



Other Worlds in Space: modern astronomy from the perspective of *Exoplanets*

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What we are doing in this class: a survey of (much of) contemporary astronomy, but with emphasis on an exciting, recent wrinkle: *exoplanets*



A deep space photograph showing a vast field of stars. The stars vary in color, including bright blue, orange, and white. The background is a dark, almost black, space filled with numerous small, distant stars. The overall scene is a rich, multi-colored stellar population.

A meditation on the study of astronomy:

*“We want to **feel**, not just observe,
what the heavens offer...”*

John Goss, Astronomical League

The motivating idea for this class

- We live on a planet (Earth) in the solar system
- All the planets orbit (and are controlled by) the Sun
- The Sun is a star
- The night sky is filled with stars
- Are there planets around some (or all) of those stars?
- Are some of those planets like the Earth?
- In 1995, we suspected the answer to (last 2 points) was yes, but we had no definite examples

A mental goal of the class: an Earthlike planet around another star

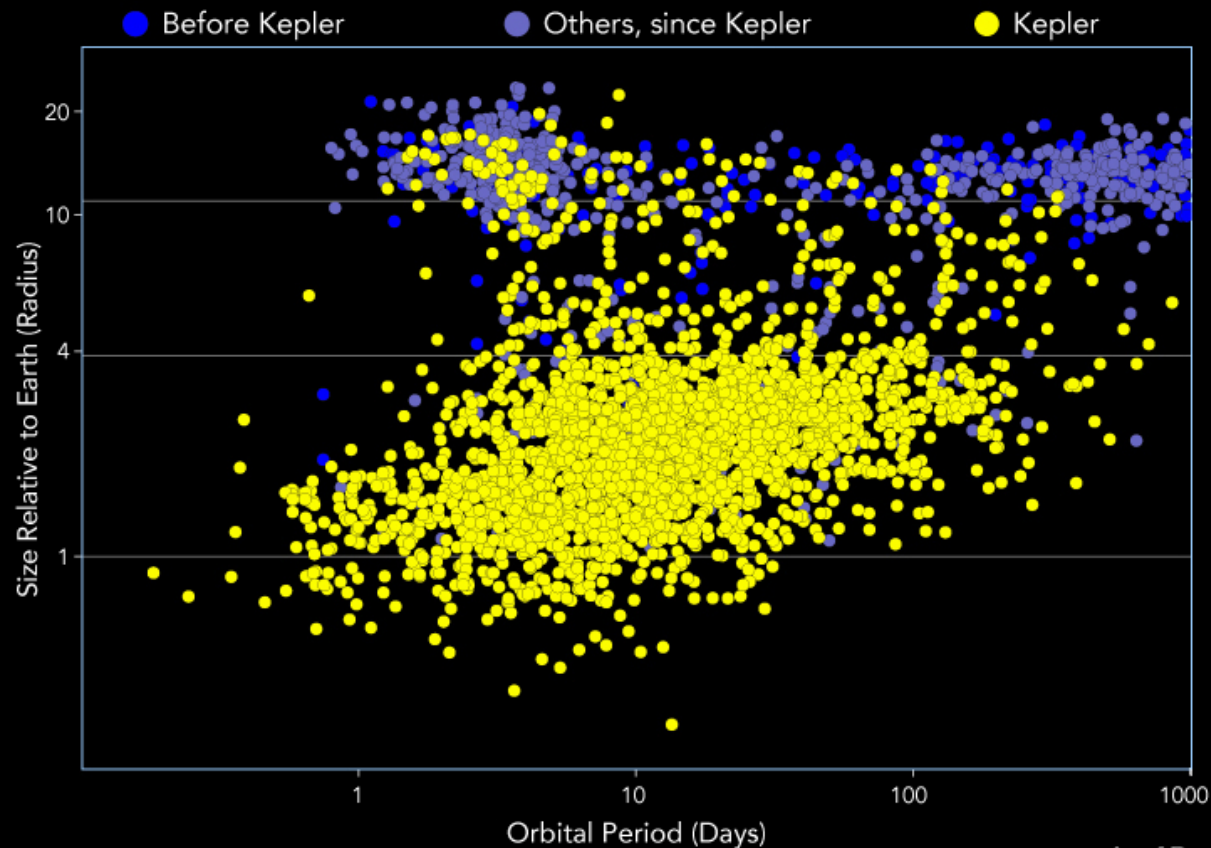


A sneak preview of where we are headed: the situation with exoplanets as of Dec. 2017

