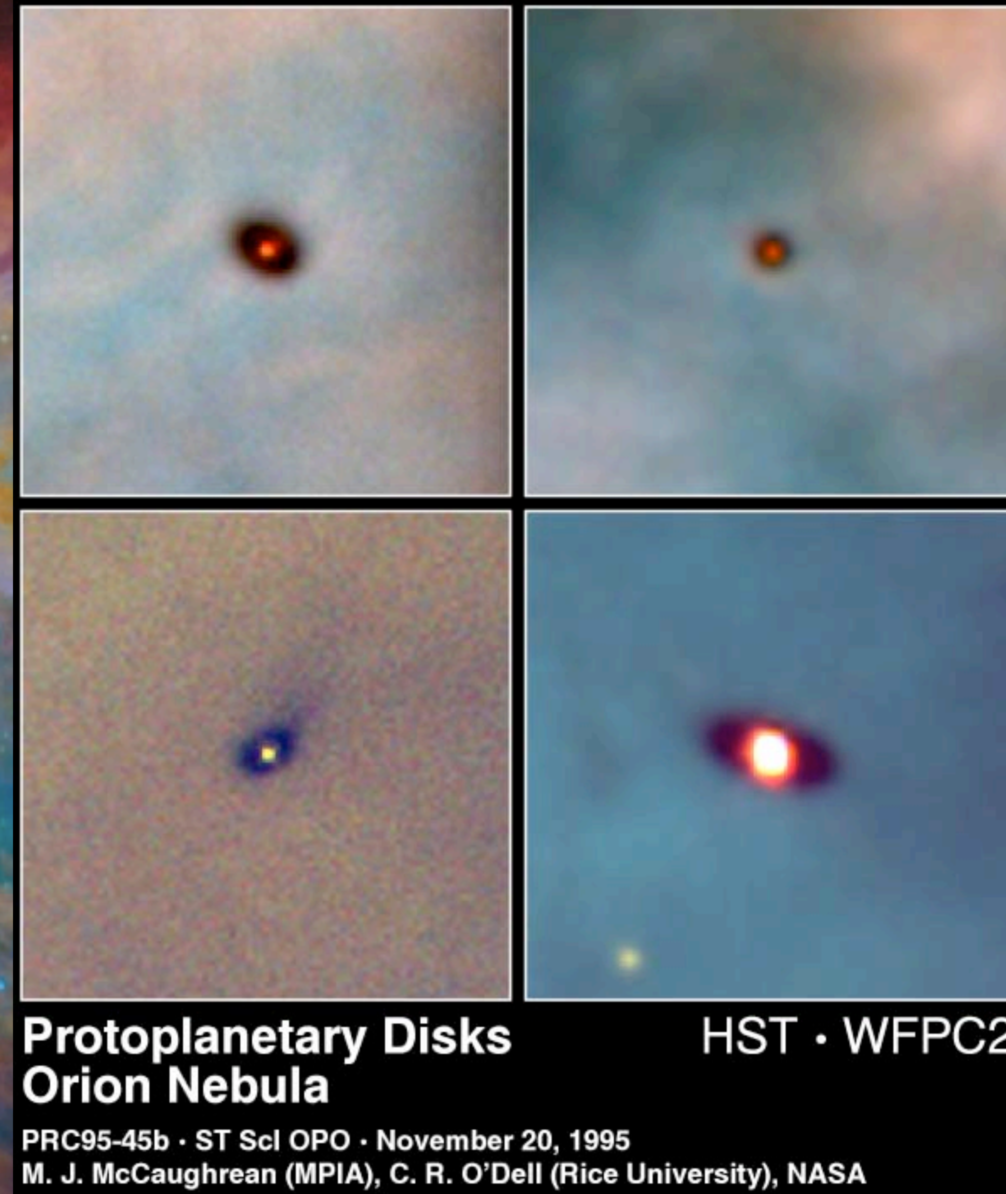
Destination	Mission	Arrival Year	Agency*
Mercury	*MESSENGER* orbiter will study surface, atmosphere, and interior	2011	NASA
Venus	*Magellan* orbiter mapped surface with radar	1990	NASA
	Venus Express focuses on atmosphere studies	2006	ESA
Moon	The United States, China, Japan, India, and Russia all have current or planned robotic missions to explore the Moon	—	—
Mars	*Spirit* and *Opportunity* rovers learn about water on ancient Mars	2004	NASA
	Mars Reconnaissance Orbiter takes very high-resolution photos, seeks future landing sites	2006	NASA
	Mars Express orbiter studies Mars's climate, geology, and polar caps	2004	ESA
	Phoenix lander studied soil near the north polar cap	2008	NASA
Asteroids	*Hayabusa* orbited and landed on asteroid Itokawa; may return a sample in 2010	2005	JAXA
	Dawn will visit the large asteroid Vesta and the dwarf planet Ceres	2011	NASA
Jovian Planets	*Voyagers 1* and *2* visited all the jovian planets and have left the solar system	1979	NASA
	Galileo's orbiter studied Jupiter and its moons; probe entered Jupiter's atmosphere	1995	NASA
	Cassini orbits Saturn; its Huygens probe (built by ESA) landed on Titan	2004	NASA
Pluto and Comets	*New Horizons,* the first mission to Pluto, passed Jupiter in 2007	2015	NASA
	Stardust flew through the tail of Comet Wild 2; returned comet dust in 2006	2004	NASA
	Deep Impact observed its "lander" impacting Comet Tempel 1 at 10 km/s	2005	NASA
	Rosetta will orbit Comet Churyumov-Gerasimenko and release a lander	2014	ESA

