Part 4: Our Solar System, Life in the Universe

Tuesday, April 11 — Reading: Chapter 15 (12th & 13th Edition of the textbook)

- Solar System: Introduction and Formation; Other Solar Systems

Thursday, April 13 — Reading: Chapter 18 (planets)

- Solar System: Jupiter, Saturn, Uranus, Neptune Pluto and the Kuiper Belt

Tuesday, April 18 — Reading: Chapter 18, 19

- Solar System: Outer Solar System, Pluto, Kuiper Belt, Comets, Satellites

Thursday, April 20 — Reading: Chapter 16, 17, 18, 19

- Solar System: Satellites, our Moon, Mercury, Asteroids

Tuesday, April 25 — Reading: Chapter 17

- Solar System: Mars and Venus

Thursday, April 27 — Reading: Chapter 16

- Solar System: Earth

Monday, May 1 — Help Session from 4 to 6 PM in RLM 4.102

Tuesday, May 2 — Exam 6

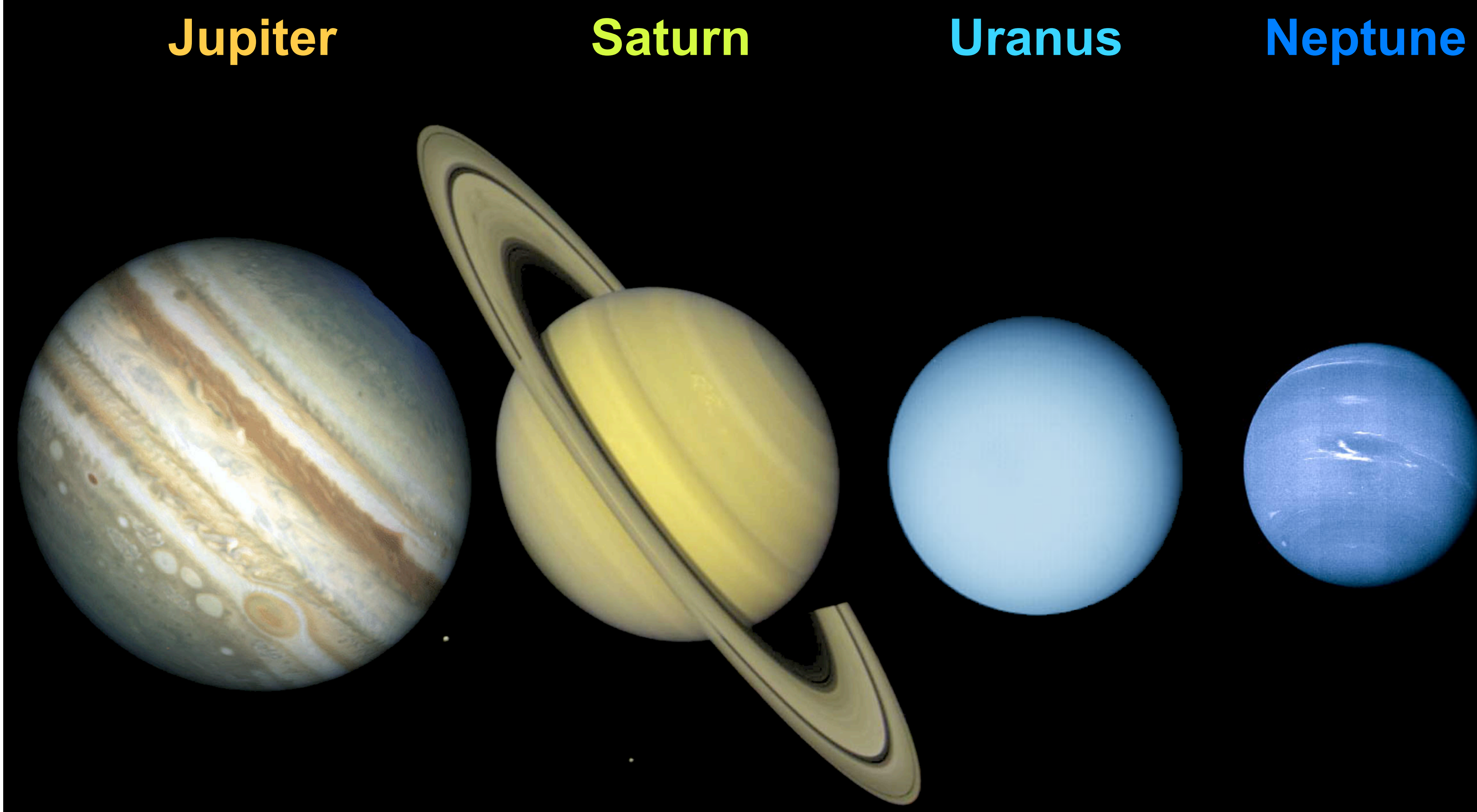
Thursday, May 4 — Reading: Chapter 20

- The history of life on Earth; Life in the Universe

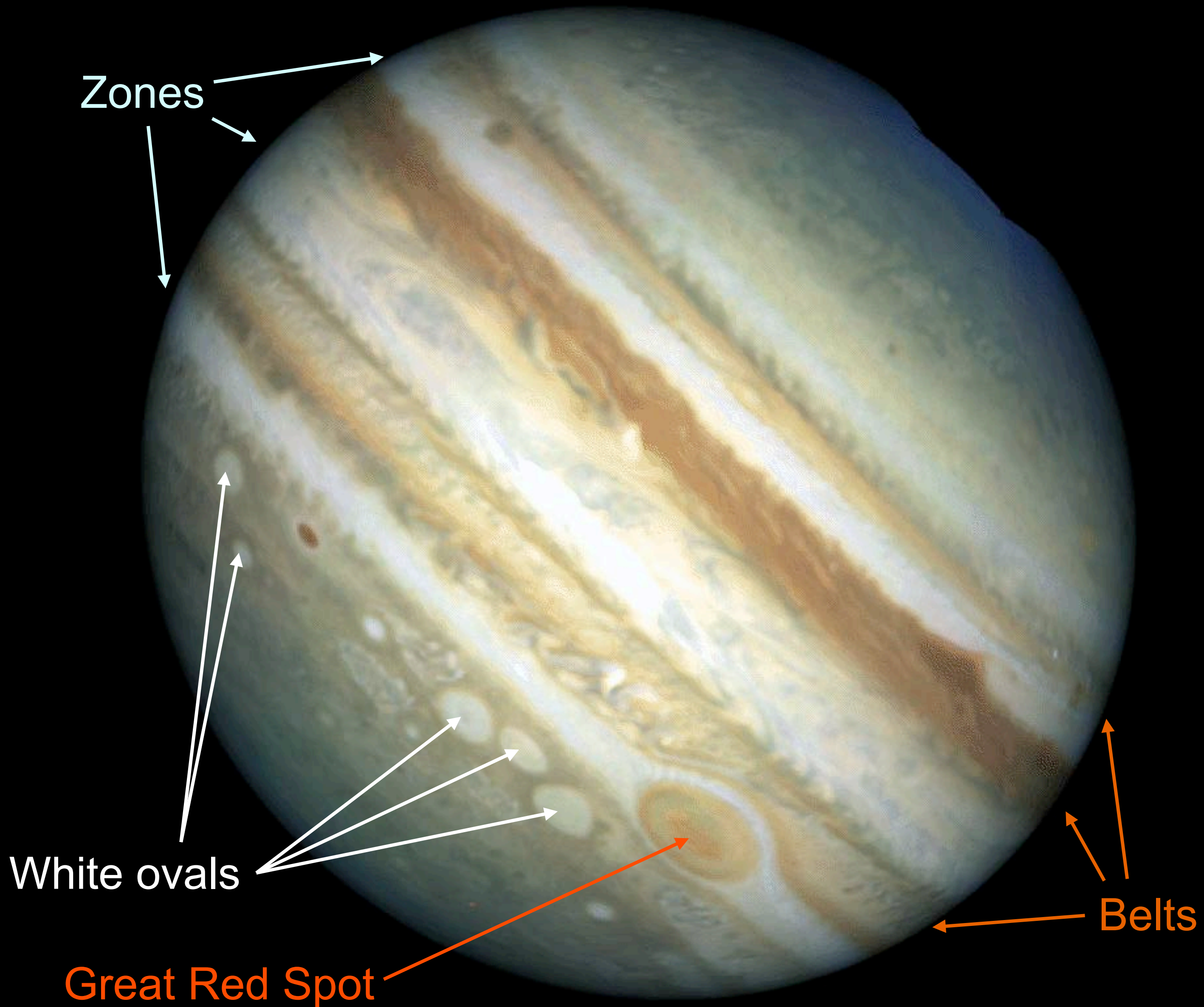
This is the only time in human history
when we will ever explore
the planets and moons in our Solar System
for the first time.

Carl Sagan

The Jovian Planets



Jupiter



Jupiter Rotation (1 Day = 9^h 55^m)

Atmospheres of the Jovian Planets

Jupiter, Saturn, Uranus, and Neptune do not have surfaces. One sign of this is the observation that the rotation period depends on latitude, as in the Sun.

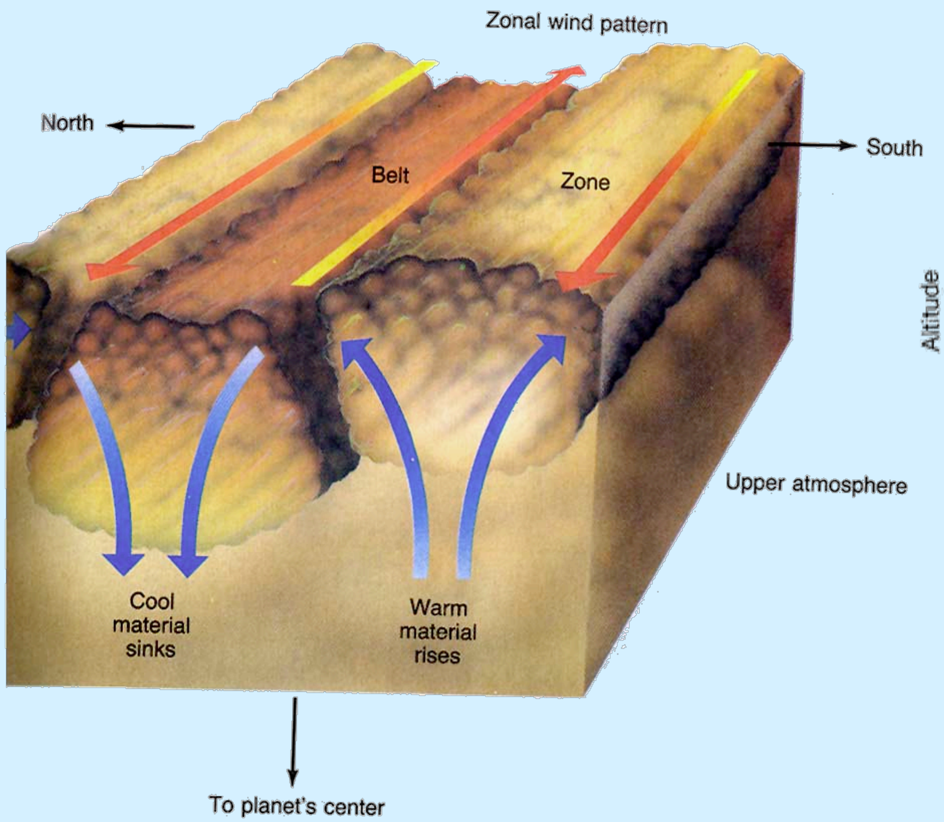
Jupiter and Saturn have thick atmospheres with many layers of clouds. Both are mostly made of hydrogen (H_2) and helium (He); they also contain ammonia (NH_3), methane (CH_4), and water (H_2O). The colors are produced by trace molecules made from the above through the action of sunlight and lightning.

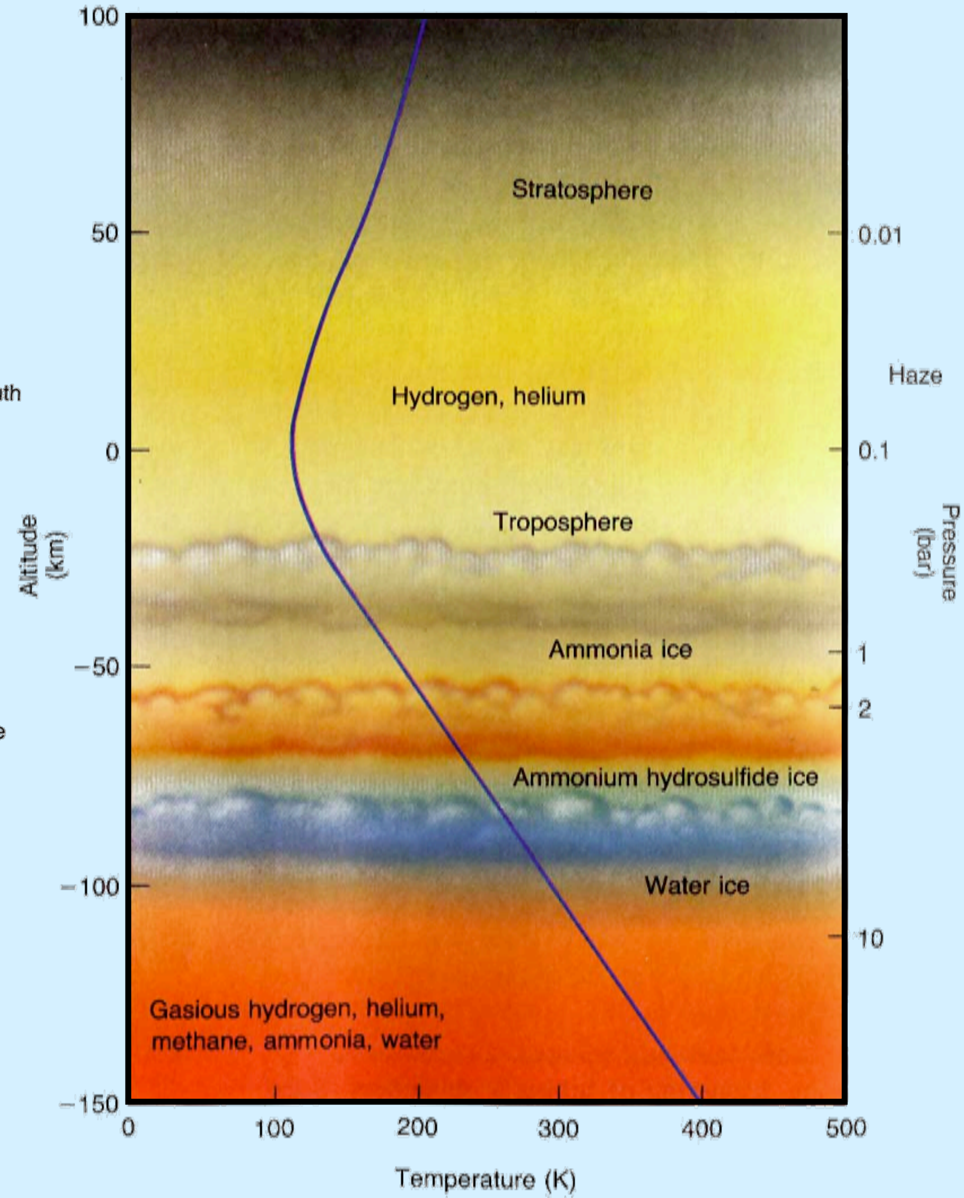
Farther inside than we can see, the atmosphere merges with the liquid interior.

Central heat in these planets is carried through their atmospheres by convection. Rapid rotation organizes the convection patterns into bands. Dark "belts" lie at lower levels than light "zones".

Spots are high-pressure storms. Jupiter's Great Red Spot has lasted for at least 3 centuries. White spots are higher-level storms; some last for decades. In 1998, two white spots that had been observed for 58 years collided and merged into one. So the weather patterns on Jupiter last a long time, but they do change.

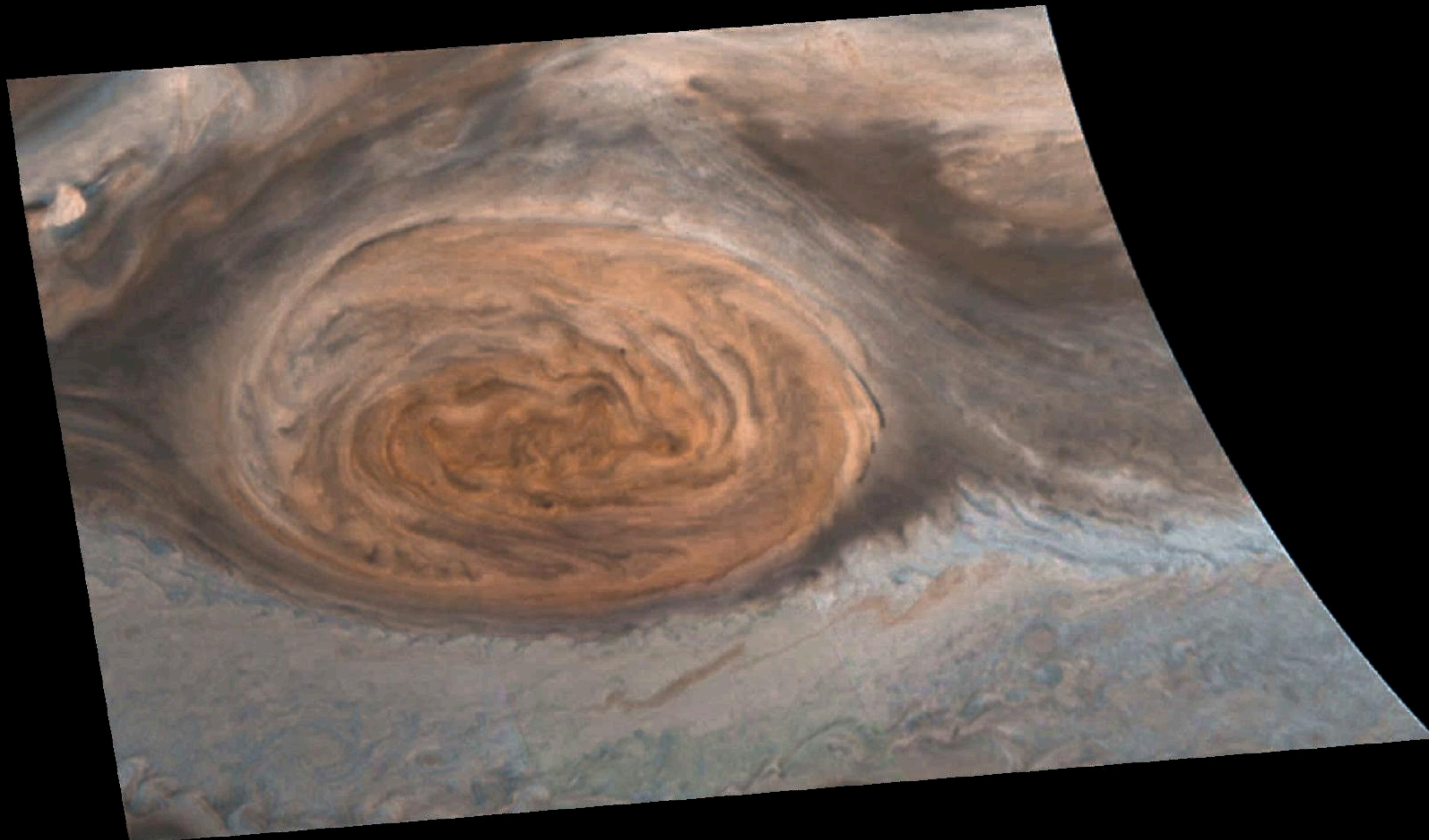
Vertical Structure of Jupiter's Atmosphere





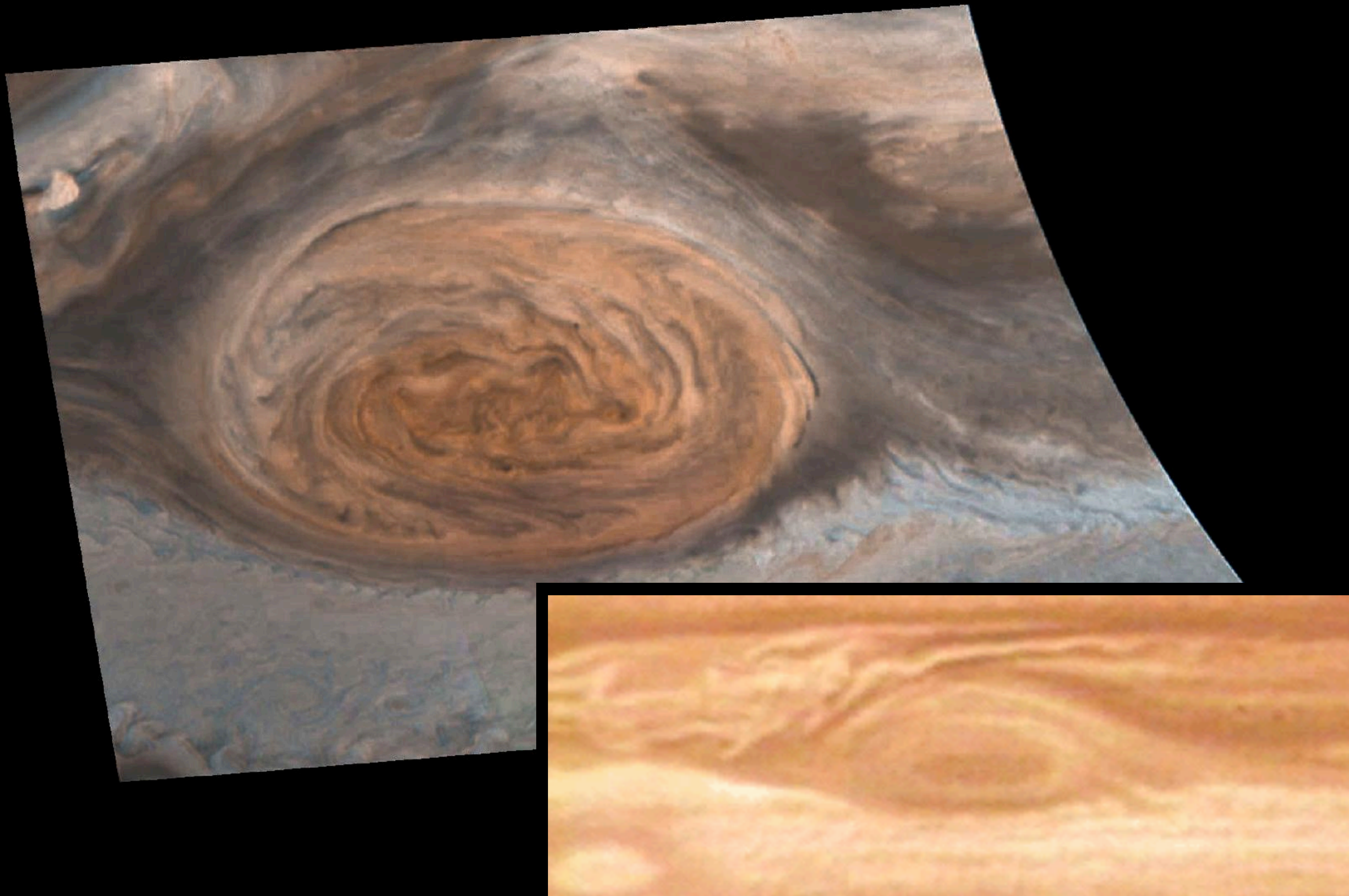
The Great Red Spot is a giant storm that has lasted at least 300 years.