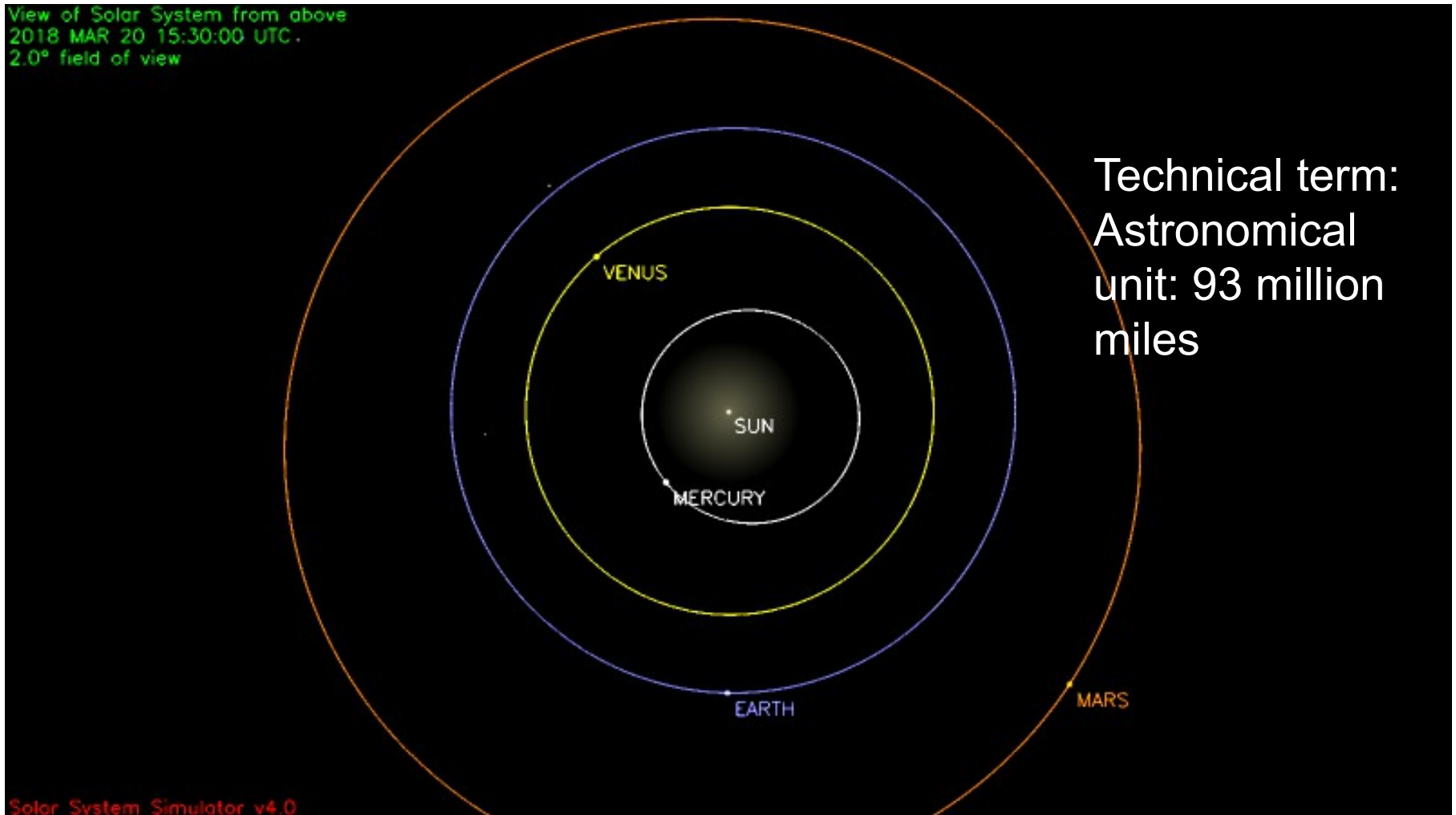
Exoplanet Discoveries

Total confirmed exoplanets = 3,567