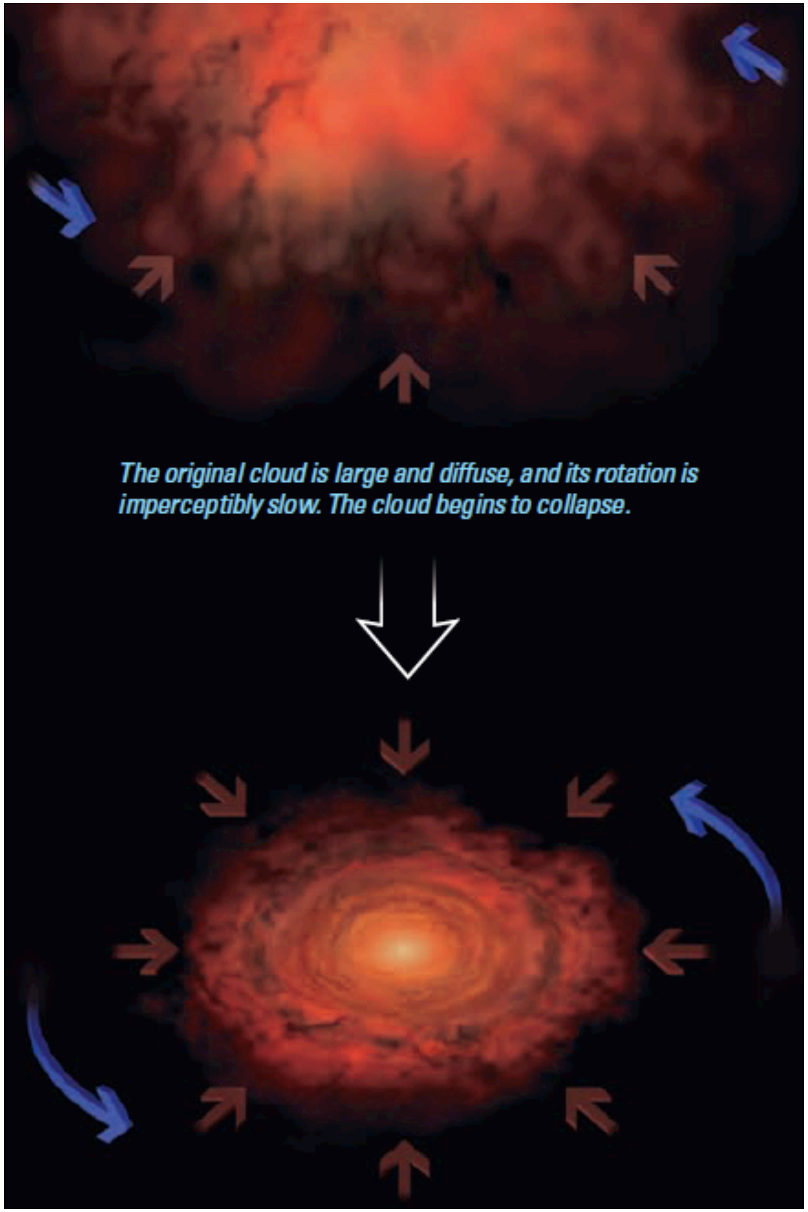
Chapter 8

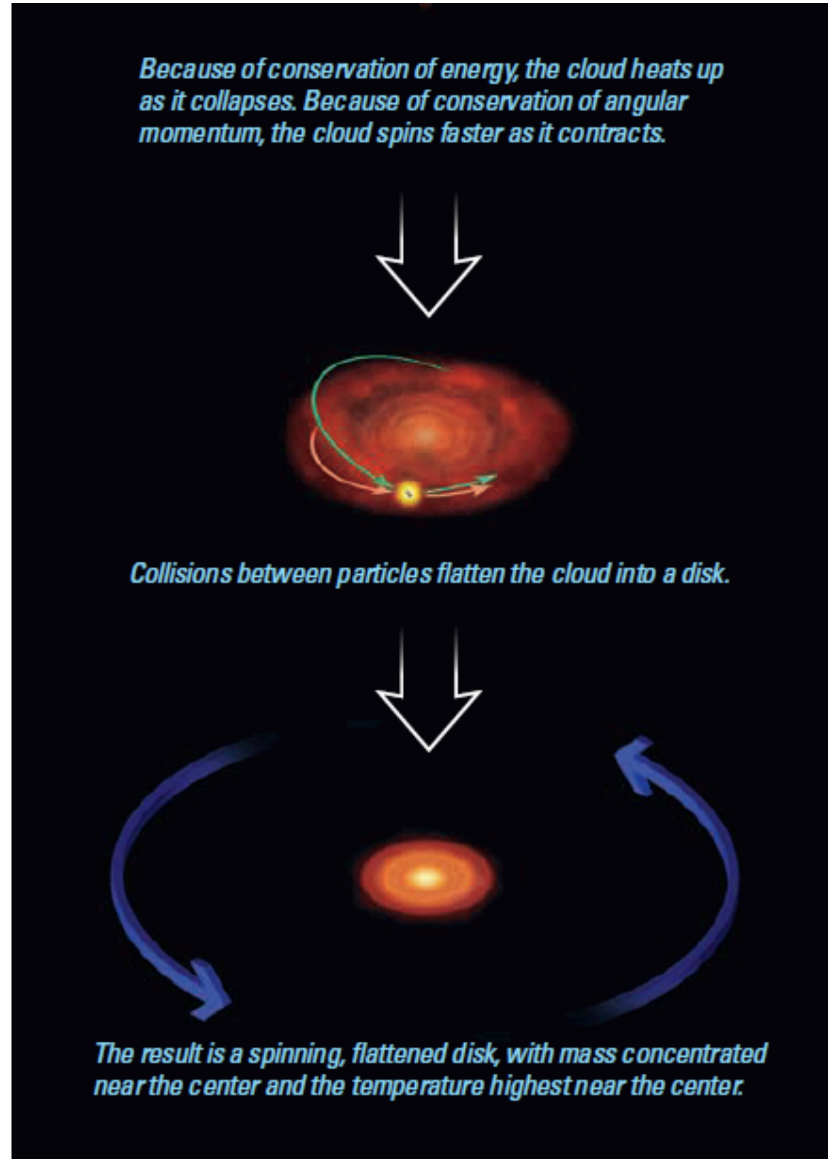
- Formation of the Solar System

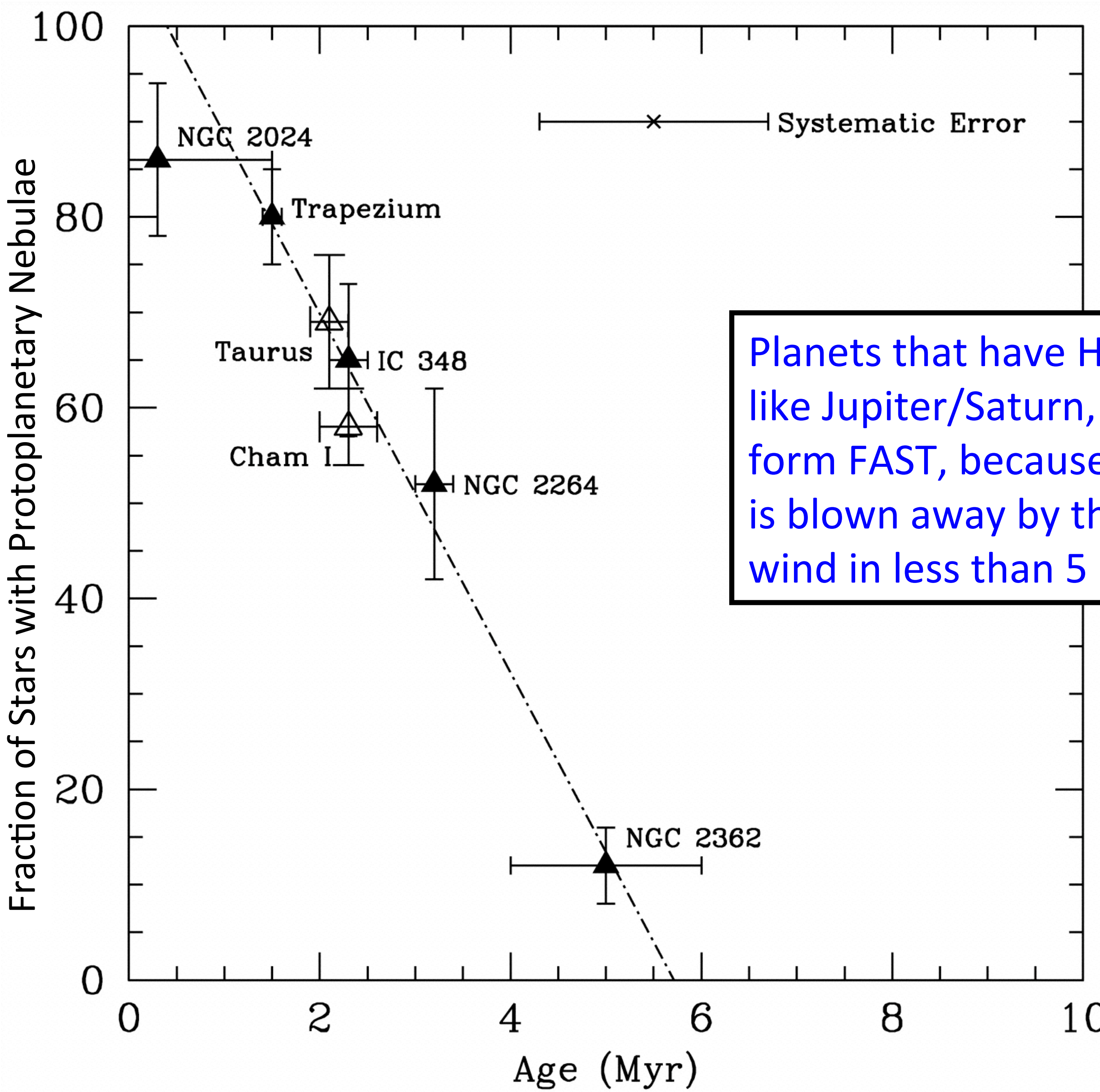

Stars are born in clouds of gas and dust.
Stars produce heavier elements from lighter ones.
Stars return material to space when they die.