The Red Spot rolls between the South Equatorial belt and the South Tropic Zone: winds to its north blow westward; winds to its south blow eastward.

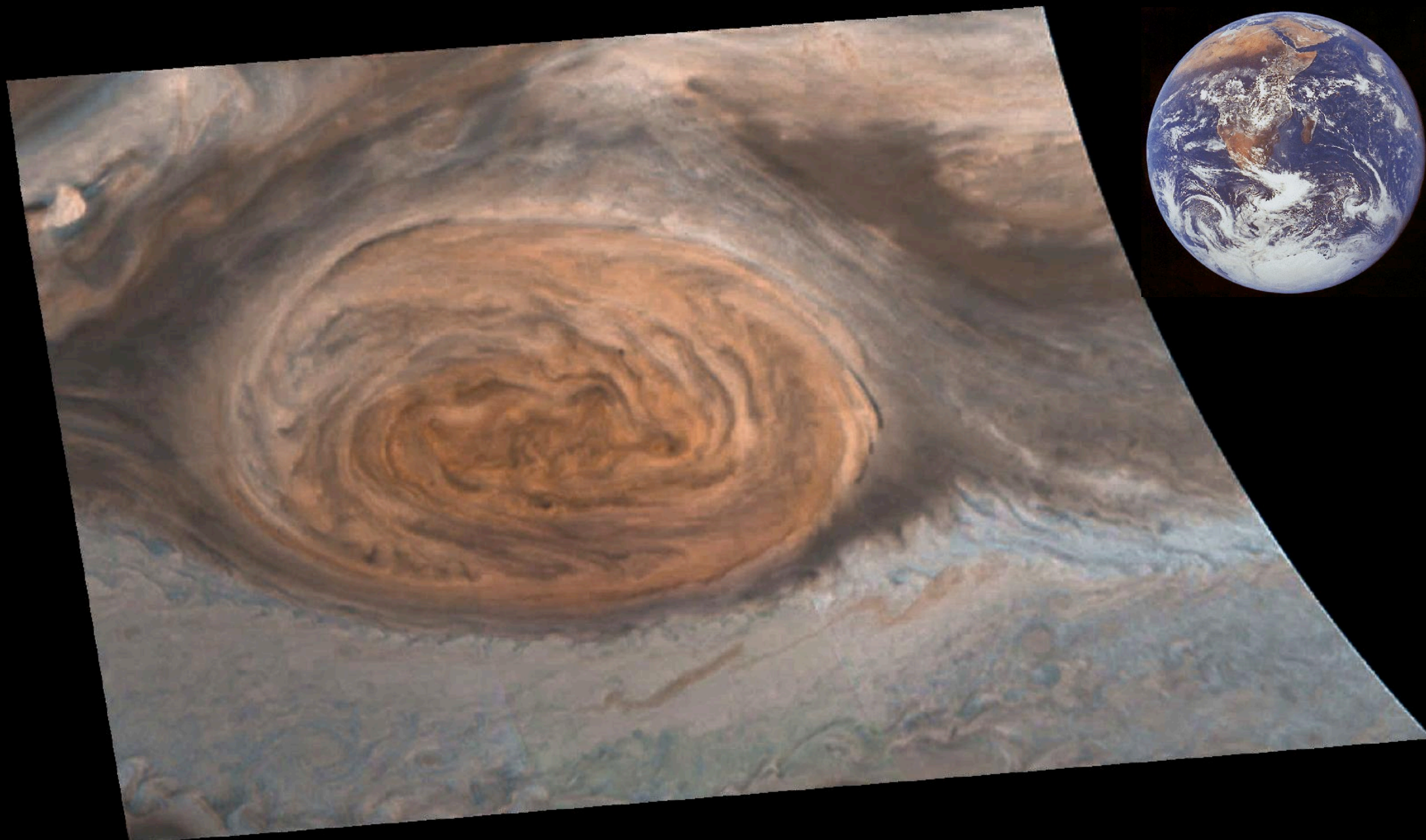


It rotates once in about 6 days.
Its top is about 8 km (5 miles) above the surrounding cloud tops.

The Red Spot rolls between the South Equatorial belt and the South Tropic Zone: winds to its north blow westward; winds to its south blow eastward.



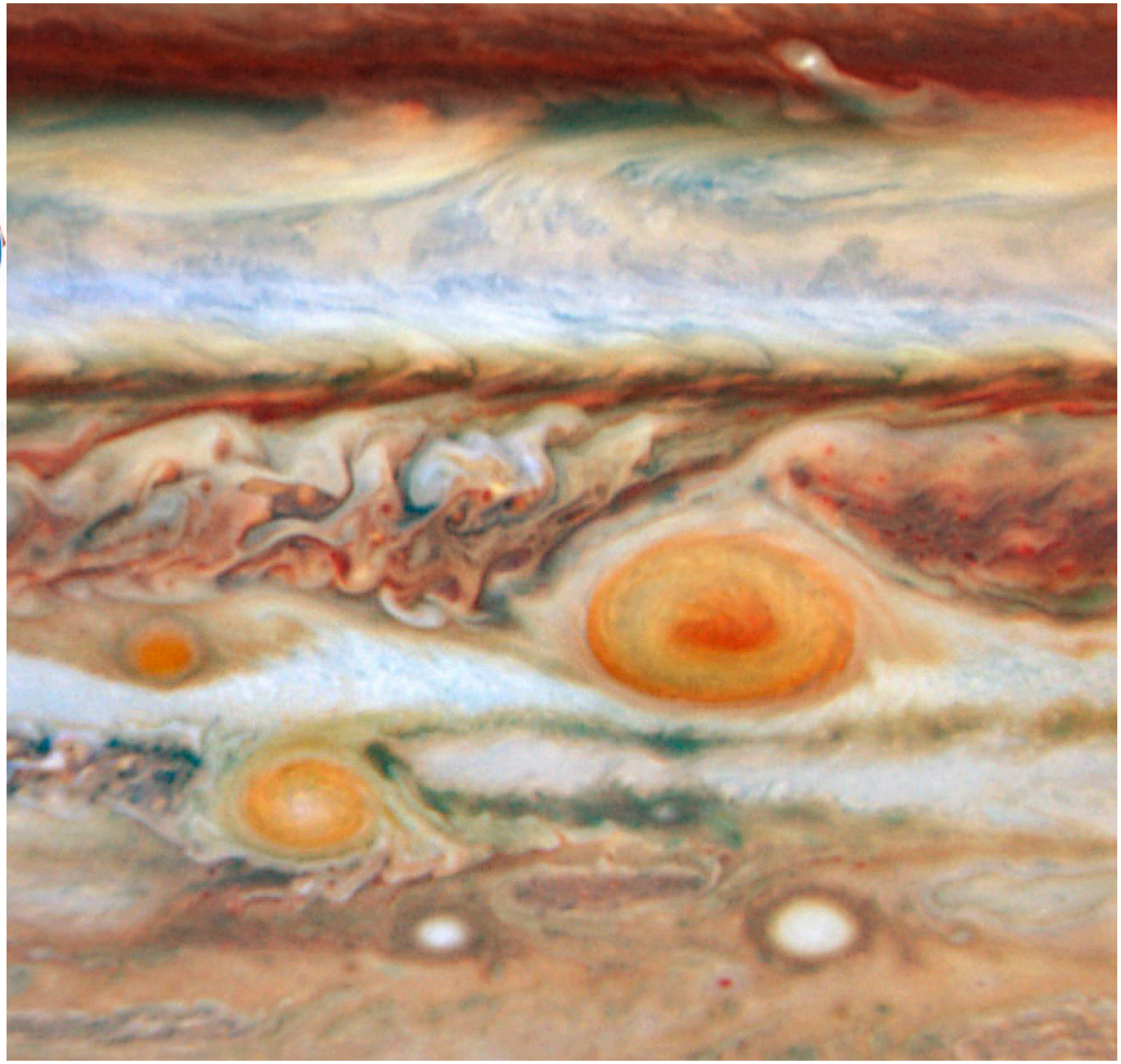
The Red Spot is about twice the diameter of the Earth.

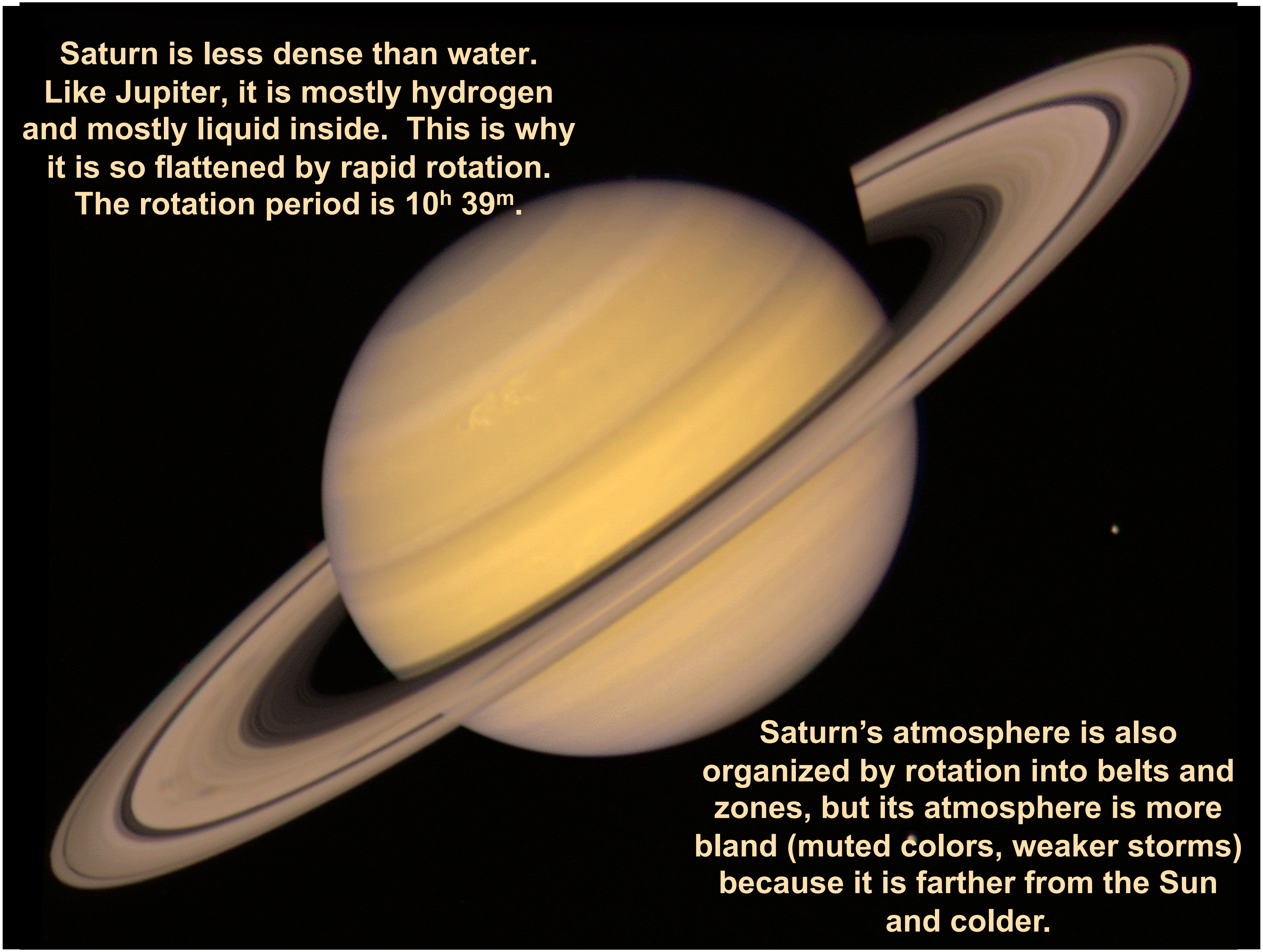


In recent years, the Red Spot has been shrinking. It could disappear.

Jupiter sometimes has two “Red Spots” In fact, …

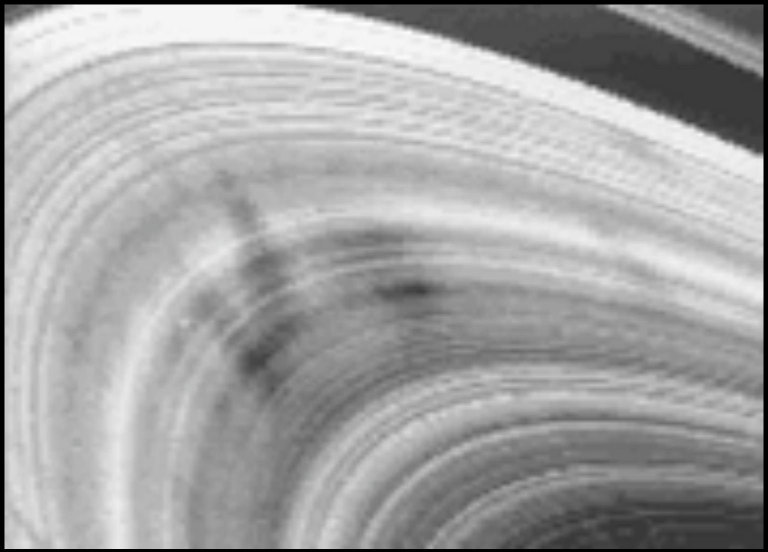
Jupiter had 3 red spots for a few months in 2008. Then the smallest was eaten up by the biggest. Eating other storms is one way that the Red Spot keeps going & going & going … .




Saturn is less dense than water.
Like Jupiter, it is mostly hydrogen
and mostly liquid inside. This is why
it is so flattened by rapid rotation.
The rotation period is 10^h 39^m.
Saturn's atmosphere is also
organized by rotation into belts and
zones, but its atmosphere is more
bland (muted colors, weaker storms)
because it is farther from the Sun
and colder.

Flying Around Saturn’s Rings

Saturn’s Rings

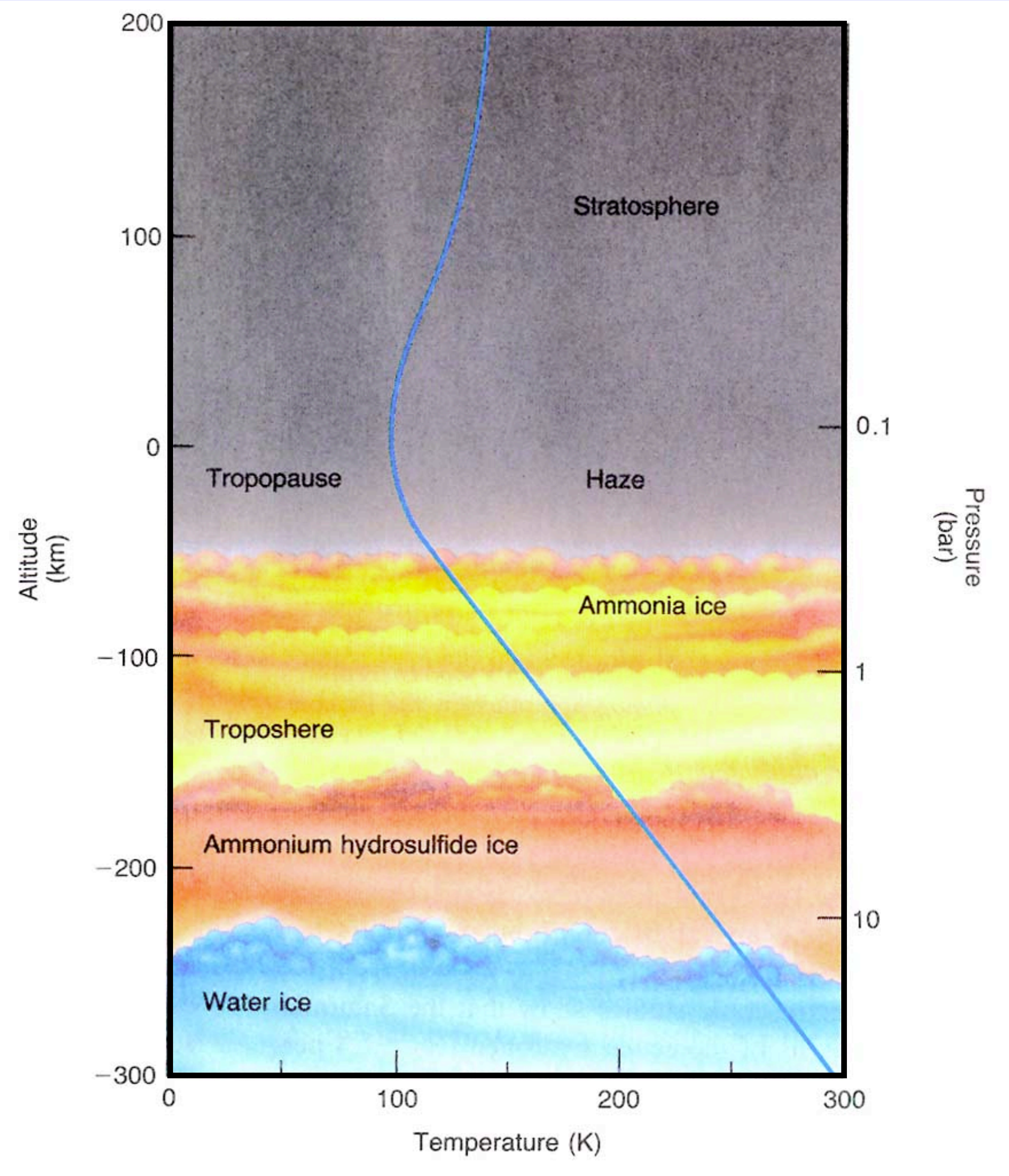


Saturn’s rings are made of billions of ice particles. Most are tiny but some are the size of houses. They rotate “differentially” − the inner rings revolve around Saturn faster than their outer rings. So each ring particle is a separate moon in its own orbit around Saturn. The rings are only a few tens of meters thick. Relative to their diameter, they are much thinner than a sheet of paper.

They are probably the remnants of icy satellites that collided with each other.

The dark “spokes” are thought to be tiny dust particles held several tens of meters above the ring plane by electrostatic forces.