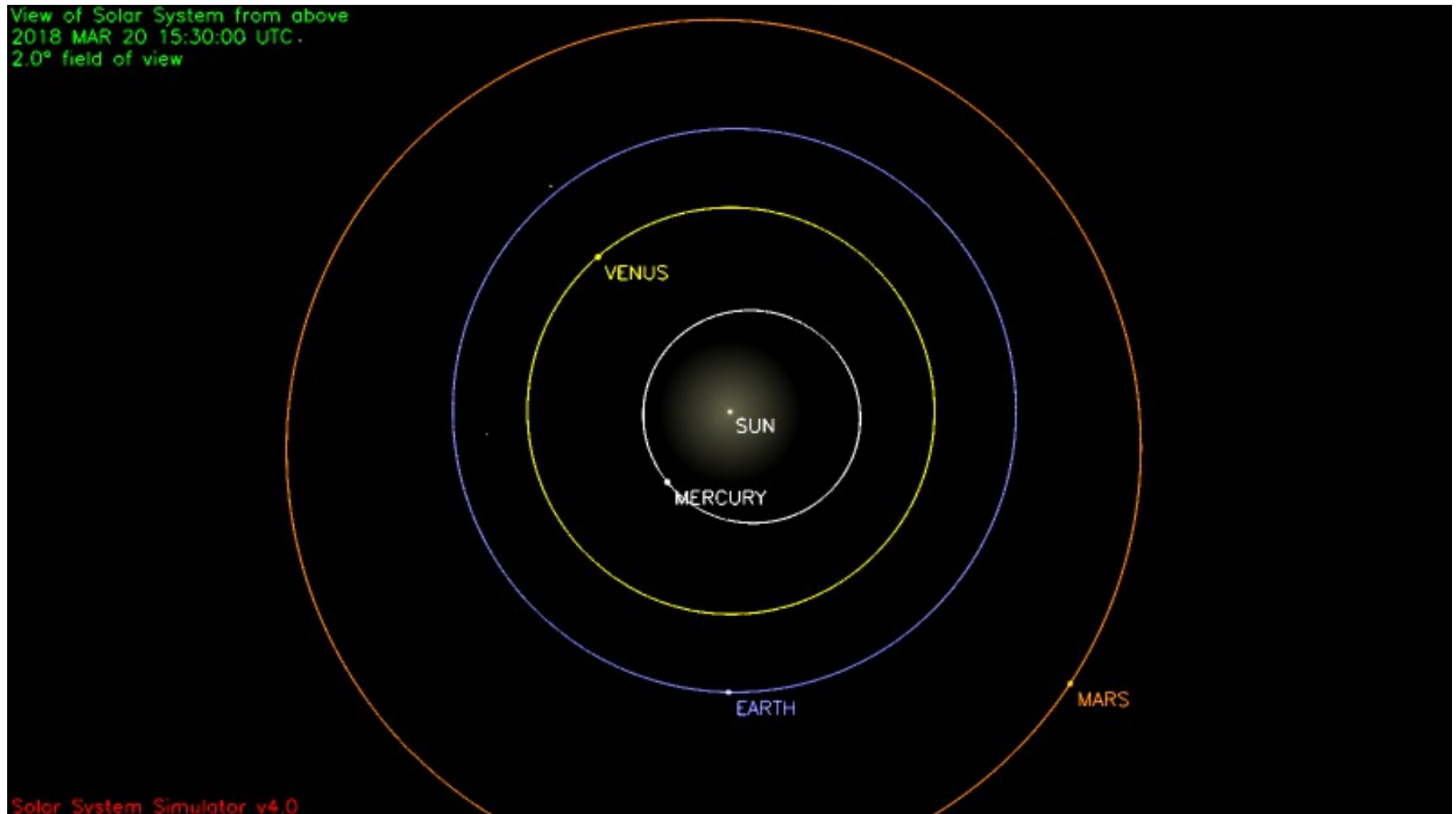
Total Kepler = 2,525



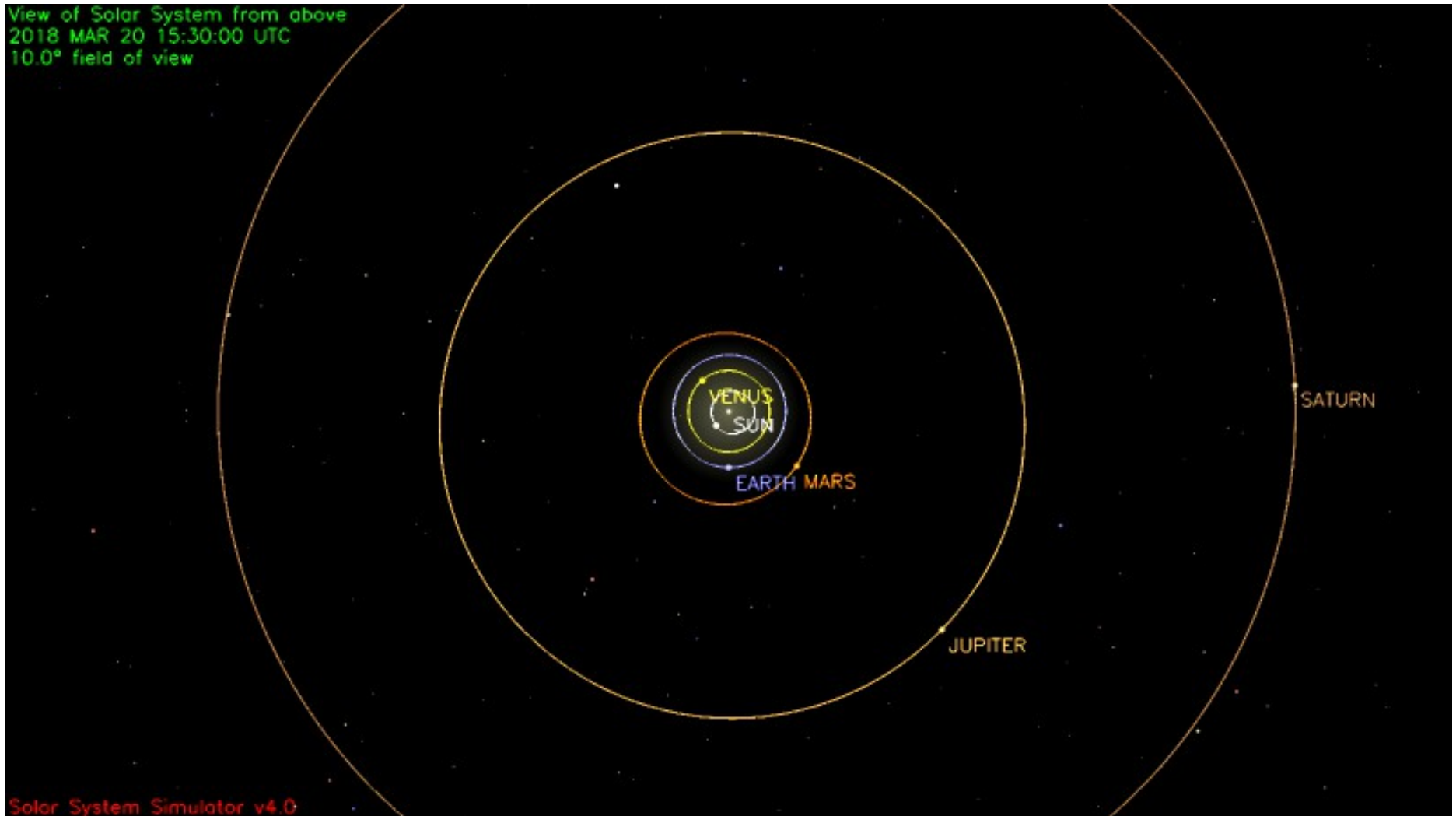
Let's get back to basics: if we are going to understand exoplanets, we need to start with our own solar system