100,000 AU


Protoplanetary Disks
Orion Nebula
HST • WFPC2
PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA


The original cloud is large and diffuse, and its rotation is imperceptibly slow. The cloud begins to collapse.

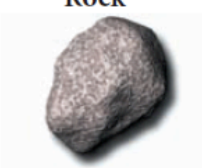

Because of conservation of energy, the cloud heats up as it collapses. Because of conservation of angular momentum, the cloud spins faster as it contracts.
Collisions between particles flatten the cloud into a disk.
The result is a spinning, flattened disk, with mass concentrated near the center and the temperature highest near the center.

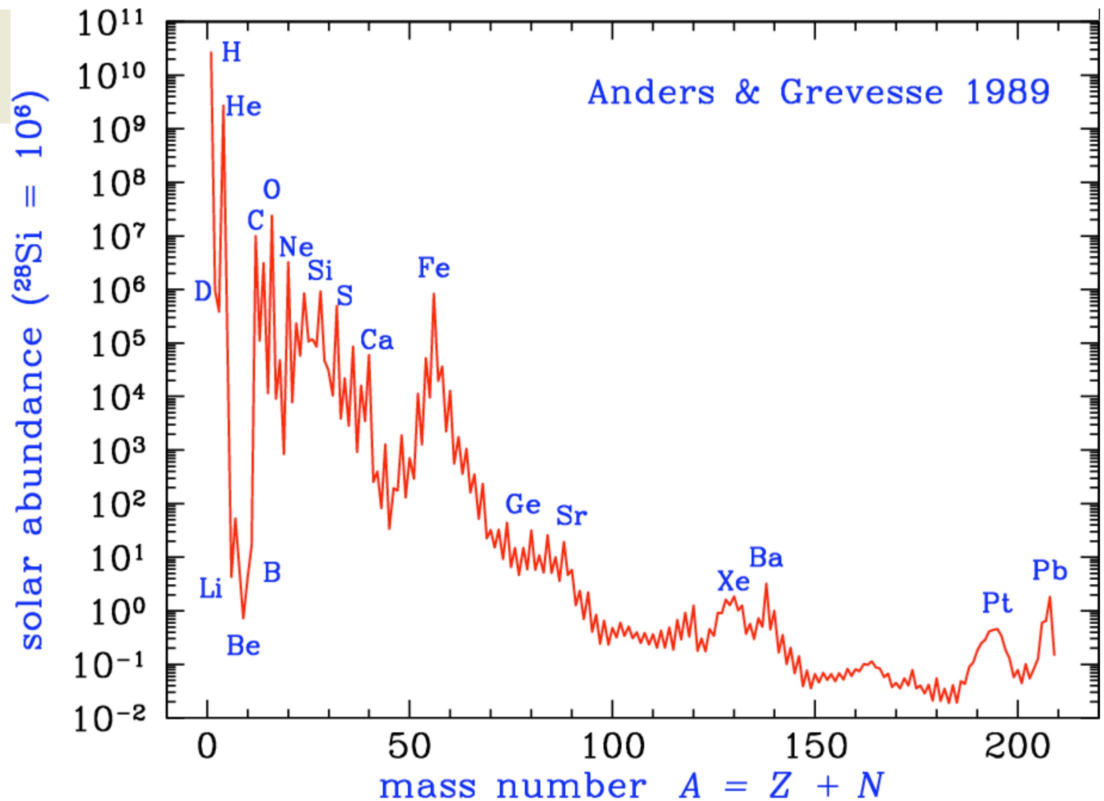


Planets that have H/He gas, like Jupiter/Saturn, must form FAST, because the gas is blown away by the solar wind in less than 5 Myr