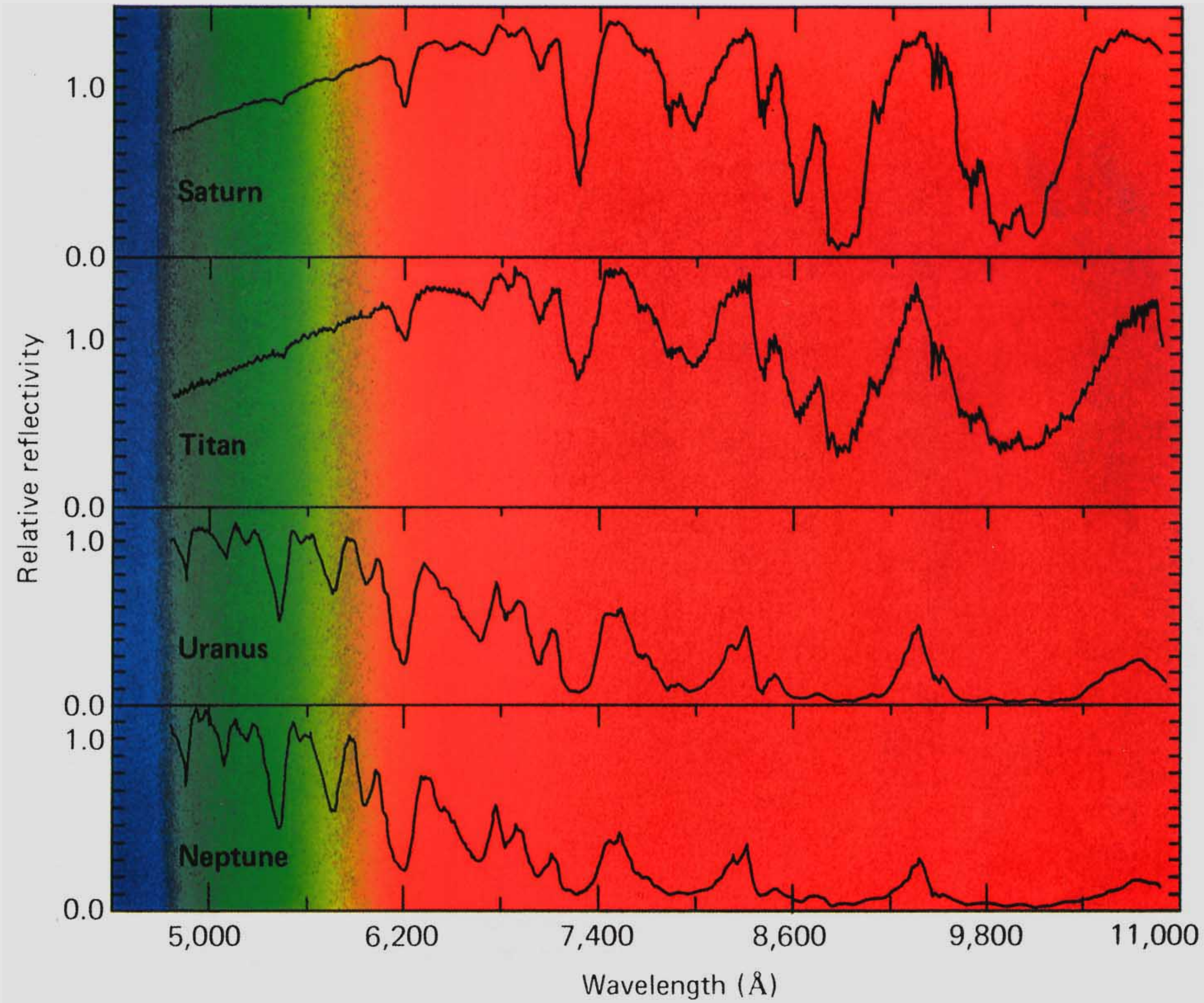
Vertical Structure of Saturn’s Atmosphere



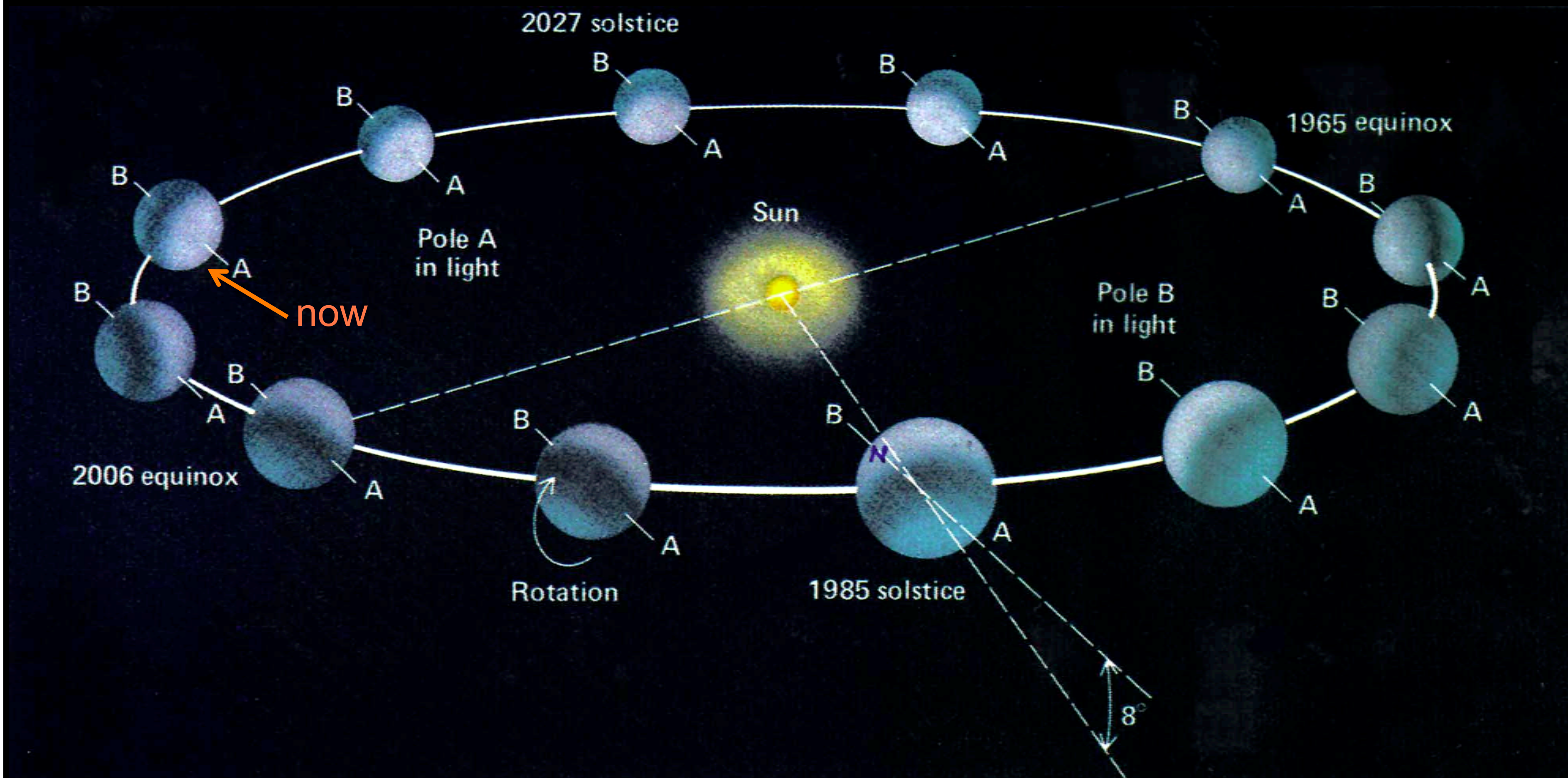
Uranus

Uranus as imaged by Voyager 2 in January 1986 showed almost no features.
It was midsummer in the Southern Hemisphere (facing us).
The blue color is due to methane,
which is 10 times more abundant (because of the cold) than in Jupiter and Saturn.

Methane (CH_4) Absorption

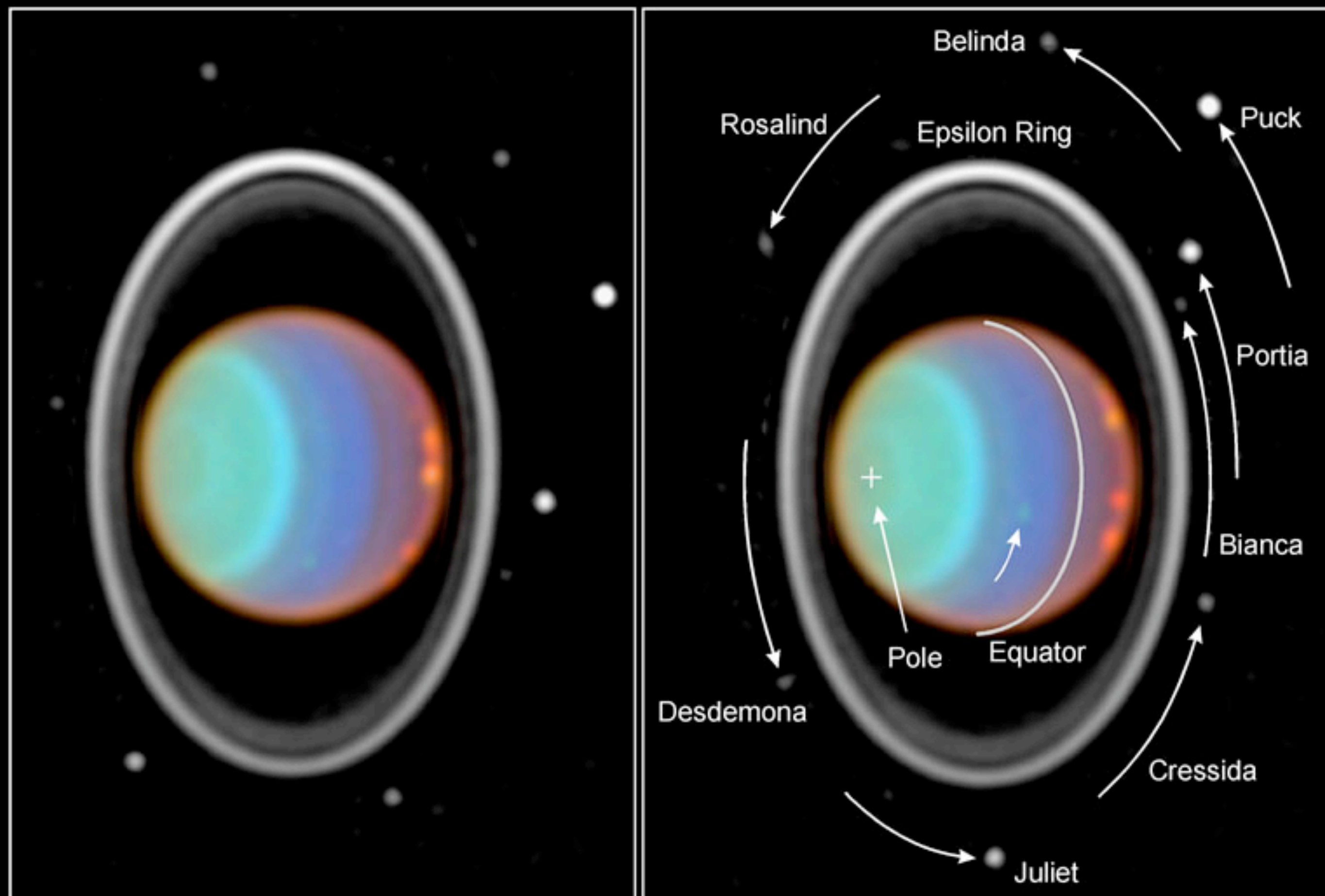


Seasons on Uranus



Uranus's rotation axis is tipped 98° to its orbital plane.
Presumably it was hit hard by another protoplanet early in its history!
The result is ferociously strong seasons, each about 20 years long.
The Sun has passed over the equator now (2017).

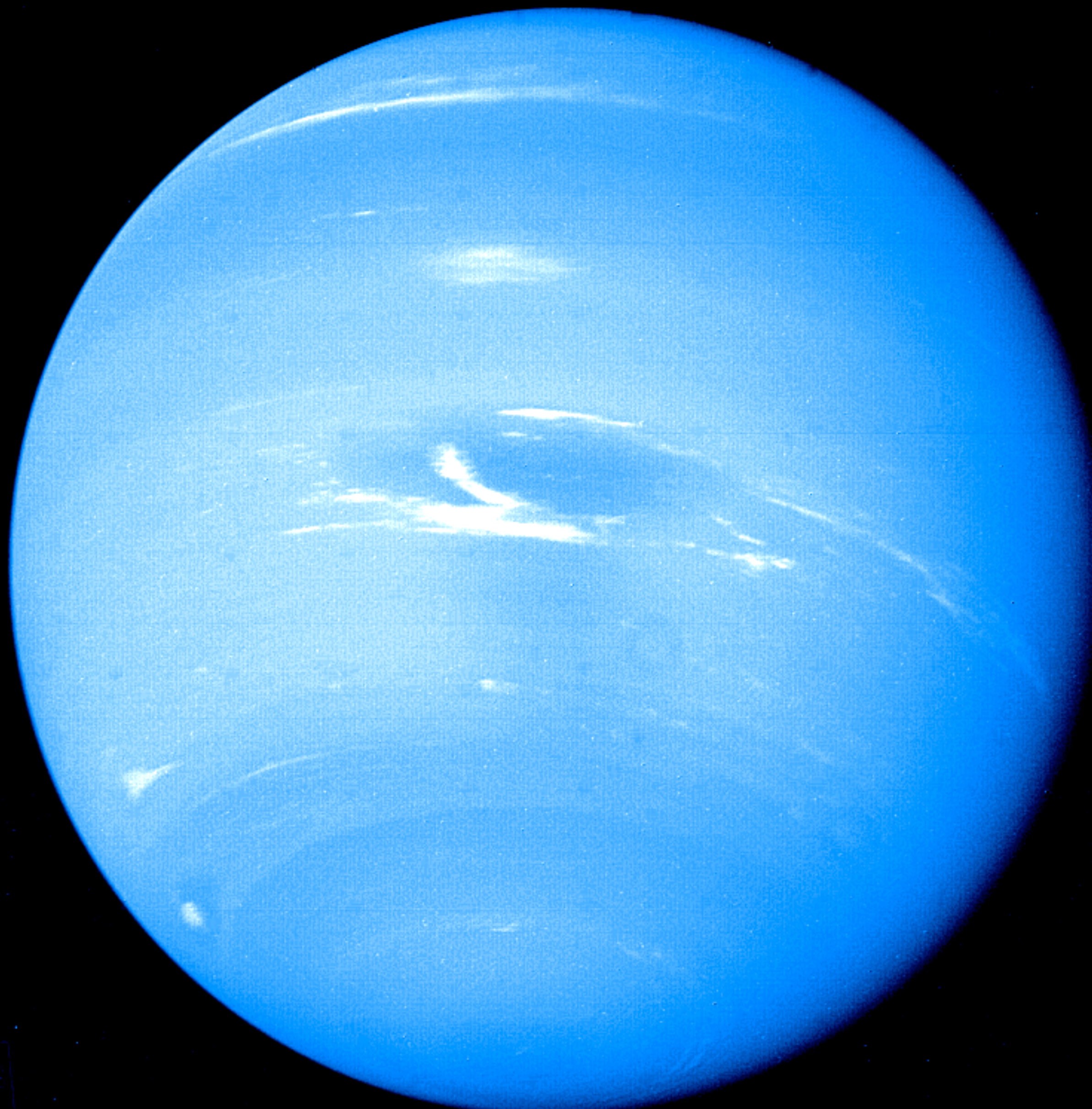
Uranus
Inner Satellites and Northern-Hemisphere Storms



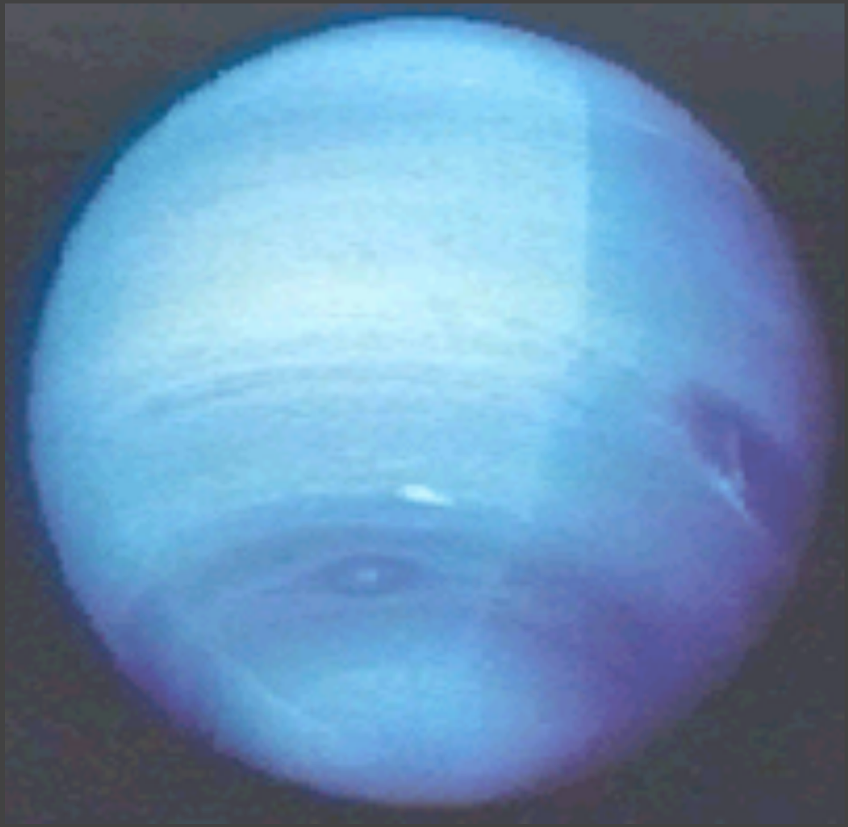
Uranus • July 28, 1997 HST • NICMOS

Spring came to the Northern hemisphere in the late 1990s after 20 years of winter. Renewed sunlight drove storms.

Neptune

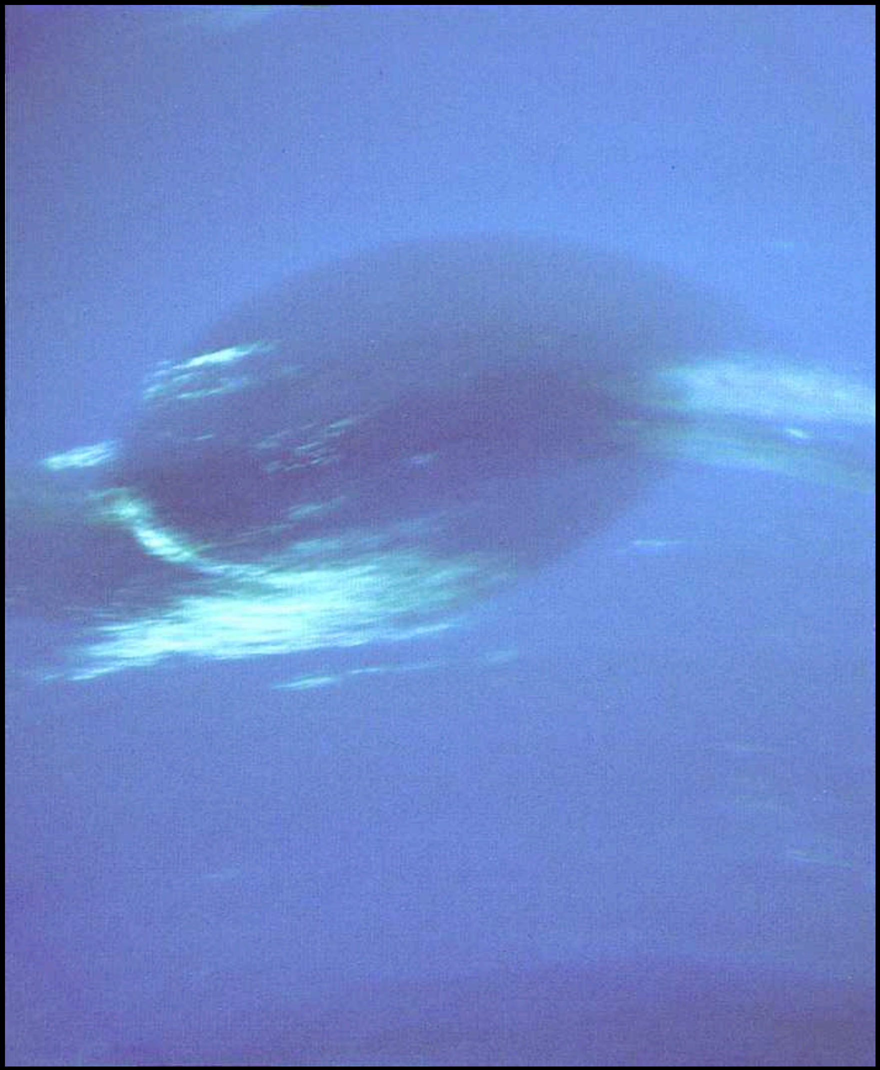


Neptune Rotation Movie From Voyager 2



After bland Uranus, it was a surprise to find big storms on Neptune.
Neptune, like Jupiter and Saturn but unlike Uranus,
radiates internal heat, and that's what it takes to drive storms.
The Great Dark Spot is about the size of the Earth.