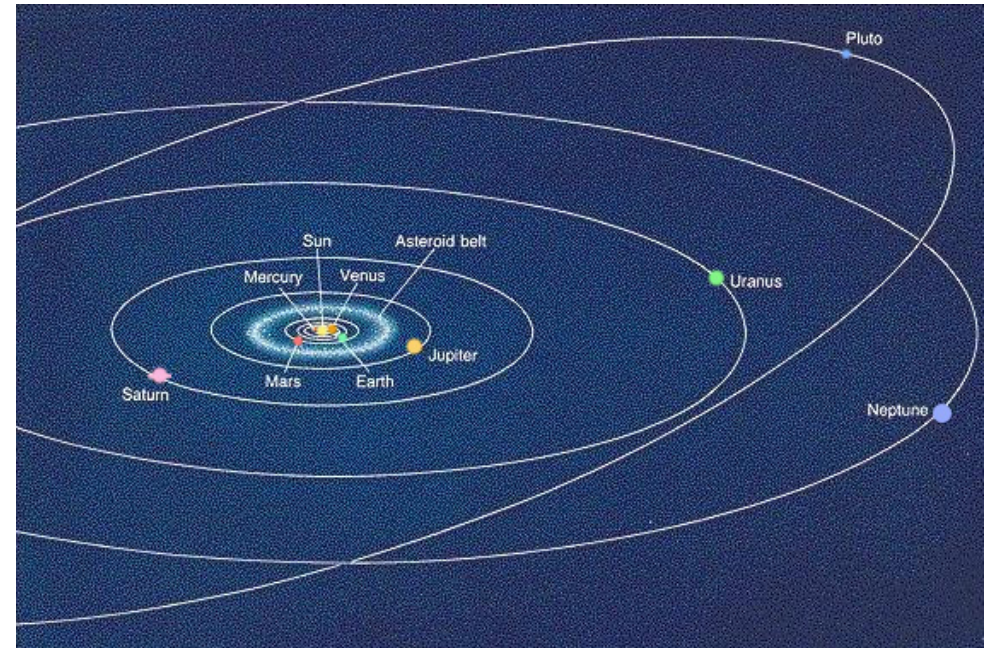
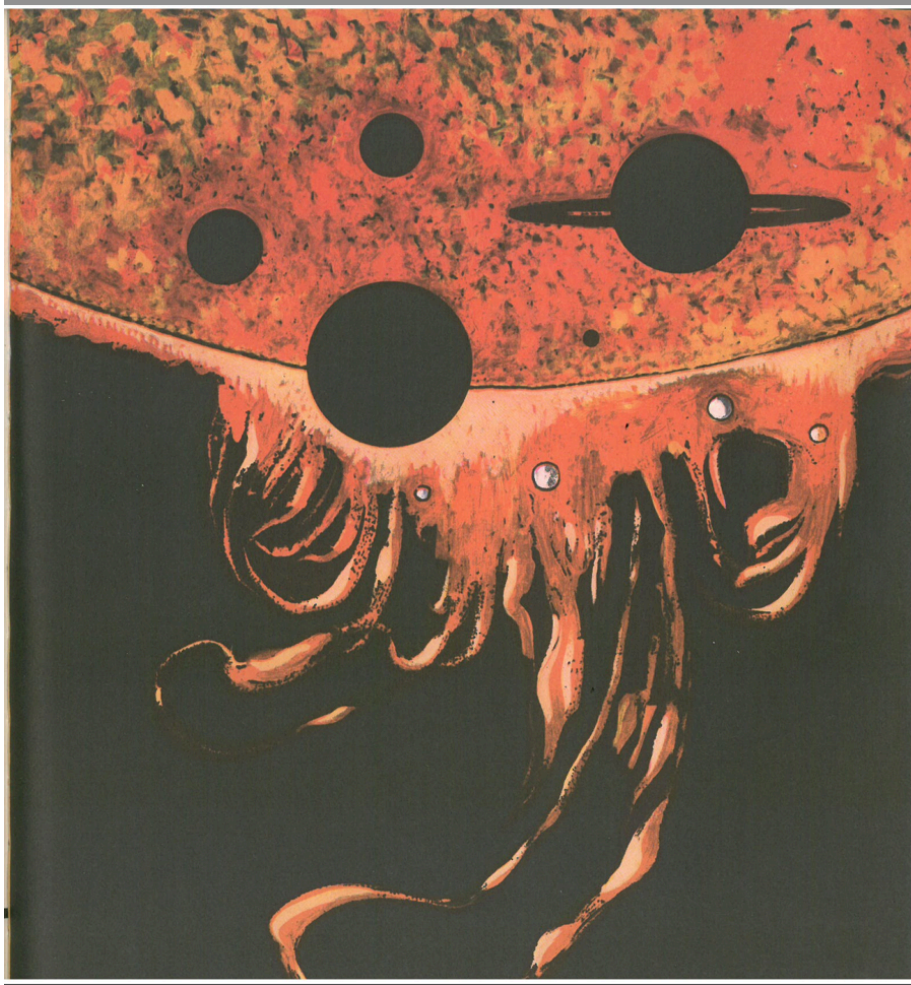
“I seem to remember from junior high that there were others...”