Protoplanetary Disks do not live a long time

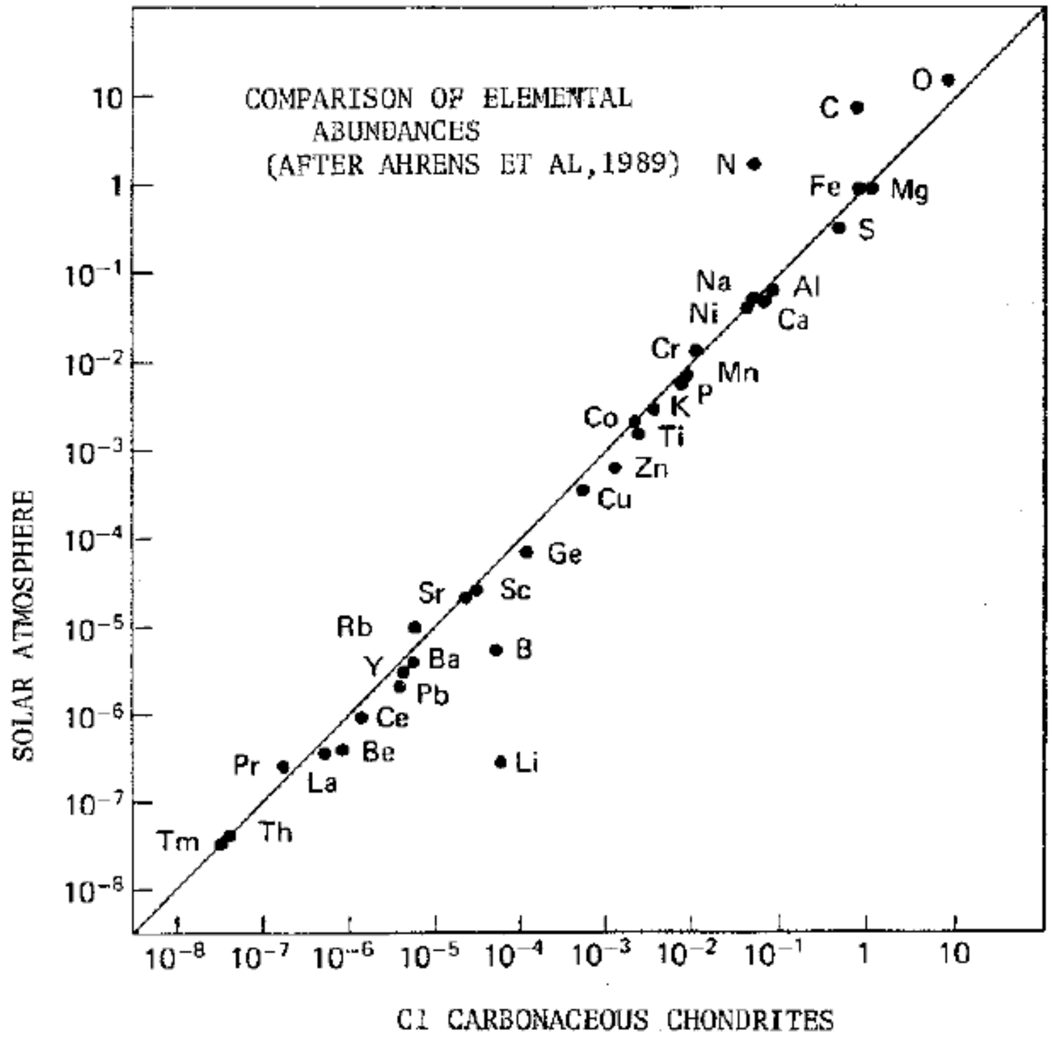
The Solar Nebula: A Protoplanetary Disk: What is it made of?

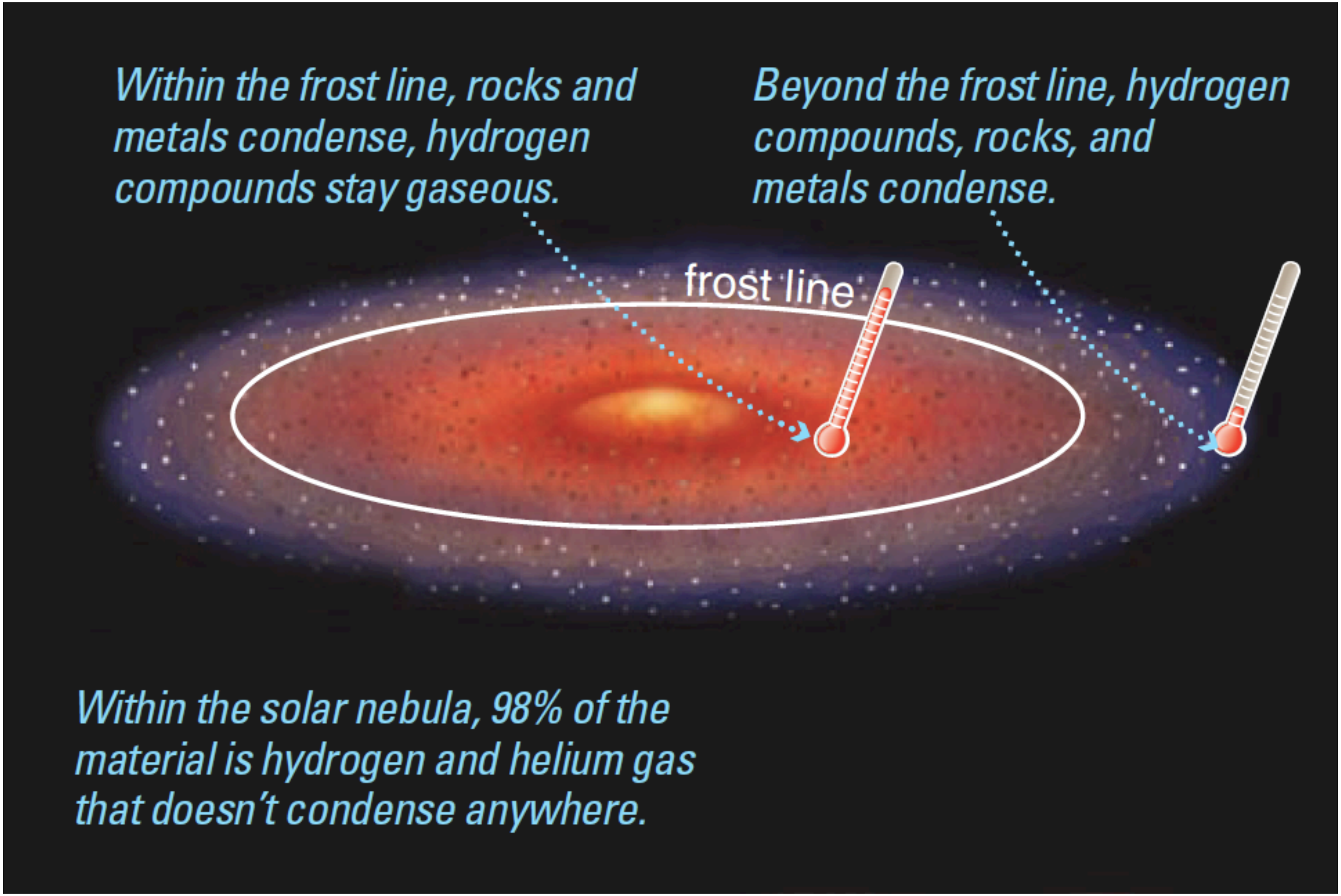
	Examples	Typical Condensation Temperature	Relative Abundance (by mass)
Hydrogen and Helium Gas 	hydrogen, helium	do not condense in nebula	98%
Hydrogen Compounds 	water (H_2O), methane (CH_4), ammonia (NH_3)	<150 K	1.4%
Rock 	various minerals	500–1300 K	0.4%
Metal 	iron, nickel, aluminum	1000–1600 K	0.2%