Neptune — Great Dark Spot (August 1989)



When the Hubble Space Telescope imaged Neptune in 1994, the Great Dark Spot had disappeared.

Internal Structure of Jupiter and Saturn

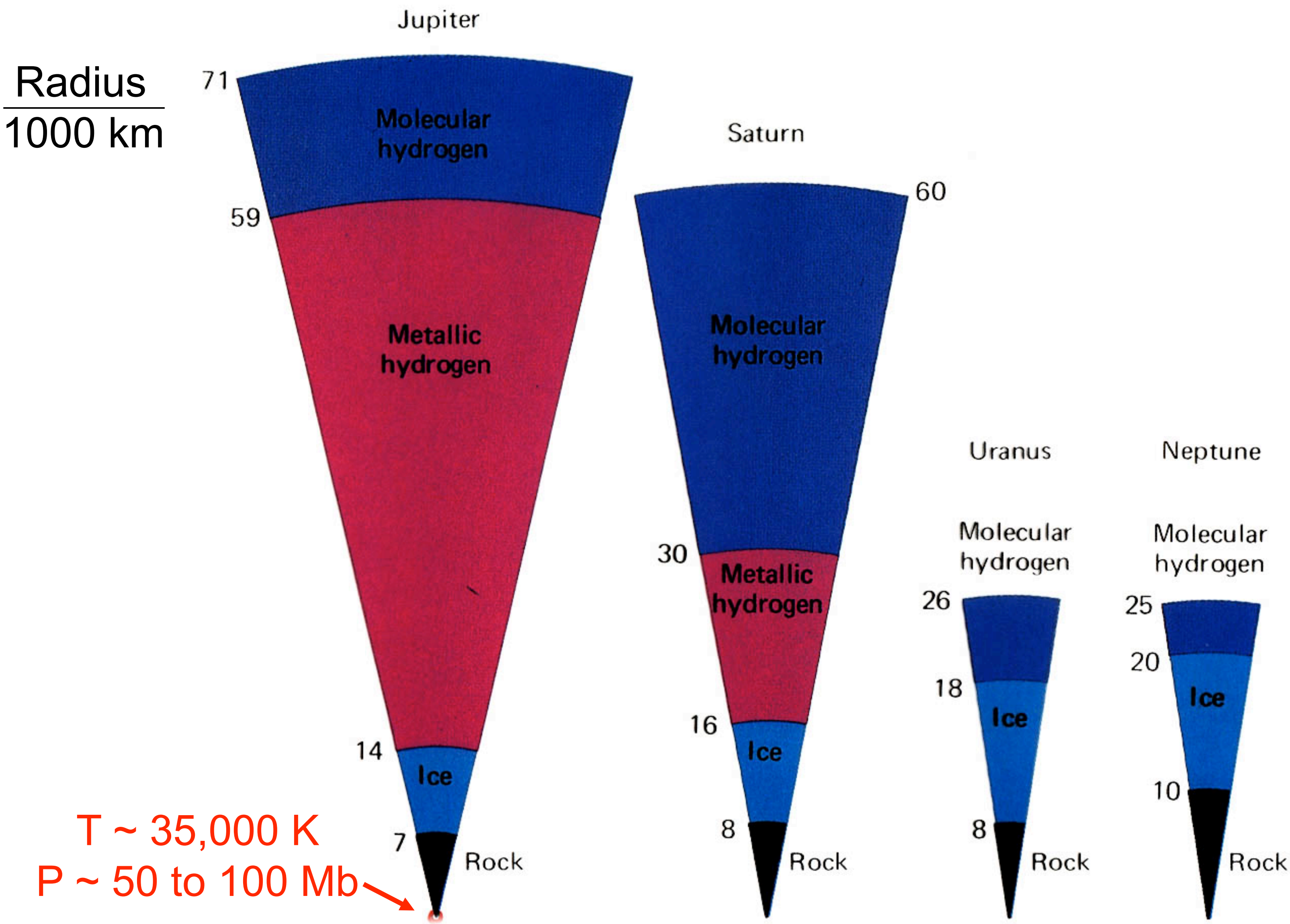
Jupiter and Saturn rotate rapidly; because of this, both planets are flattened. The amount of flattening is a clue to internal structure: if Jupiter and Saturn had constant internal densities, they would be about 80 % flatter than they are. Jupiter's central density is more than 20 times its average density.

The high central densities of these planets are due to the enormous weight of their thick atmospheres. Descending into these atmospheres, you would feel enormous pressures and temperatures.

At pressures several million times the pressure of the Earth's atmosphere, hydrogen molecules break up into protons and electrons ($H_2 \rightarrow 2p + 2e$). The result is <u>liquid hydrogen that behaves as a molten metal</u>.

Both Jupiter and Saturn are thought to have rocky cores. Jupiter's is about 13 times as massive as the Earth but probably less than 10,000 km in radius. Surrounding this is a layer of metallic hydrogen 40,000 km thick. Saturn is less massive than Jupiter, so its rocky core is less compressed and its layer of metallic hydrogen is not so thick.

Internal Structures of the Giant Planets



Jupiter is a failed star.

For a few hundred million years,
while it was forming and contracting most quickly,
Jupiter was as bright as a faint star.

Seen from the Earth at that time,
it would have been 100 times brighter than the full Moon is now!

But the interior never got hot enough for nuclear reactions.

Jupiter fizzled out.

Jupiter and Saturn are Failed Stars

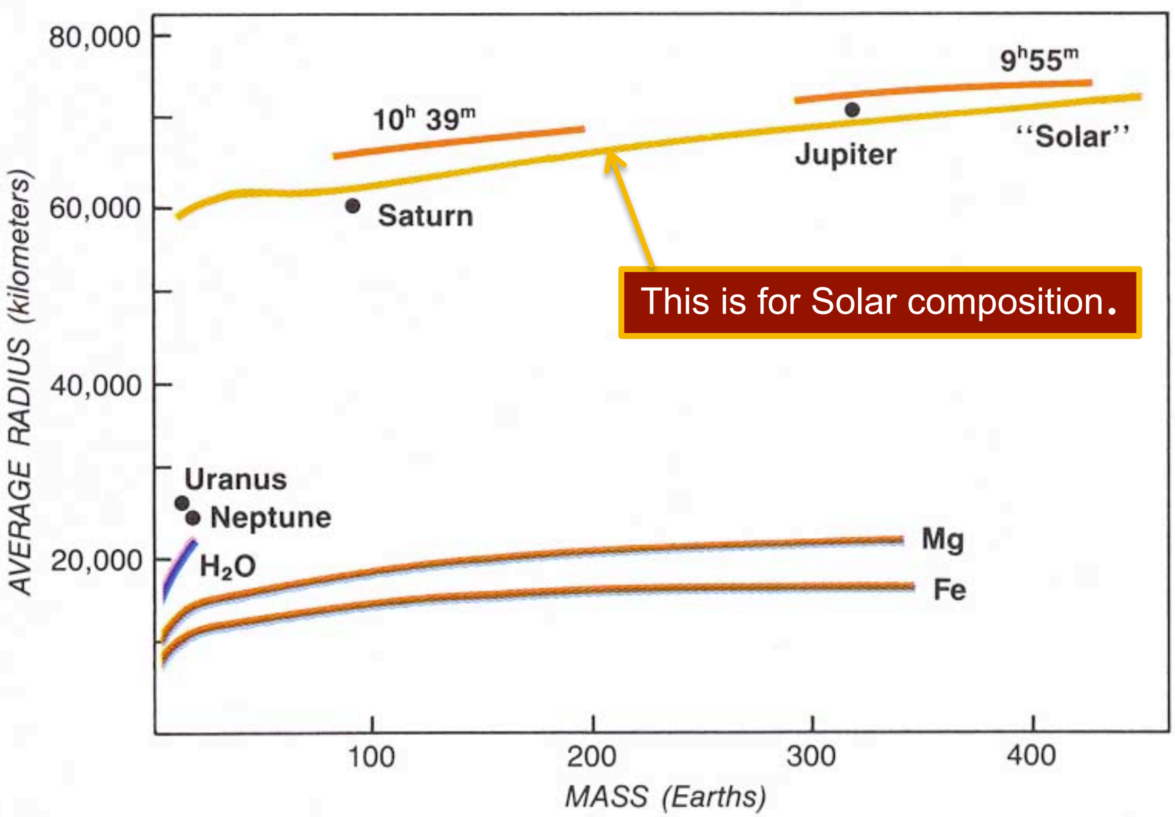


Figure 3. Theorists can calculate just how big Jovian planets would be assuming various masses and possible compositions. The longest curve is the radius-mass relation predicted for a liquid body of solar composition with its interior in equilibrium. The short arcs, labeled with the rotation periods of Jupiter and Saturn, show how much spinning planets having this composition would be flattened at their equators by centrifugal force. At the bottom are curves for pure magnesium and iron ("terrestrial") planets, as well as a curve for liquid water based on its experimentally determined characteristics under pressure. Dots show the actual values for the four giant planets.

Jupiter and Saturn are Failed Stars

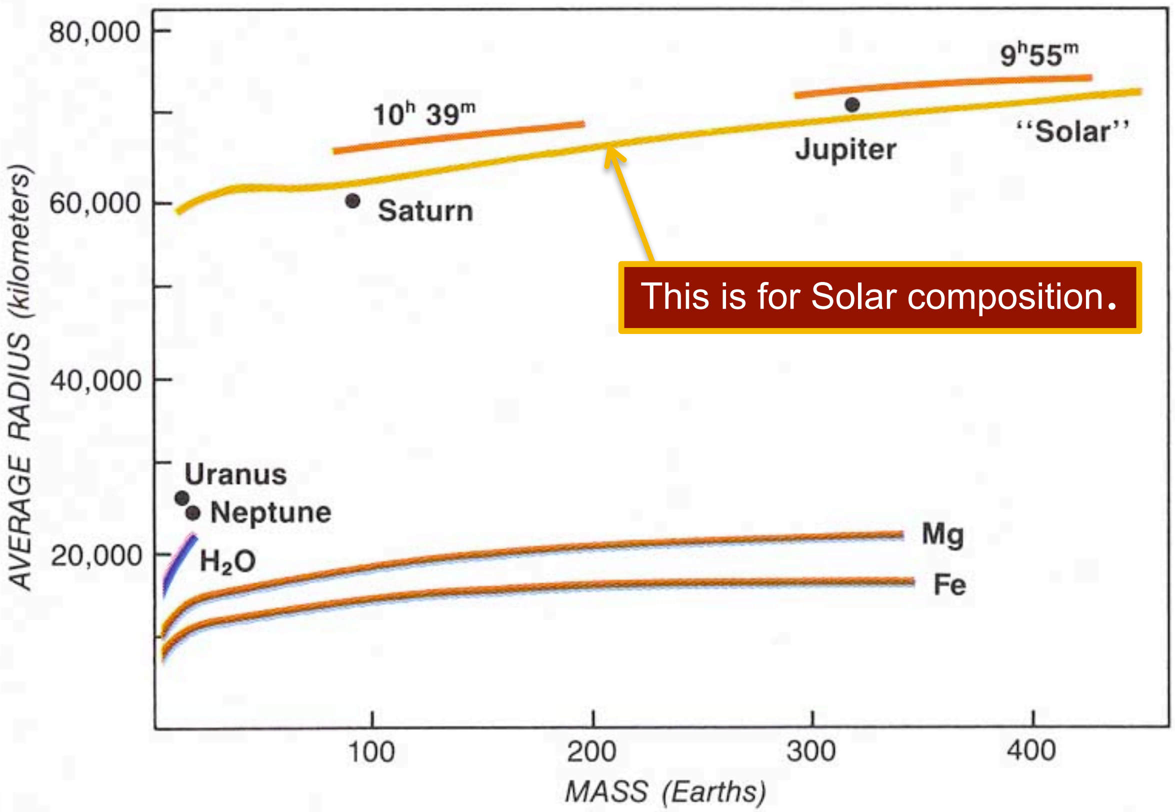


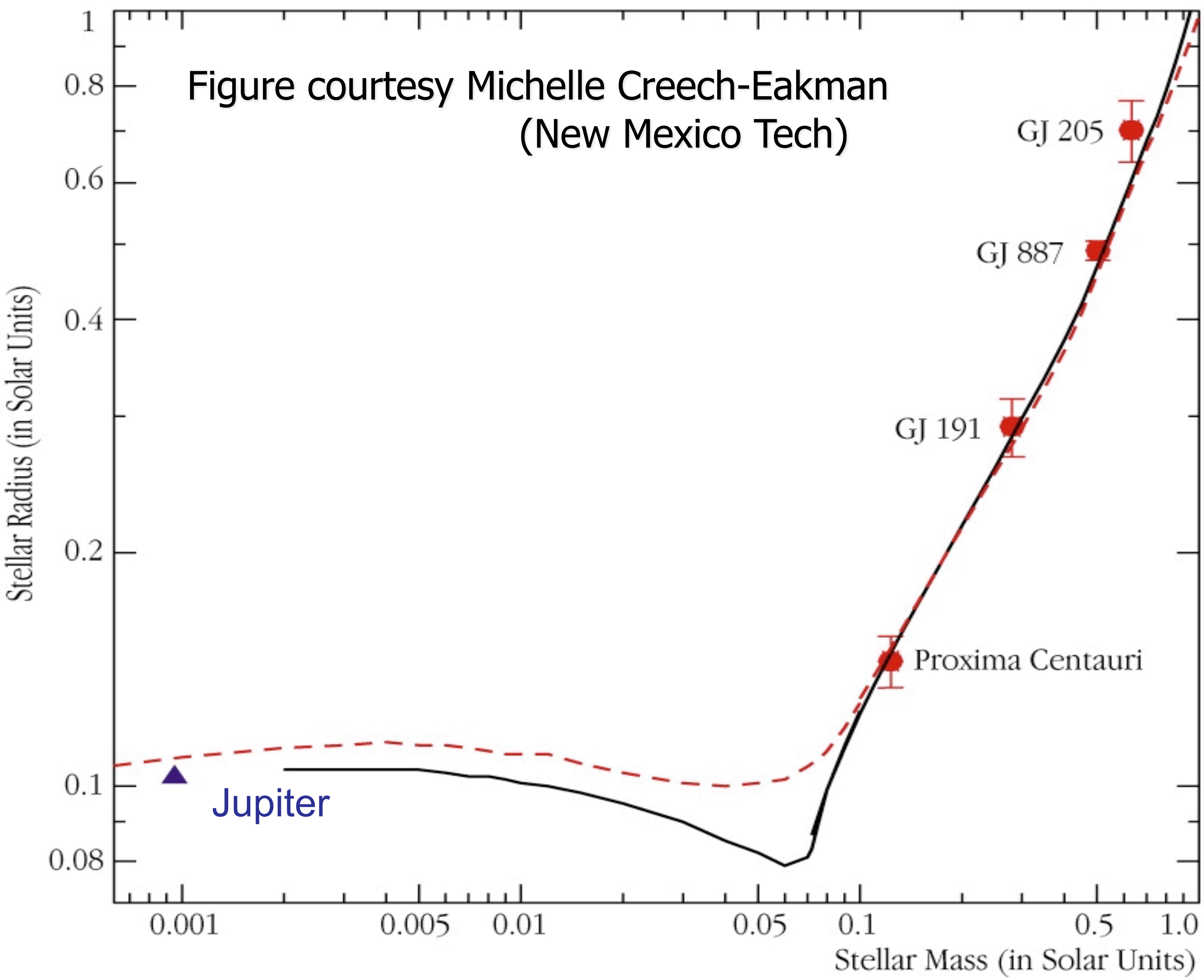
Figure 3. Theorists can calculate just how big Jovian planets would be assuming various masses and possible compositions. The longest curve is the radius-mass relation predicted for a liquid body of solar composition with its interior in equilibrium. The short arcs, labeled with the rotation periods of Jupiter and Saturn, show how much spinning planets having this composition would be flattened at their equators by centrifugal force. At the bottom are curves for pure magnesium and iron ("terrestrial") planets, as well as a curve for liquid water based on its experimentally determined characteristics under pressure. Dots show the actual values for the four giant planets.

The biggest "cold" possible planet is about 80,000 km in radius and has mass ≈ 3 M_J .

Still more massive planets are more compressed and therefore smaller.

At about 80 M_J , nuclear reactions become possible and we get stars.

When the mass is big enough so that nuclear reactions are possible, then we have a dwarf star, not a planet. Then the radius increases rapidly as mass increases, because faster nuclear reactions ⇒ the stars are hotter.



The biggest "cold" possible planet is about 80,000 km in radius and has mass ≈ 3 M_J .

Still more massive planets are more compressed and therefore smaller.

At about 80 M_J , nuclear reactions become possible and we get stars.

Failed Stars Have Internal Heat

Jupiter gives off several times as much heat as it gets from the Sun. It does not have enough radioactive rock to explain the heat that it emits.

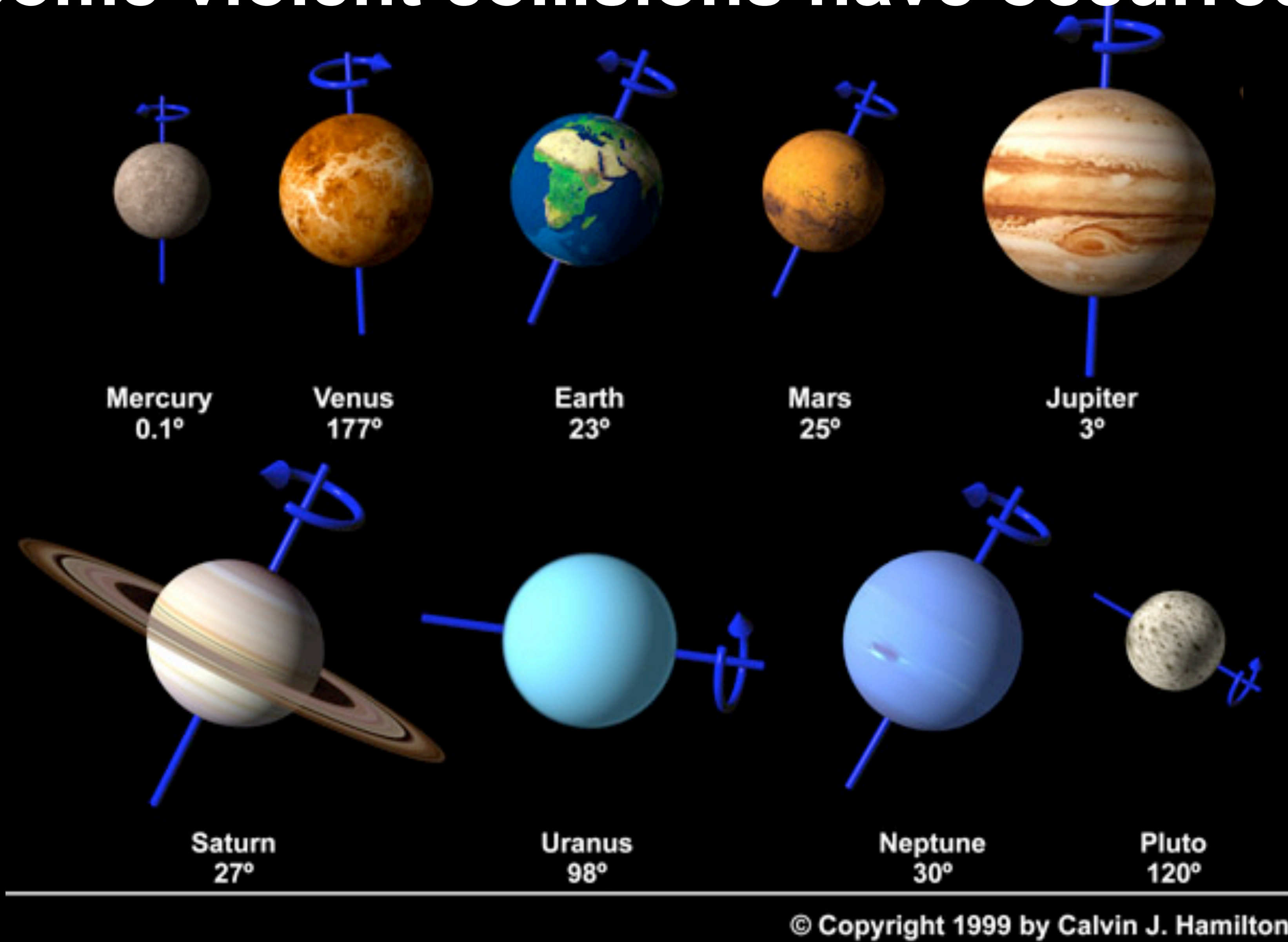
Residual Heat

Planets like Jupiter form by the infall of gas onto a dense central core. Like a meteor striking the Earth, this infalling gas gets very hot when it hits. Thiat heat is still escaping from Jupiter.

Magnetic Fields

As a result of rapid rotation, convection, and electrically conducting, metallic interiors, Jupiter and Saturn have magnetic fields. Jupiter's magnetic field is 13 times stronger than Earth's. Saturn's field is a little weaker than the Earth's.

The tilts of planetary axes show that some violent collisions have occurred.



Summary of Important Features of the Jovian Planets

Jupiter and Saturn are failed stars. They have the same composition as the Sun but are not massive enough for the nuclear reactions that power stars. However, they shone like faint stars for a few hundred million years while they were forming, radiating away the excess energy from their gravitational collapse. Jupiter has about 1/80th of the mass of the tiniest successful stars.

Jupiter is almost the largest planet possible. Its radius = 71,400 km. A planet that is three times more massive would have the largest possible radius = 80,000 km. Still more massive planets compress more, so they are smaller. We know that such planets exist in other Solar Systems.

Jupiter has 2/3 of the mass of the Solar System that is not in the Sun.

Saturn is less massive, so it is less compressed. On average, it is less dense than water.

Jupiter, Saturn, and Neptune radiate 2 — 3 times as much energy as they get from the Sun. Much of the energy comes from slow contraction. This is the last remnant of planet formation.

None of the giant planets has a surface. The gas just gets gradually denser toward the center until it behaves like a liquid. Jupiter and Saturn get so dense that much of the hydrogen is a liquid metal.

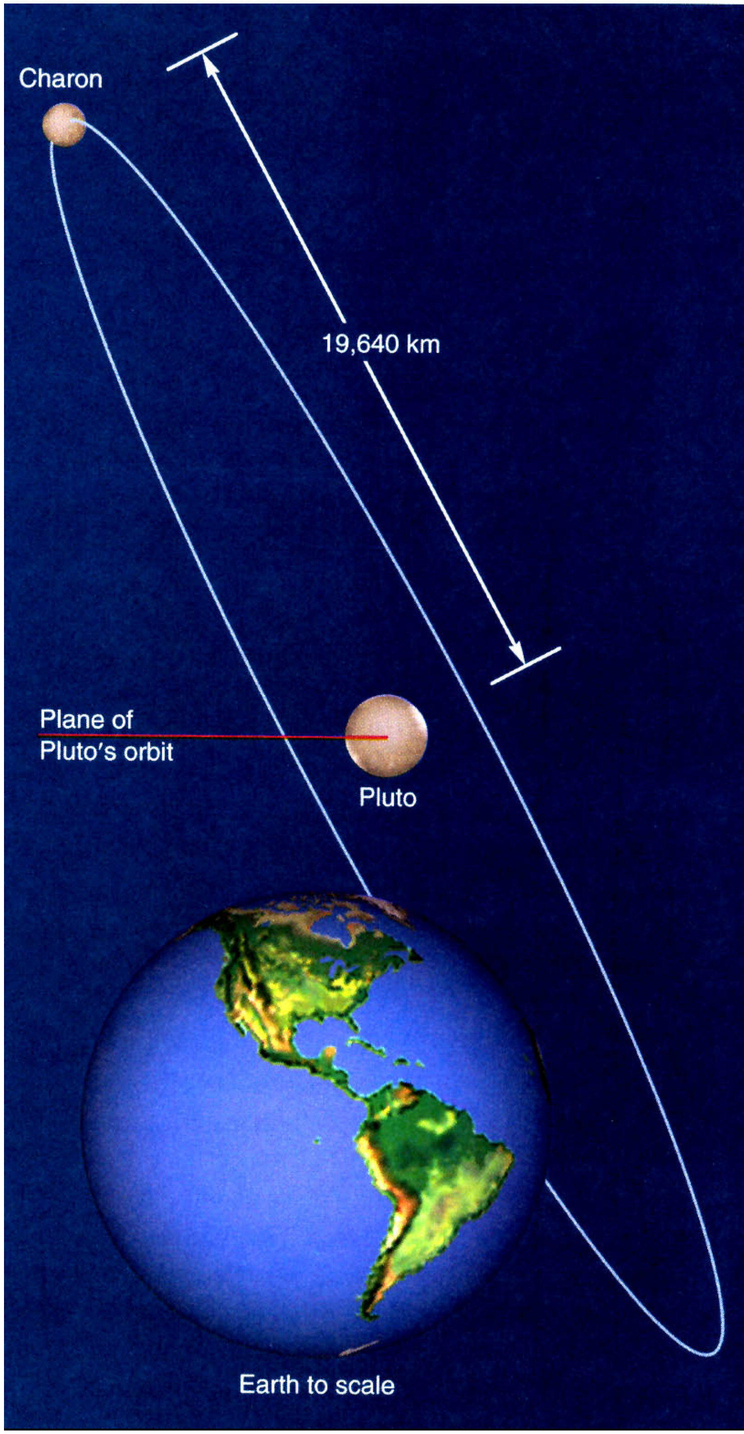
The visible atmospheres of the giant planets contain trace amounts of ammonia (NH_3) and methane (CH_4). More complicated molecules like ammonium hydrosulfide produce the reddish-brown clouds. Uranus and Neptune look blue because methane clouds dominate at low temperatures. Methane absorbs red sunlight.

Summary of Important Features of the Jovian Planets

The atmospheres convect; this carries internal heat outward. Rapid rotation organizes the convection into bands parallel to the equator. Dark “belts” are low-pressure regions of falling gas; light “zones” are high-pressure regions of rising gas. Zones and belts rotate at different rates. On Jupiter, the windshear between them is about 125 m/s or about 450 km/h. On Saturn, it is four times larger (we don't know why).

Oval storms lasting many months to many decades are common, especially on Jupiter and Neptune. The best known is the Red Spot of Jupiter, which has lasted for at least 300 years. It is typically about twice the diameter of the Earth. The Red Spot is a high-pressure hurricane “rolling” between a zone and a belt. It rotates once in 6 days. It feeds off of windshear, so it is a fundamental consequence of differential rotation and convective heat flow. The red spot also feeds on smaller storms. A similar dark spot (about the size of the Earth) was the main storm system on Neptune in 1989 but has since disappeared. Saturn and Uranus have fewer storms, although storms are now happen in the Southern Hemisphere of Uranus as the spring season advances into summer.

Uranus’s rotation axis is tipped 98º to its orbital plane. The poles are almost in the orbit plane. In 1985, the north pole pointed almost at the Sun; independent of the planet’s rotation, it then experienced perpetual daylight and the south pole was in perpetual darkness. In 2006, the Sun is in the equatorial plane and the planet has solar days that are about 17 hours long. In 2027, the south pole will point at the Sun and be in perpetual daylight. So the seasons are strange. The reason for the unusual inclination is probably a violent collision with another protoplanet.



Pluto and Charon

Maximum distance from Sun	49.24 AU
Minimum distance from Sun	29.64 AU
Eccentricity of orbit	0.25
Orbital period	248 years
Pluto mass	$0.002\ M_{Earth}$
Pluto diameter	2374 km
Charon diameter	1212 km
Charon orbital radius	19,640 km
Charon orbital period	6.4 days
Surface temperature	-230^{o} C = -382^{o} F

Pluto was discovered in 1930 by Clyde Tombaugh.

LOWELL OBSERVATORY

Observation Circular

THE DISCOVERY OF A SOLAR SYSTEM BODY APPARENTLY TRANS-NEPTUNIAN

The message sent last night (March 12) to Harvard Observatory for distribution to astronomers read as follows:

> "Systematic search begun years ago supplementing Lowell's investigations for TransNeptunian planet has revealed object which since seven weeks has in rate of motion and path consistently conformed to Trans-Neptunian body at approximate distance he assigned. Fifteenth magnitude. Position March twelve days three hours GMT was seven seconds of time West from Delta Geminorum, agreeing with Lowell's predicted longitude."

(For ease in finding object was referred to Delta Geminorum. Position March 12.14 G.M.T. R.A. $7^h\ 15^m\ 50^s$ Dec. 22° 6′ 49″)

The finding of this object was a direct result of the search program set going in 1905 by Dr. Lowell in connection with his theoretical work on the dynamical evidence of a planet beyond Neptune. (See L. O. Memoirs, Vol. I, No. 1, "A Trans-Neptunian Planet," 1914). The earlier searching work, laborious and uncertain because of the less efficient instrumental means, could be resumed much more effectively early last year with the very efficient new Lawrence Lowell telescope specially designed for this particular problem. Some weeks ago, on plates he made with this instrument, Mr. C. W. Tombaugh, assistant on the staff, using the Blink Comparator, found a very exceptional object, which since has been studied carefully. It has been photographed regularly by Astronomer Lampland with the 42-inch reflector, and also observed visually by Astronomer E. C. Slipher and the writer with the large refractor.

The new object was first recorded on the search plates of January 21 (1930), 23rd, and 29th, and since February 19 it has been followed closely. Besides the numerous plates of it with the new photographic telescope, the object has been recorded on more than a score of plates with the large reflector, by Lampland, who is measuring both series of plates for positions of the object. Its rate of motion he has measured for the available material at intervals between observations with results that appear to place the object outside Neptune's orbit at an indicated distance of about 40 to 43 astronomical units. [redacted] per day. In its apparent path and in its rate of motion it conforms closely to the expected behavior of a Trans-Neptunian body, at about Lowell's predicted distance. There has not been opportunity yet to complete measurements and accurate reductions of positions of the object requi-

Pluto and Charon

Charon was discovered in 1978. It is bigger, compared to Pluto, than is any satellite compared to its planet.

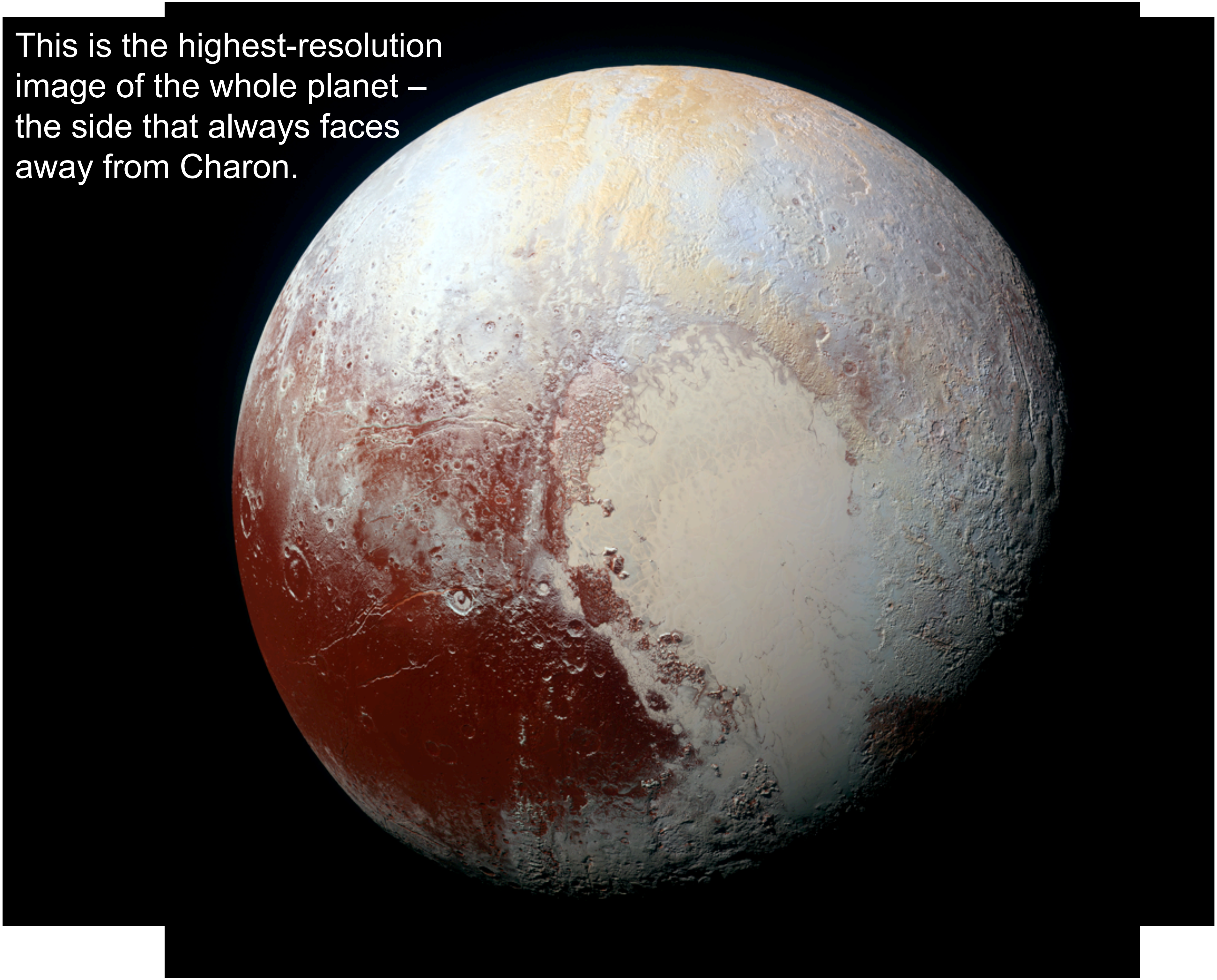
Pluto is only 0.1 arcsec in diameter as seen from the Earth. Pluto and Charon were visited by the NASA New Horizons spacecraft in July 2015, so we know a lot more about it now than we did just a few years ago!

Pluto and Charon are thought to be made mostly of ice plus a little rock, based on their densities. At -382^{o} F, water ice is as strong as steel.

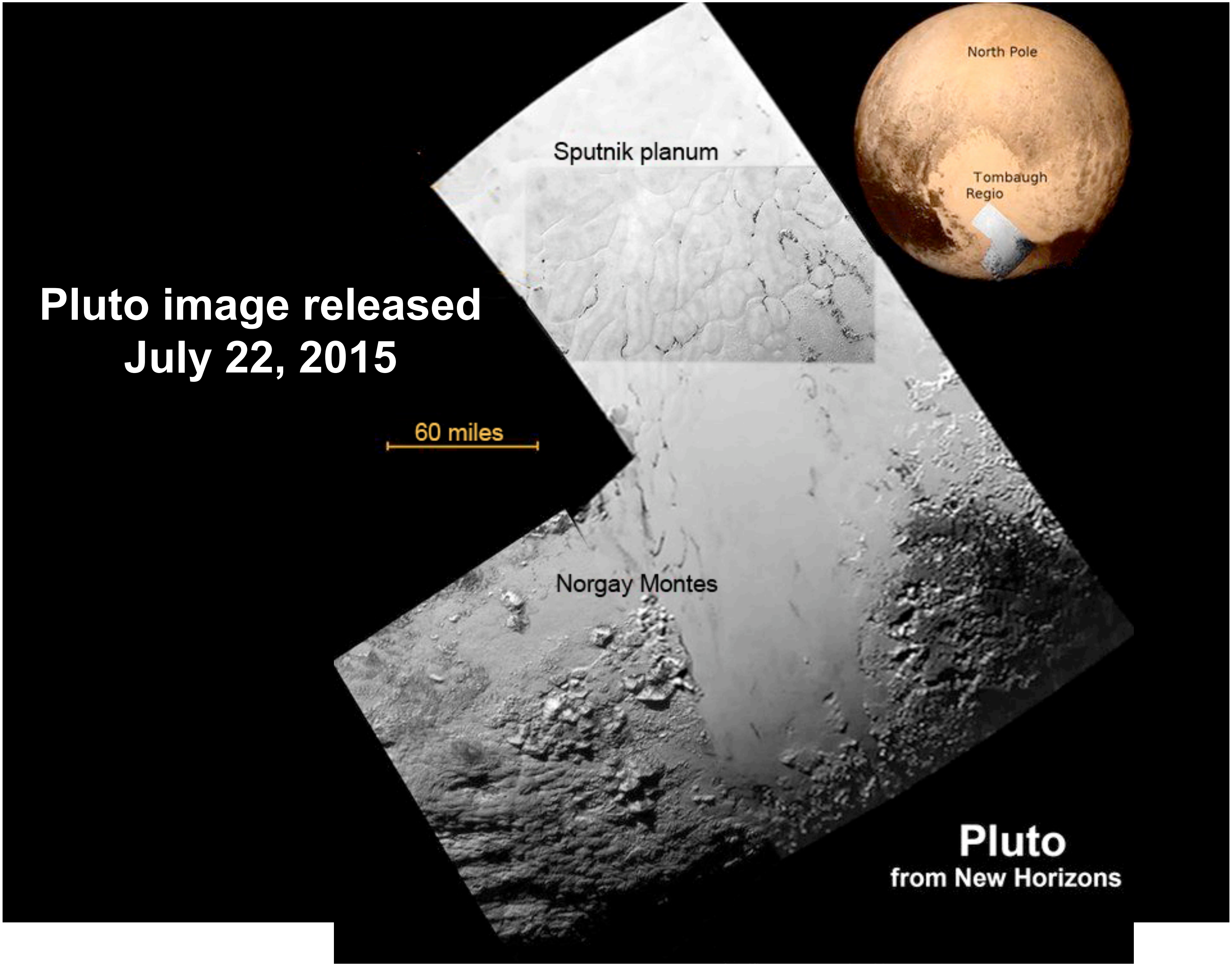
For a planet, Pluto is tiny. It is the 16th largest body in the Solar System, smaller than many satellites and less than 2.5 times bigger than the biggest asteroid.

New Horizons shows that Pluto has a mostly water and methane ice surface with very few craters. If the surface is only a few hundred million years old, there may be subsurface liquid water and water volcanoes.

Could there be life in an ocean under the frozen surface?

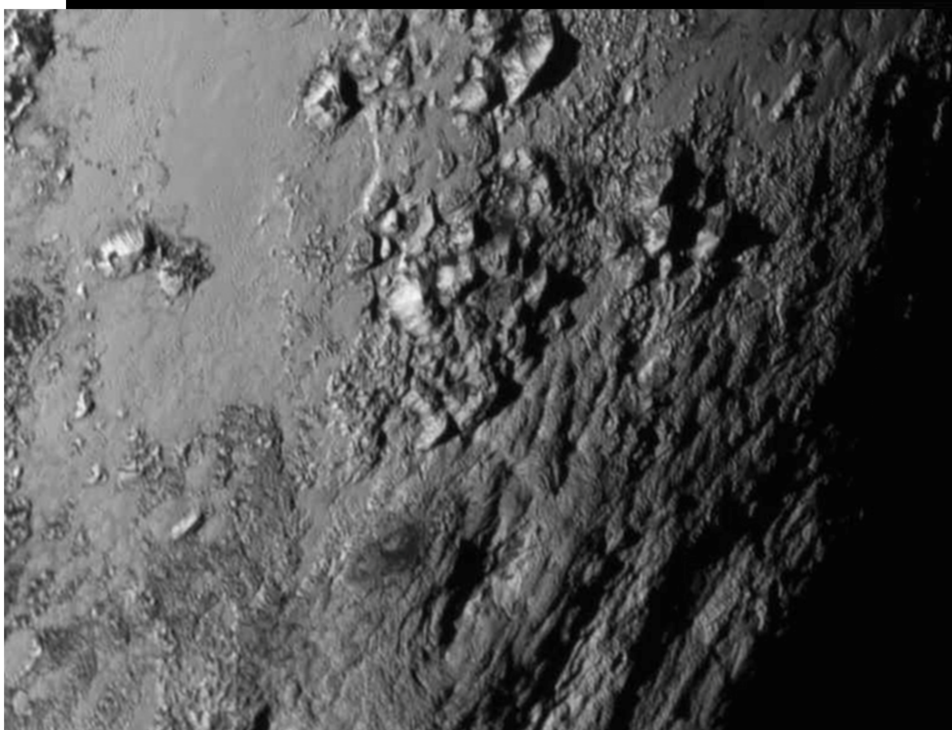


This is the highest-resolution image of the whole planet – the side that always faces away from Charon.


Pluto image released
July 22, 2015
Sputnik planum
North Pole
Tombaugh
Regio
60 miles
Norgay Montes
Pluto
from New Horizons

Pluto has a young, water ice surface with few craters.