Mostly H and He, with everything else making up less than 2% by mass

The Sun and Carbonaceous Chrondrites (old unprocessed meteorites) are made of the same stuff




Within the frost line, rocks and metals condense, hydrogen compounds stay gaseous.
Beyond the frost line, hydrogen compounds, rocks, and metals condense.
frost line
Within the solar nebula, 98% of the material is hydrogen and helium gas that doesn't condense anywhere.

Clicker: Why do we think that the solar system formed from a rotating, collapsing gas cloud that ended up as a disk orbiting the Sun?

A. Most of the planets revolve and rotate in the same
direction and in the same plane.
B. Conservation of angular momentum means a collapsing
cloud will spin faster and faster.
C. We see clouds of gas and dust in space.
D. We see disks around young stars.
E. all of the above

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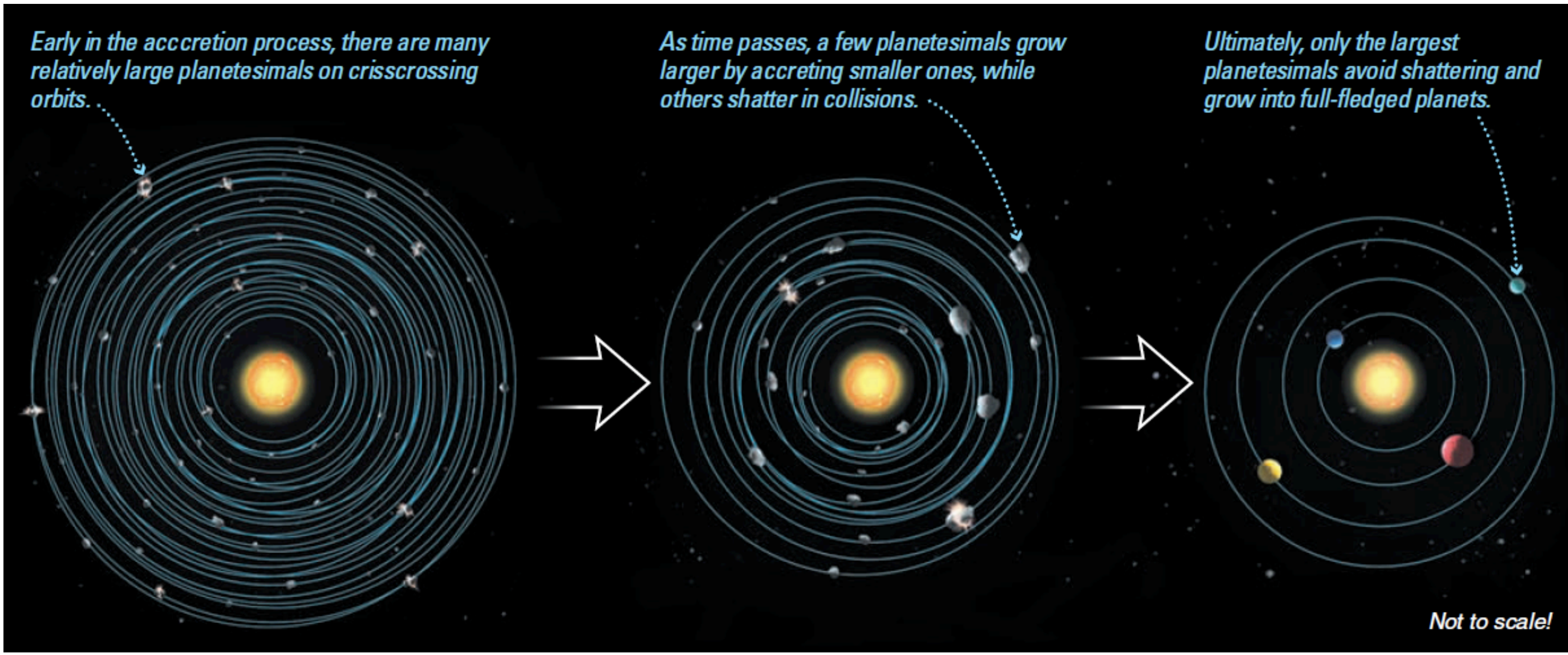
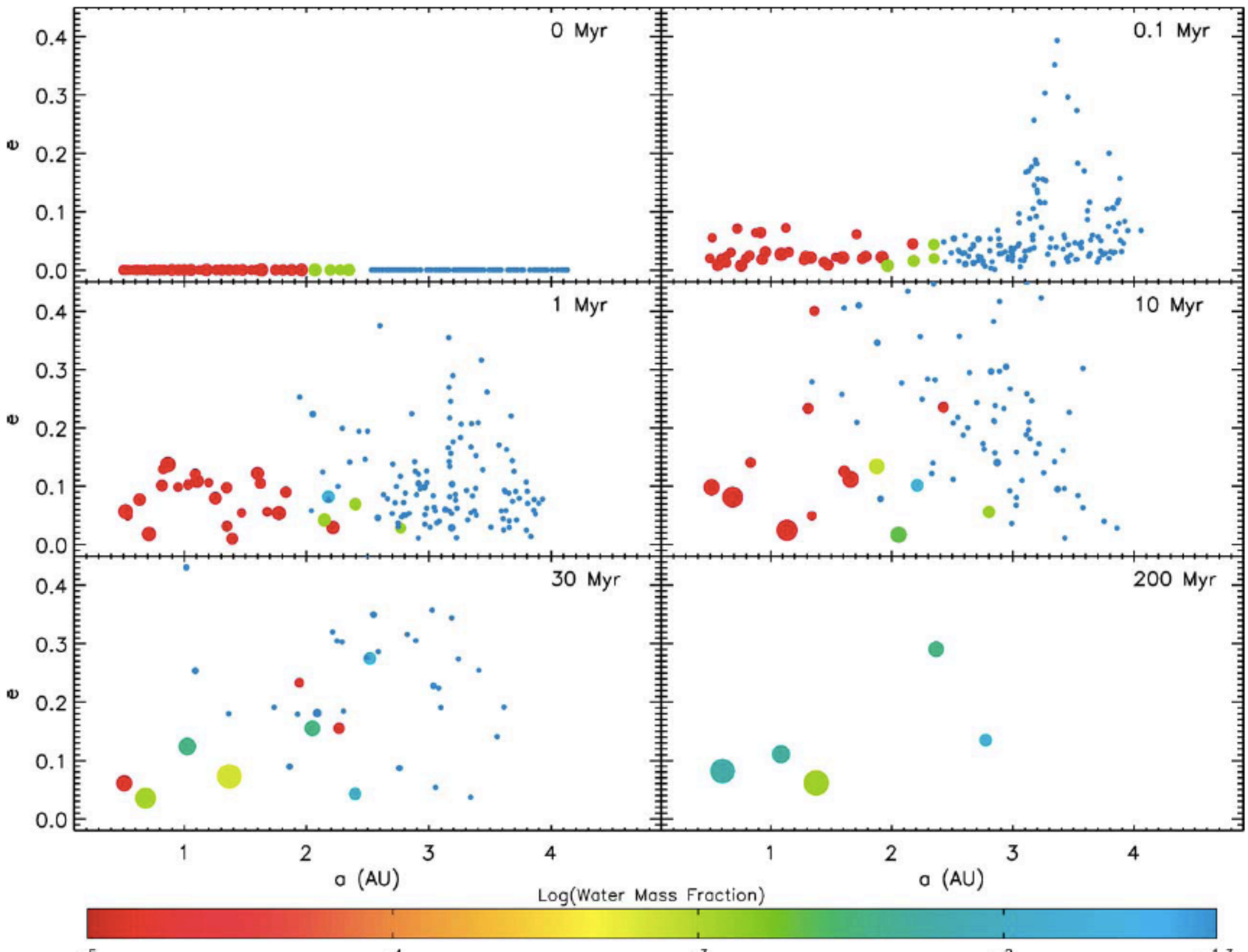
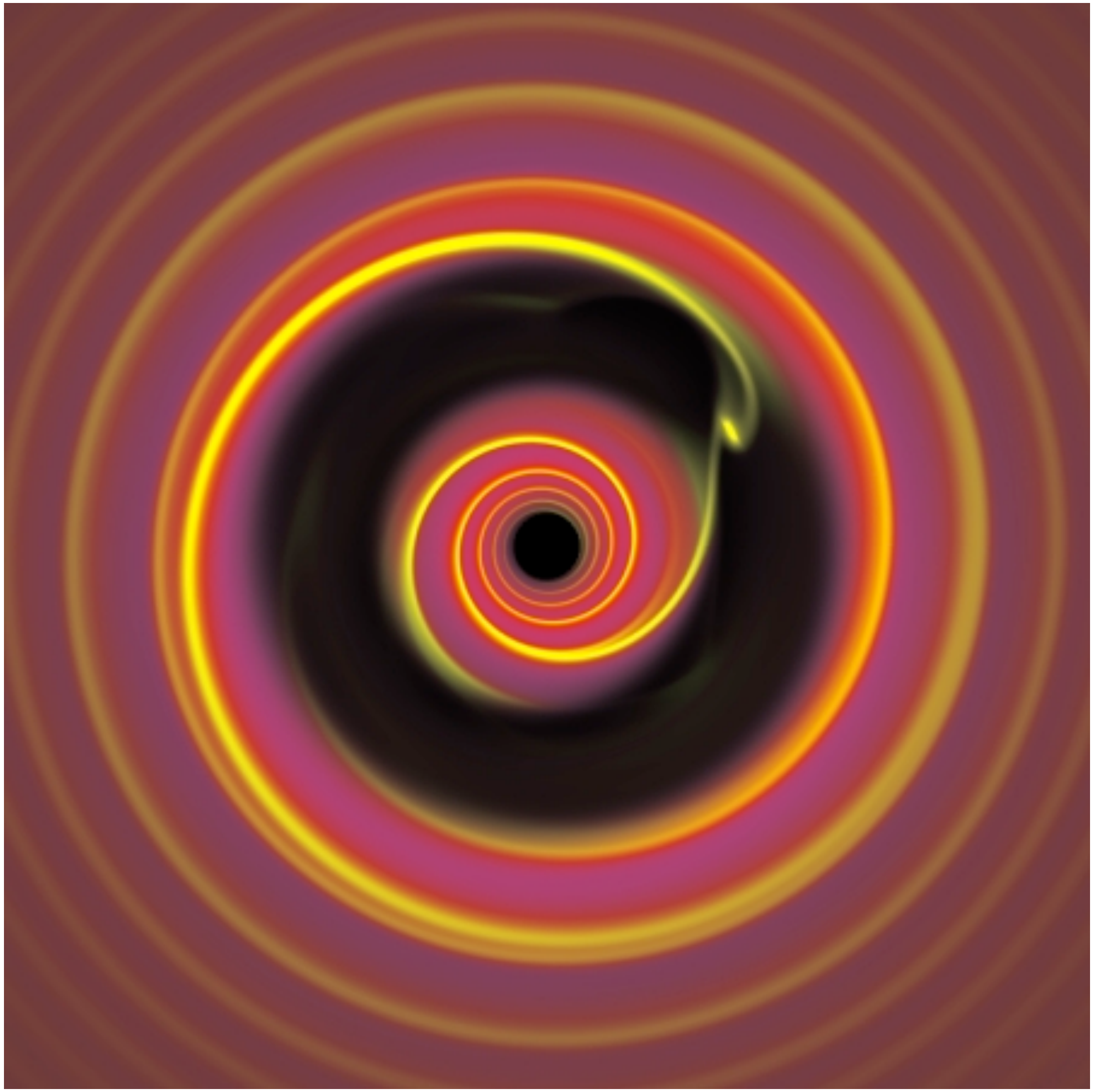