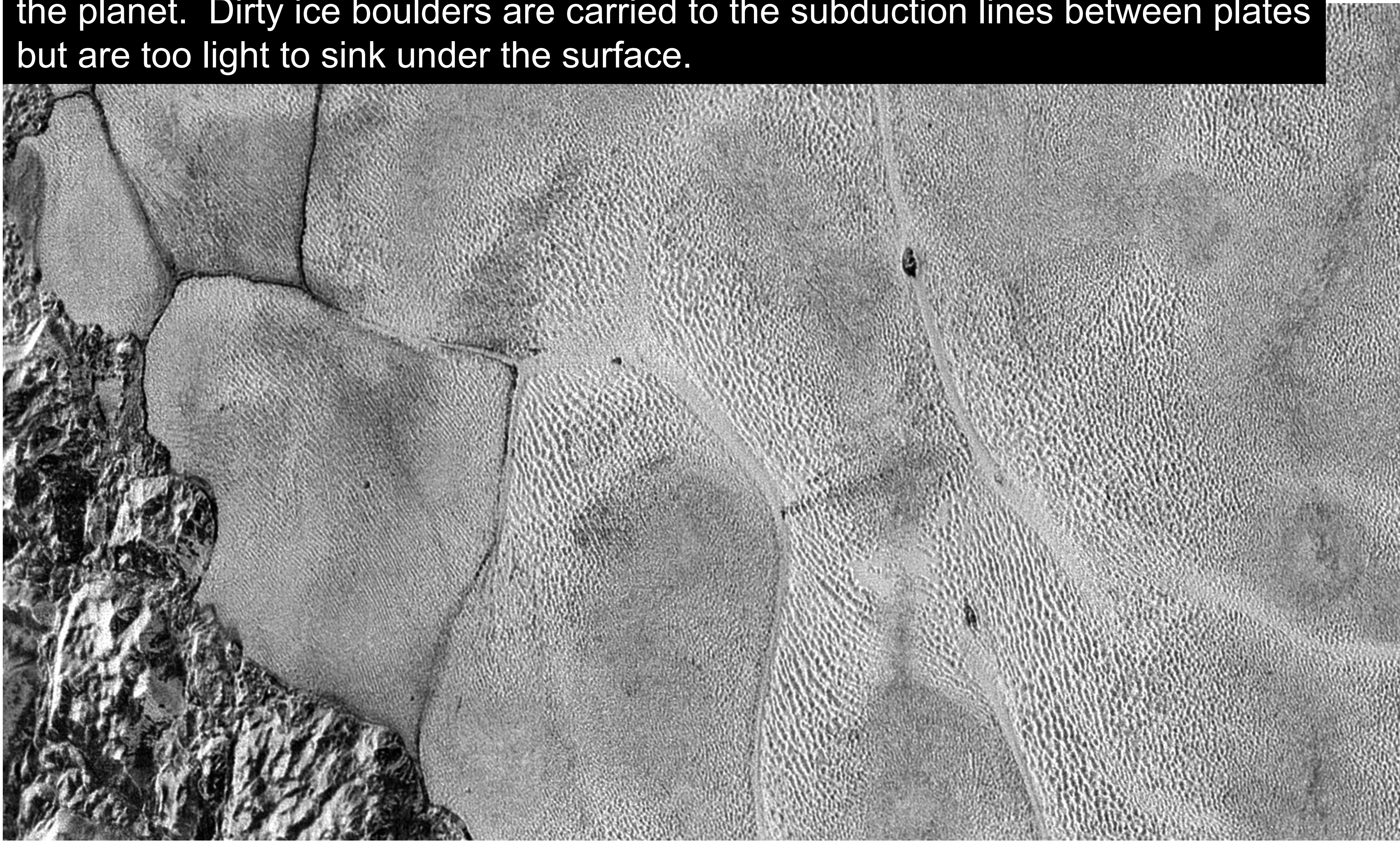
Could there be a liquid ocean under the frozen surface?



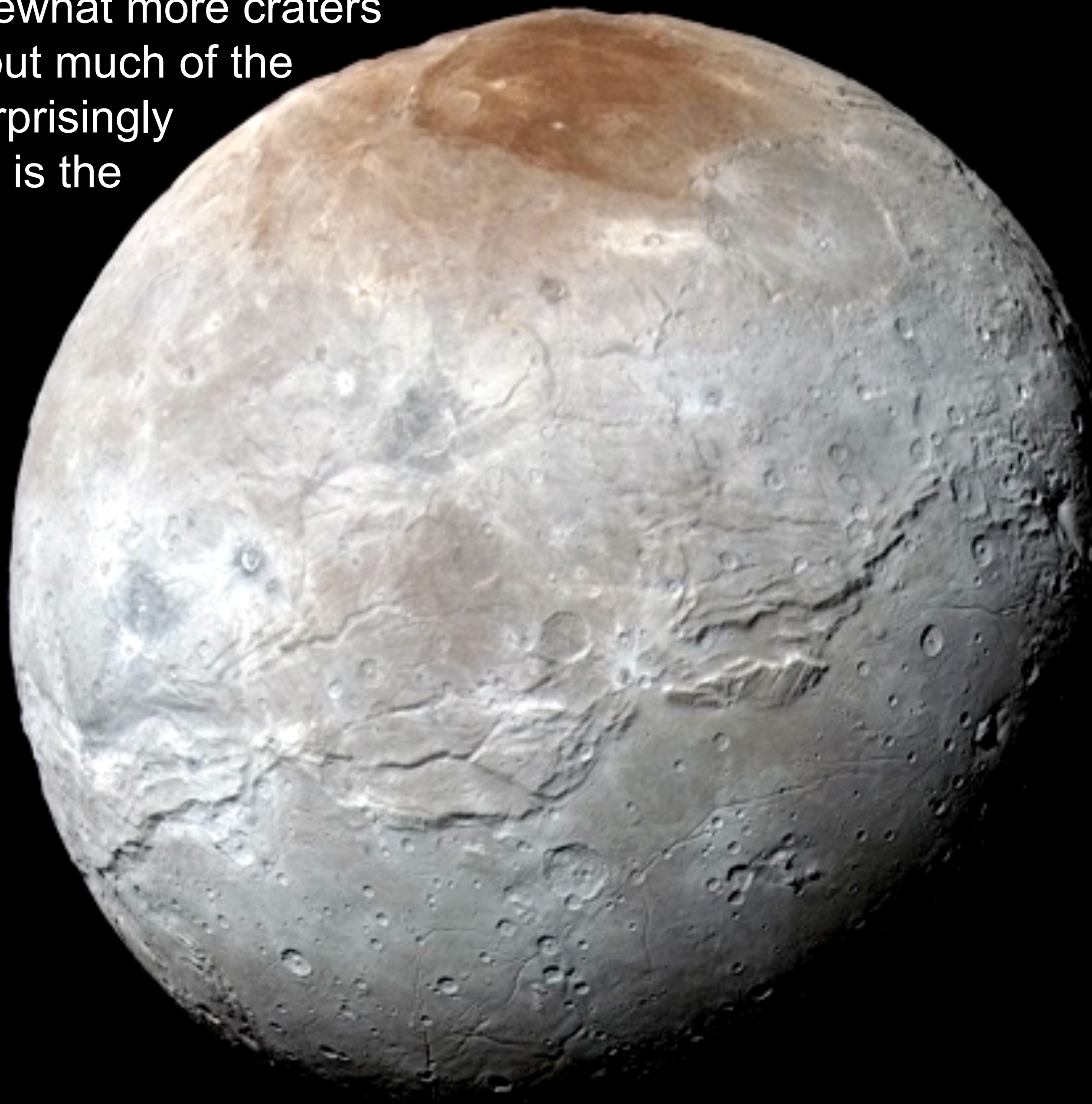
Water ice mountains as tall as the Rockies

Craterless plains must be young.

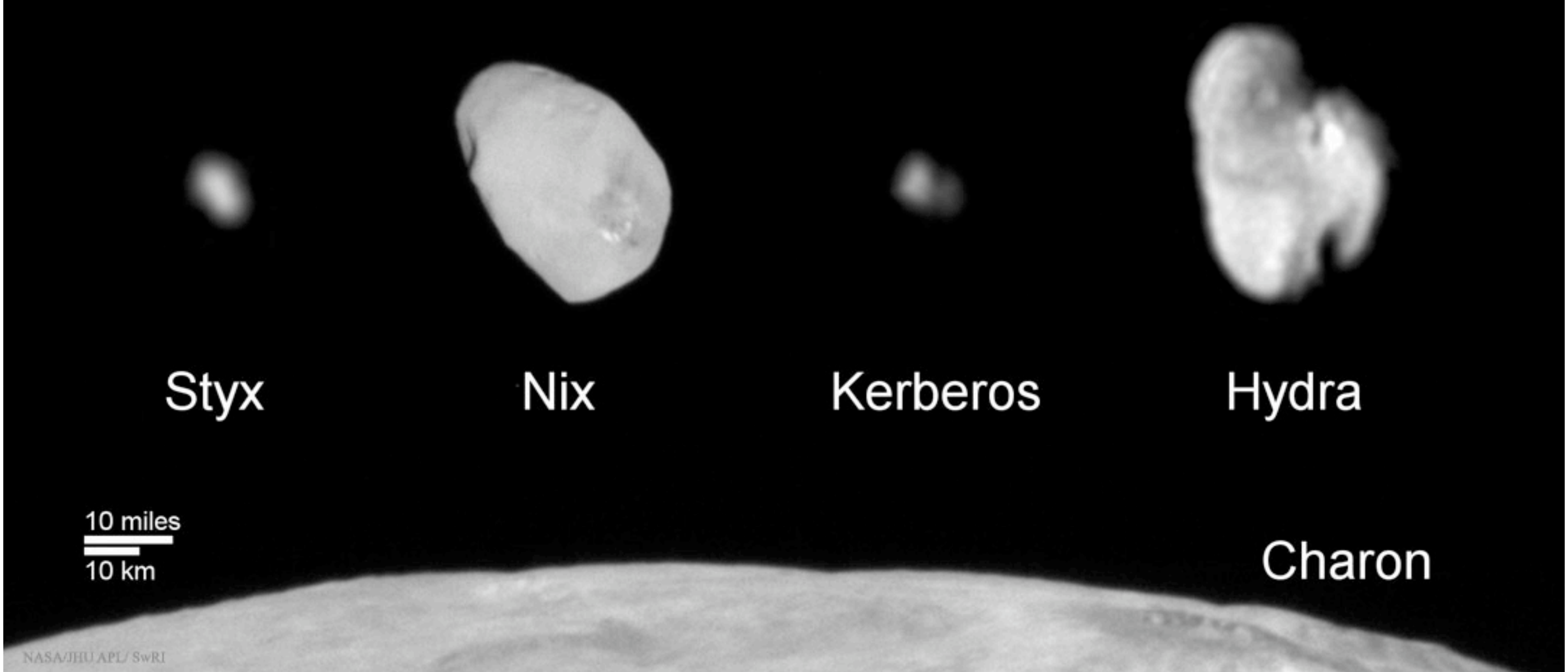
High-resolution image: 1 pixel = 250 feet. The image is about 50 miles high. It shows a boundary between mountains and Sputnik Planum, a nitrogen ice plain marked by polygonal areas of (we think) convection as internal heat flows out of the planet. Dirty ice boulders are carried to the subduction lines between plates but are too light to sink under the surface.



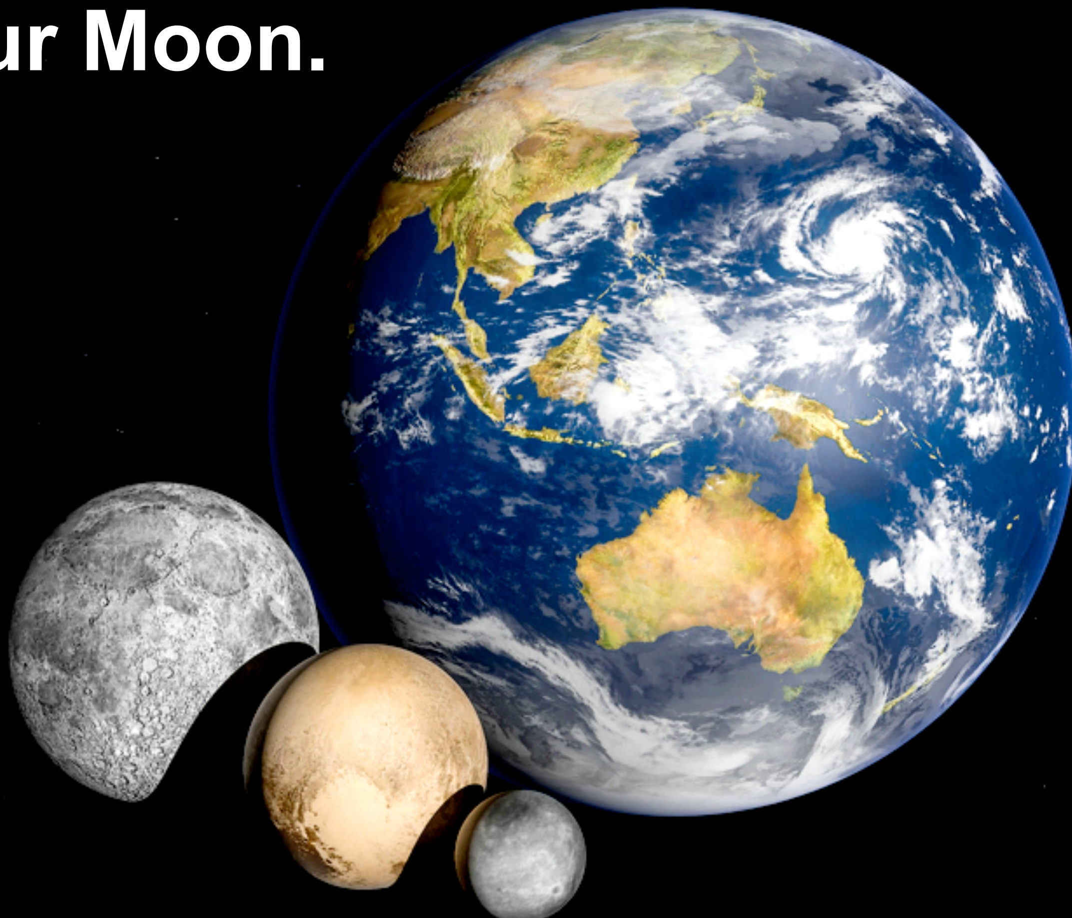
Charon has somewhat more craters and global rifts, but much of the surface is still surprisingly smooth ice. This is the side that always faces Pluto.



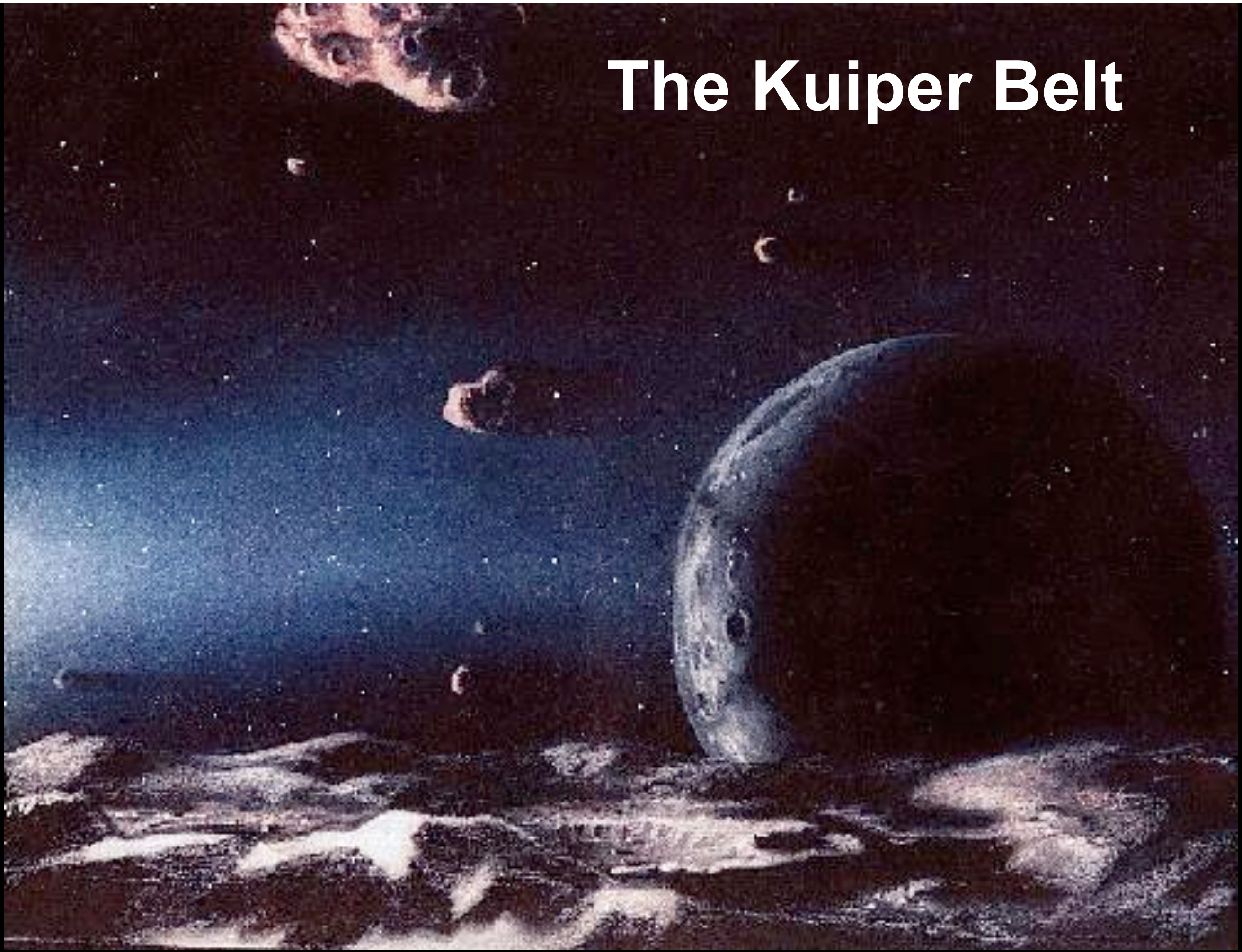
Charon and the Small Moons of Pluto



Pluto and Charon are small: Pluto's mass is only 18 % of the mass of our Moon.



Recent work shows that Pluto should **<u>not</u>** be thought of as a planet.
Instead, it is the second-largest object known so far
in the Kuiper Belt of icy planetesimals and comets.

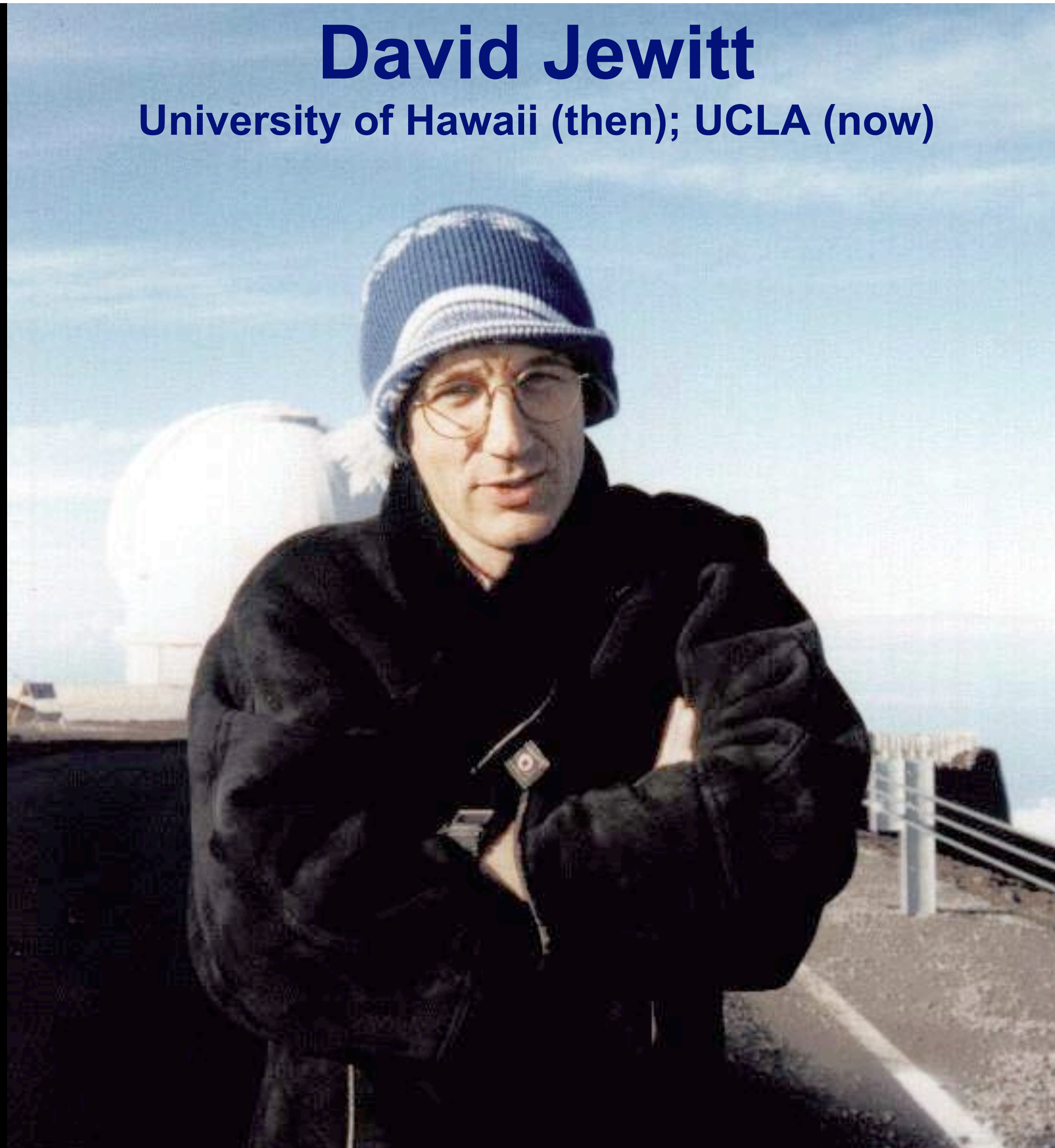


Starting in 1992, astronomers discovered a vast population of small bodies that orbit the Sun beyond Neptune. At least 70,000 have diameters larger than 100 km. They extend outward from ~30 AU to ~50 AU. Most are in a thick band around the ecliptic — a ring called the “Kuiper Belt”.

<u>The Kuiper Belt is important for two reasons.</u> <u>1 – Kuiper Belt objects are primitive icy remnants from the early Solar System.</u> The inner parts of the pre-planetary disk condensed into the major planets in a few million to tens of millions of years. The outer parts were less dense. Accretion was much slower – it is in fact not finished. 2 – <u>The Kuiper Belt is the source of short-period comets.</u> It is a reservoir for these comets in the same way that the Oort Cloud is a reservoir for long-period comets. *David Jewitt*

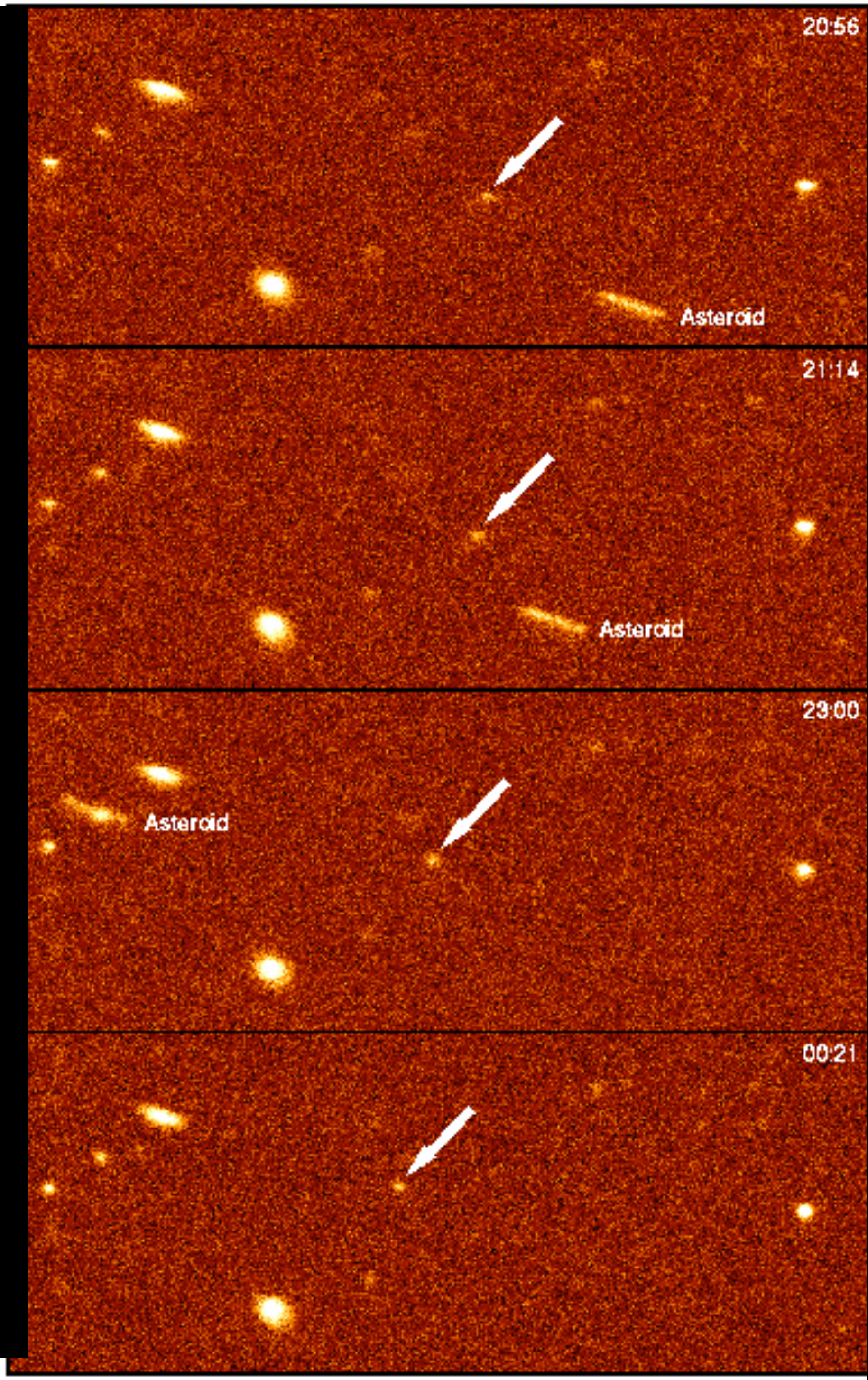
David Jewitt

University of Hawaii (then); UCLA (now)



Discovery of the first Kuiper Belt Object:

1992QB1



IAU Circular 5611
(1992 Sept. 14)

David Jewitt, University of Hawaii and Jane Luu, University of California at Berkeley, report the discovery of a very faint object with very slow (3” / hour) retrograde near-opposition motion, detected in CCD images obtained with the University of Hawaii 2.2-m telescope on Mauna Kea.

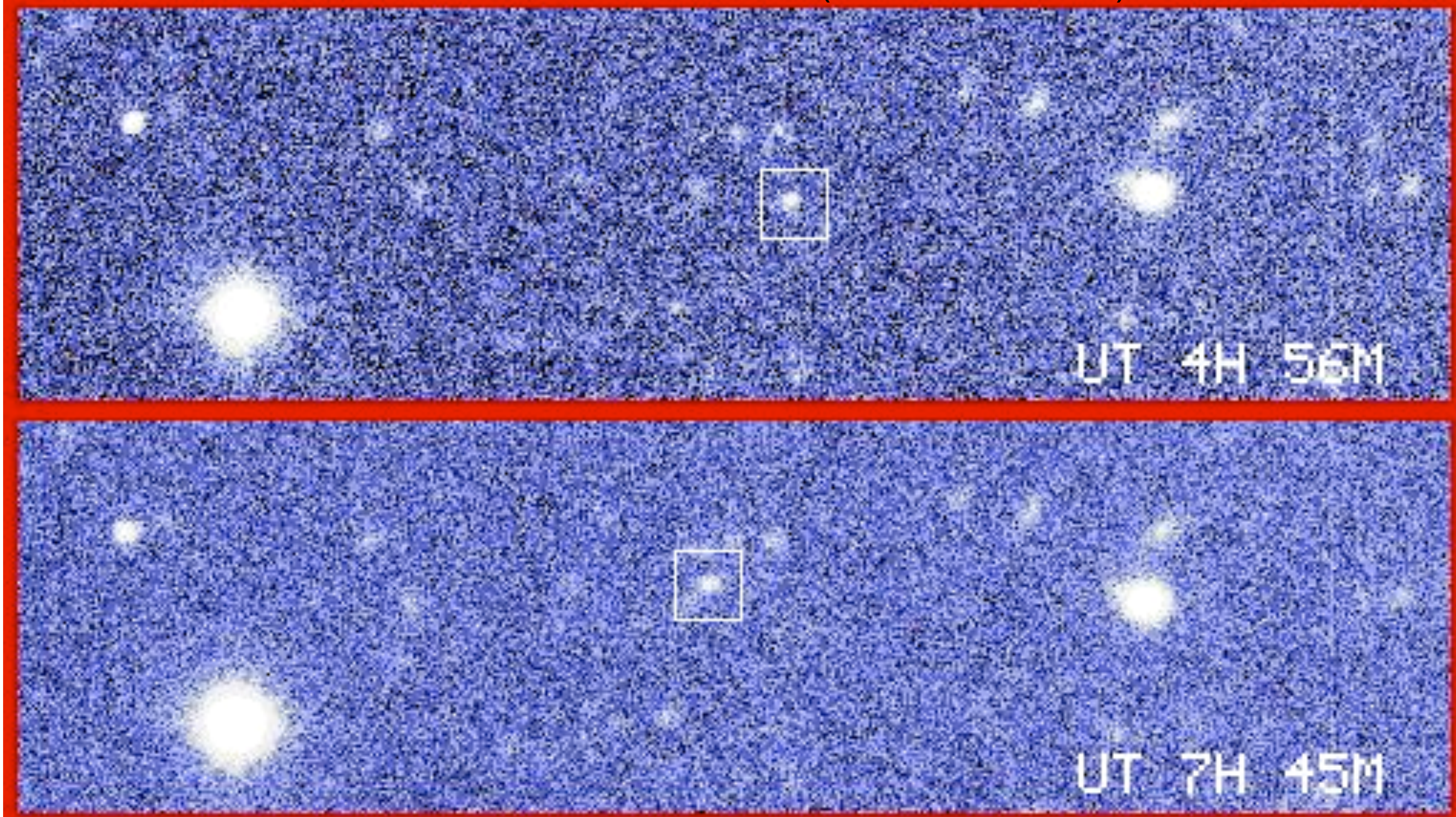
Kuiper Belt Object 1995-QX9

Discovery images with UH 88” telescope, 1995, Oct. 26

This is the 29th Kuiper Belt object discovered.

Diameter ~ 270 km

Orbital radius ~ 39.39 AU (Pluto: 39.44 AU)



Plutinos

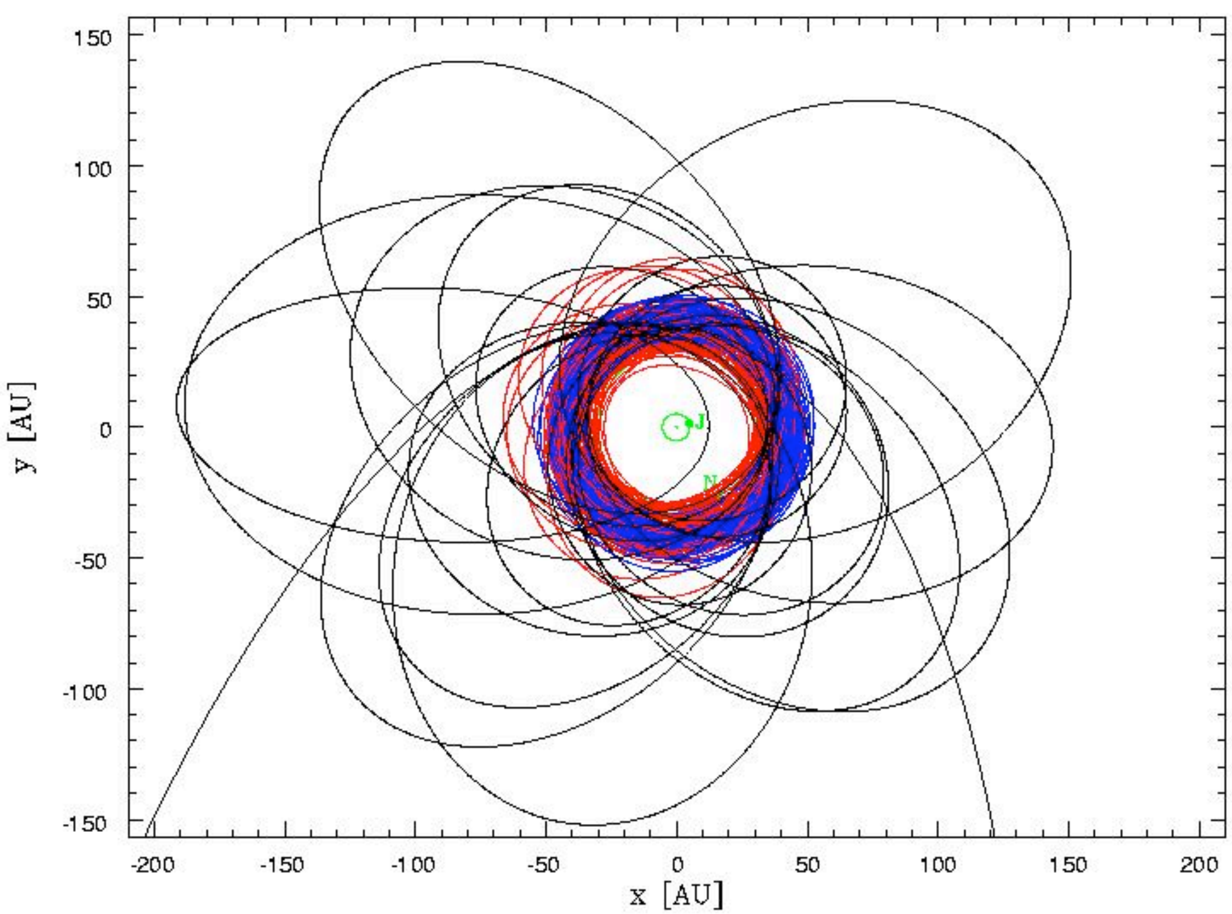
Surprisingly, many Kuiper belt objects are in 3:2 resonance with Neptune: They make 2 orbits around the Sun while Neptune makes 3 orbits. Pluto is in the same resonance. These objects are called “Plutinos” (“little Plutos”). It is sensible to think of Pluto as the biggest Plutino, not than the smallest planet.

The 3:2 resonance stabilizes Plutinos against gravitational perturbations by Neptune. Resonant objects approach the orbit of Neptune without ever coming close to it. Pluto's orbit crosses inside that of Neptune, but Pluto never comes near Neptune.

About 35% of the trans-Neptunian objects are Plutinos. A few more are in other resonances. Jewitt and Luu estimate that there are ~ 25,000 Plutinos larger than 100 km diameter. Pluto is distinguished from other Plutinos only because it is bigger: it is 2374 km in diameter. Even Charon, is 1212 km in diameter. Quaoar (discovered 2002) is 1200 km in diameter. Ixion is 1065 km in diameter.

Why is the 3:2 resonance so full? We believe that, via angular momentum exchanges, the planets migrated in radius from the Sun. Neptune moved outward, and so its resonances pushed the surrounding planetesimal disk outward and swept up objects like a snow plough sweeps up snow.

The Outer Solar System

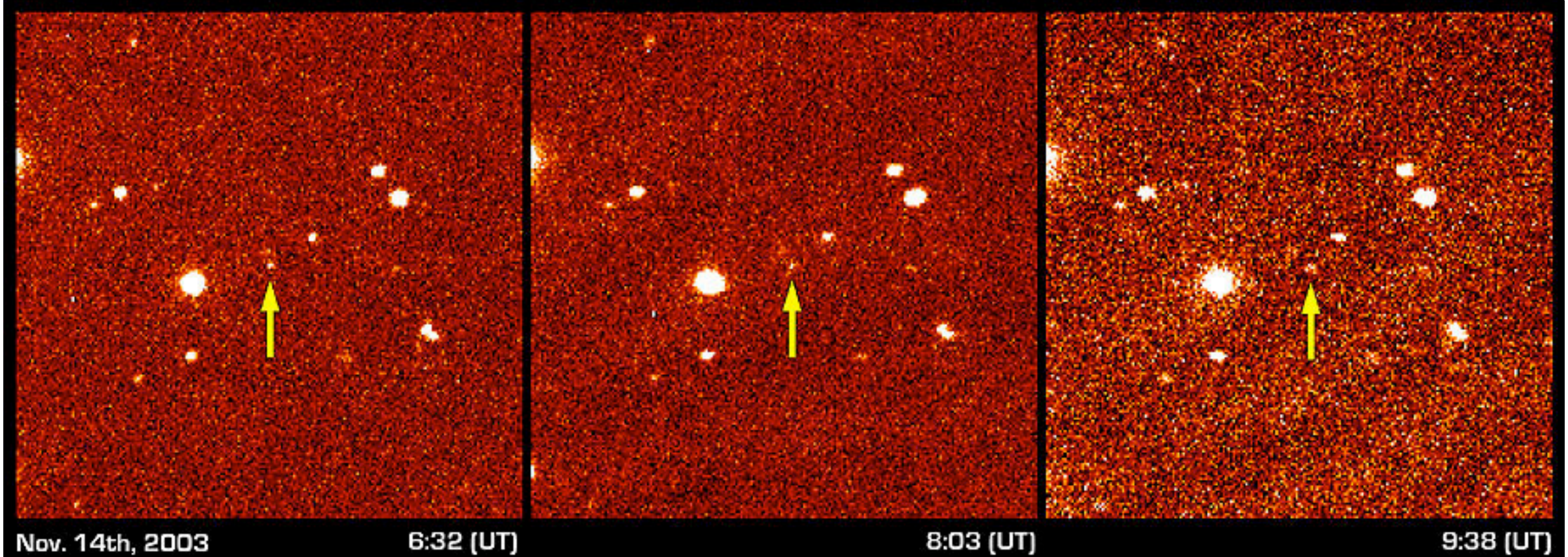


Main Kuiper belt objects are shown in blue. “Scattered-disk objects” are shown with black orbits. Astronomers think that they have been scattered to these large radii by encounters with Neptune. If this is true, then they are examples of planetesimals that were almost ejected from the Solar System.

Jewitt, Luu, and others continue to push the frontiers of knowledge of the Solar System further out from the Sun.

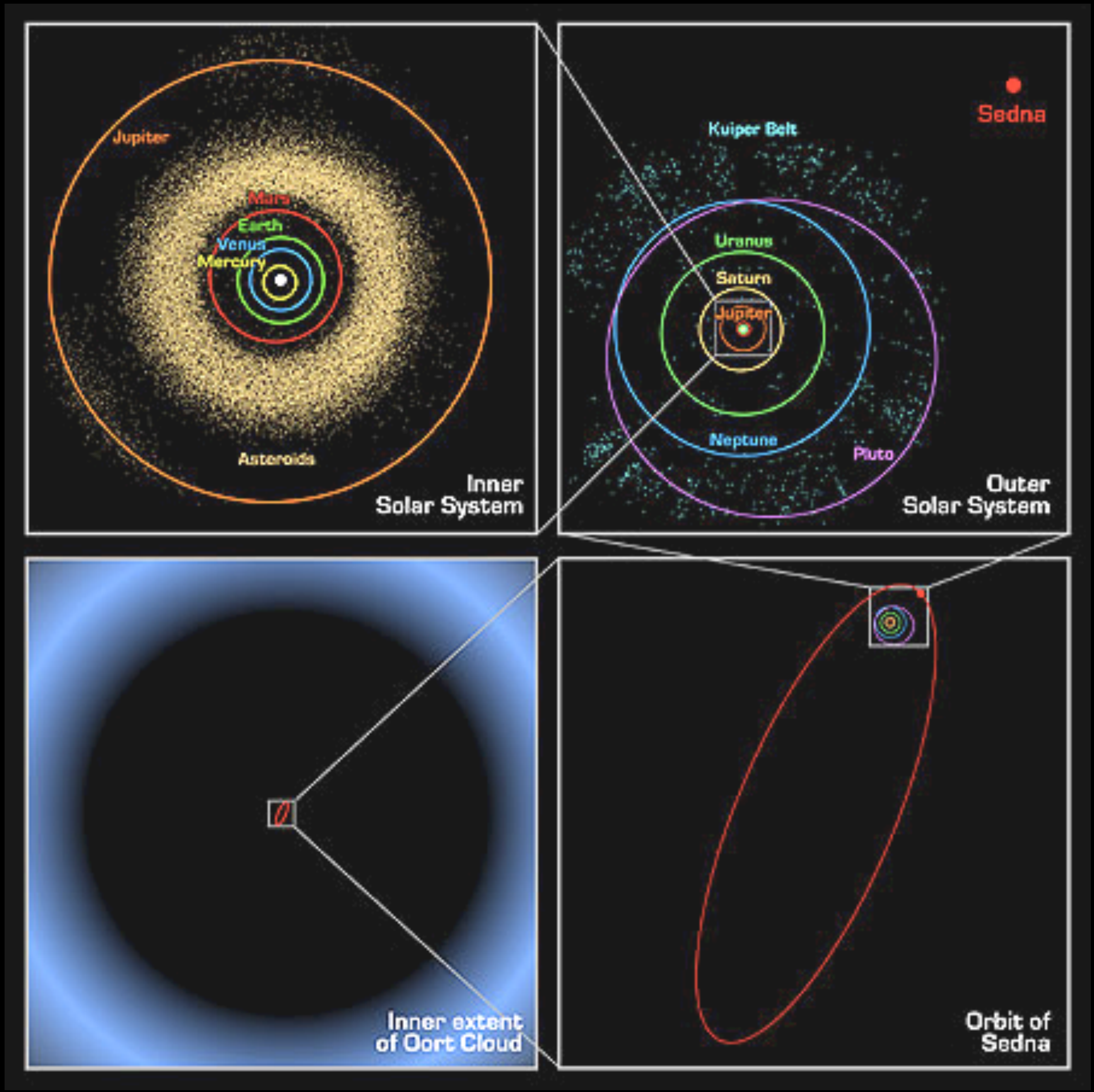
Sedna

http://www.spitzer.caltech.edu/Media/releases/ssc2004-05/release.shtml



The second-most distant known object in the Solar System and one of the biggest far from the Sun, is Sedna. It was discovered in 2003 by Mike Brown (Caltech), Chad Trujillo (Gemini Observatory, Hawaii), and David Rabinowitz (Yale). It may be a scattered Kuiper belt object.