Early in the acccretion process, there are many relatively large planetesimals on crisscrossing orbits.
As time passes, a few planetesimals grow larger by accreting smaller ones, while others shatter in collisions.
Ultimately, only the largest planetesimals avoid shattering and grow into full-fledged planets.
Not to scale!


0 Myr
0.1 Myr
1 Myr
10 Myr
30 Myr
200 Myr
e
0.0
0.1
0.2
0.3
0.4
1
2
3
4
a (AU)
Log(Water Mass Fraction)
-5
-4
-3
-2
-1.3



Beyond the frost line, water is a solid, so there are a lot of solids available

10 M_{Earth} objects can form quickly

Due to gravity, H/He gas, if present, is pulled on, too

Jupiter is 300 M_{Earth} of H/He gas pulled onto a 10-15 M_{Earth} core

Saturn is 85 M_{Earth} of H/He pulled onto a 10-15 M_{earth} core

Uranus/Neptune are several M_{Earth} of H/He pulled onto 15 M_{earth} cores

The Terrestrial Planet / Jovian Planet Connection

Both Terrestrial and Jovian planets form in the same way---the buildup of small planetesimals to form planets, but:

Jovian planets form quickly beyond the frost line, while the H/He gas remains (less than 5 Myr)

Terrestrial planets form within the frost line, where rocks and iron are the only solids, so take longer to form, and do not reach their final masses until after the gaseous disk is gone. (Tens of Myr)

The large satellites of Jupiter and Saturn formed in a "subnebula," a flattened disk around each giant planet, giving rise to a mini solar system