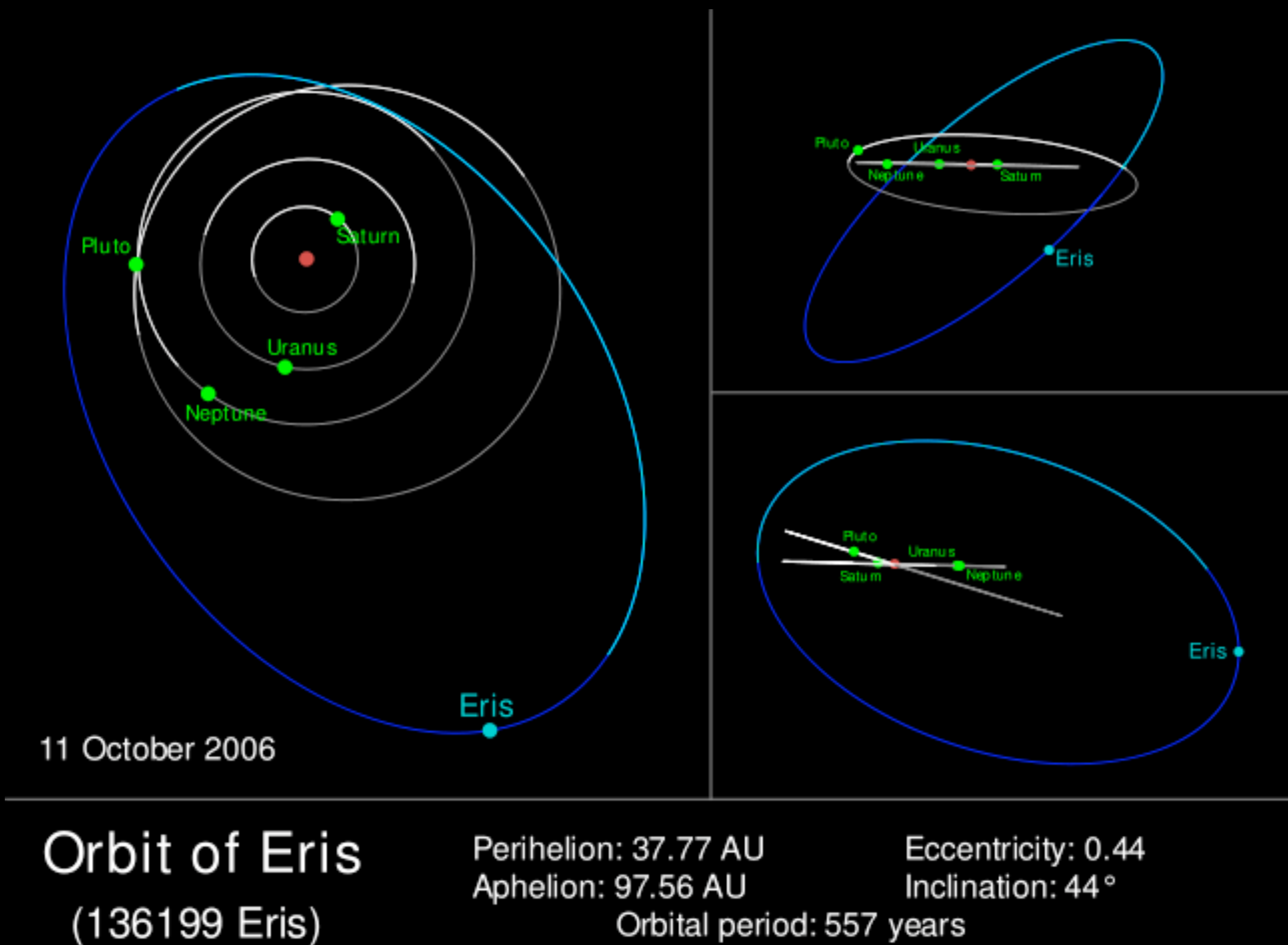
Sedna

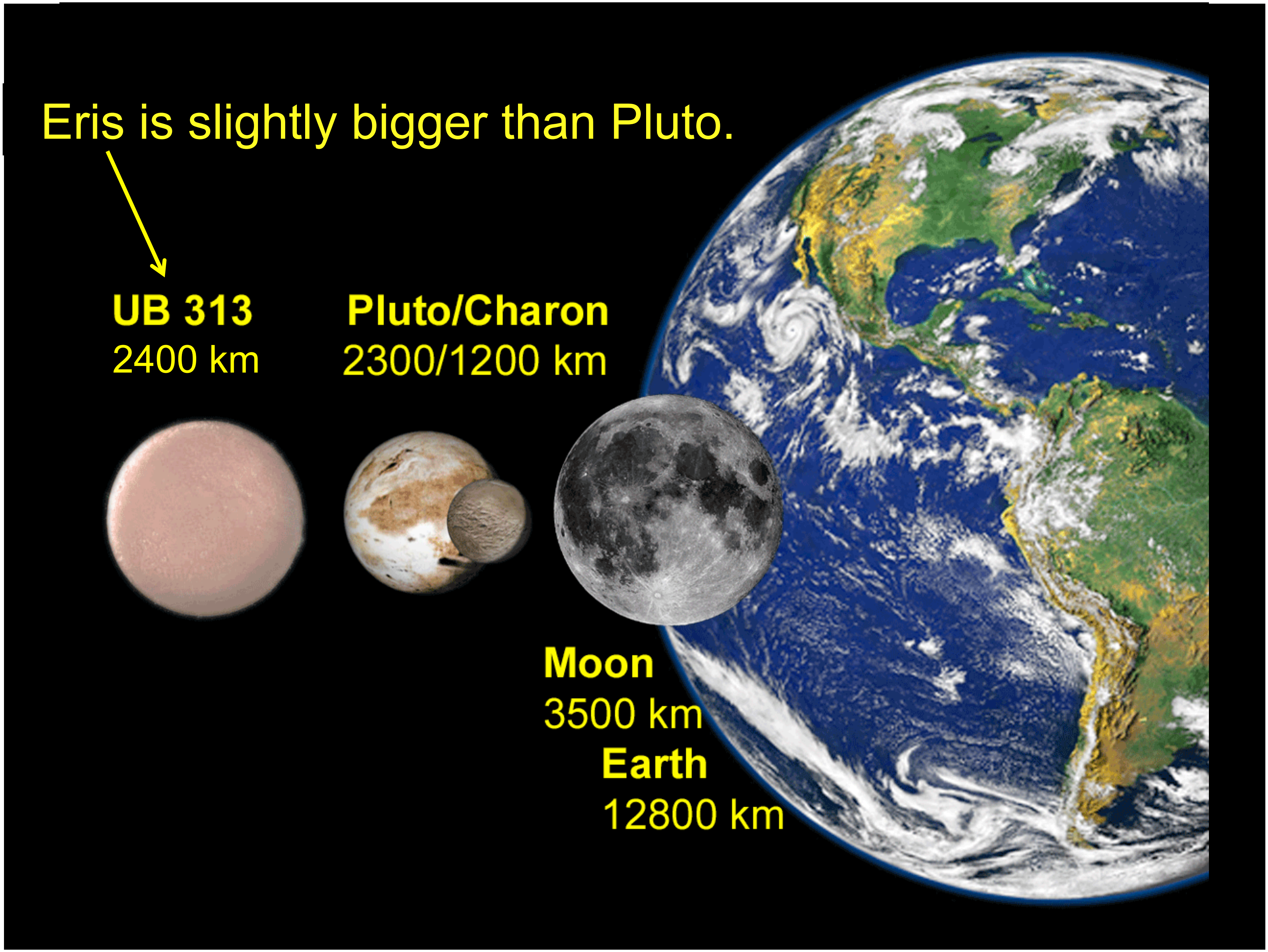


Sedna is currently near its closest approach to the Sun, but it is twice as far from the Sun as Pluto. At its farthest, it is 900 AU from the Sun. It's period is 10,500 yr!

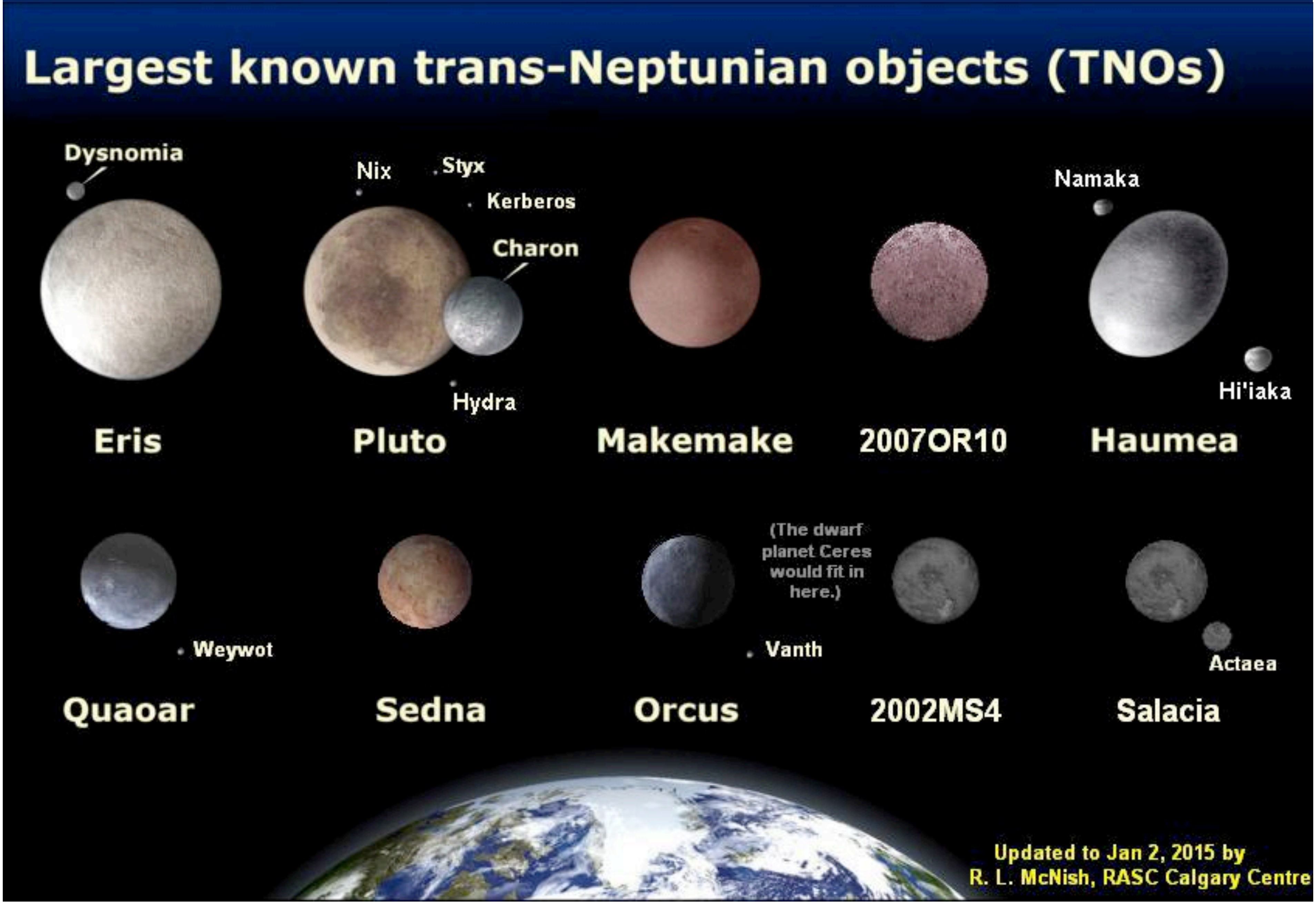

July 29, 2005: Announcement of discovery of
2003 UB313, “Eris”: diameter ~ 2400 miles
(slightly bigger than Pluto)
and 3 times as far from the Sun as Pluto.
Is this the 10th planet?
No, it is another big Kuiper belt object.

Eris is currently the most distant object known in the Solar System.

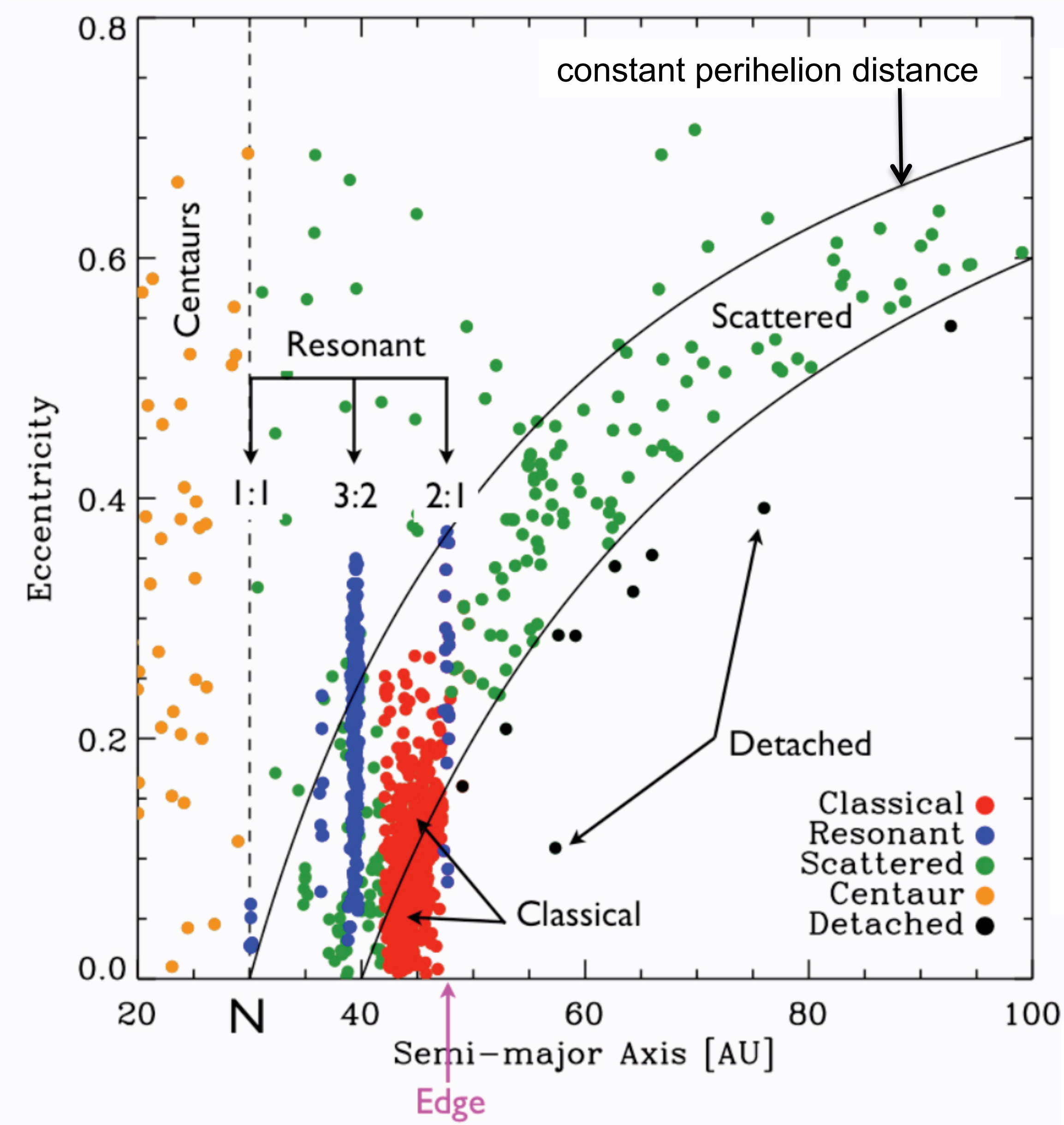



Eris is slightly bigger than Pluto.
UB 313
2400 km
Pluto/Charon
2300/1200 km
Moon
3500 km
Earth
12800 km

Recent Update (But Stay Tuned)



Classes of Icy Objects in the Outer Solar System



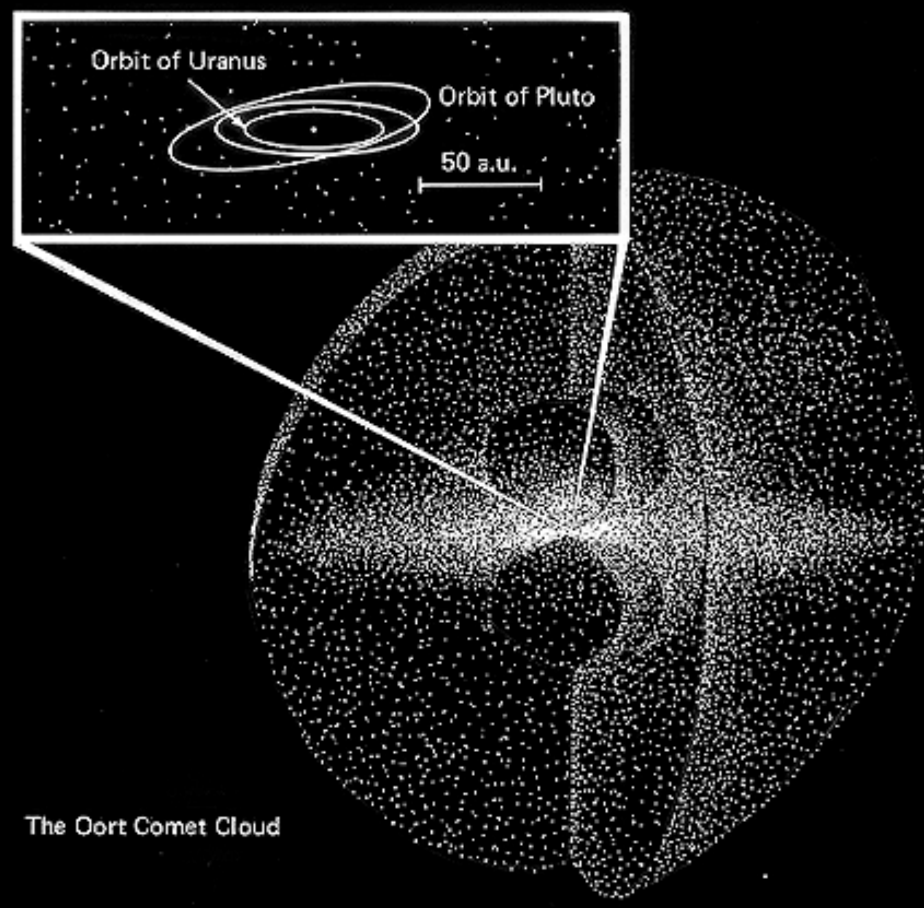
The unexpectedly large number of Plutinos (3:2 resonance with Neptune) is convincing evidence for planetary migration.
We believe that Neptune moved outward by ~ 10 AU and that Jupiter moved inward by ~ 1 AU.

Finding faint objects that are far from the Sun is difficult … but it is suspicious that there is such a sharp edge to the Kuiper belt at a perihelion distance of 47 AU, the 2:1 resonance with Neptune.

It has been suggested that there is another big planet out there, perhaps scattered by Neptune.

This figure is from David Jewitt's Shaw Prize lecture.

Long-Period Comets Come From The Oort Cloud



1923

1980

Jan Oort suggested in the 1950s that a reservoir of comets extends out to 100,000 AU from the Sun. Gravitational perturbations by passing stars are thought to gradually send some comets into the inner Solar System where we can see them. These comets are thought to be remnants of the protosolar nebula.