Jupiter, Saturn, Uranus, and Neptune are all further out

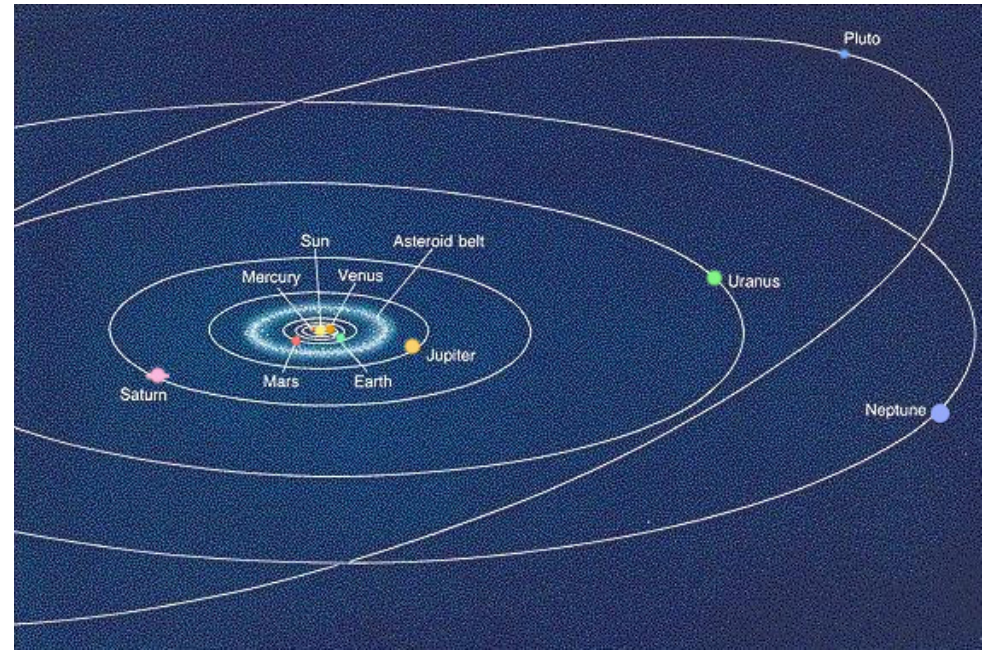
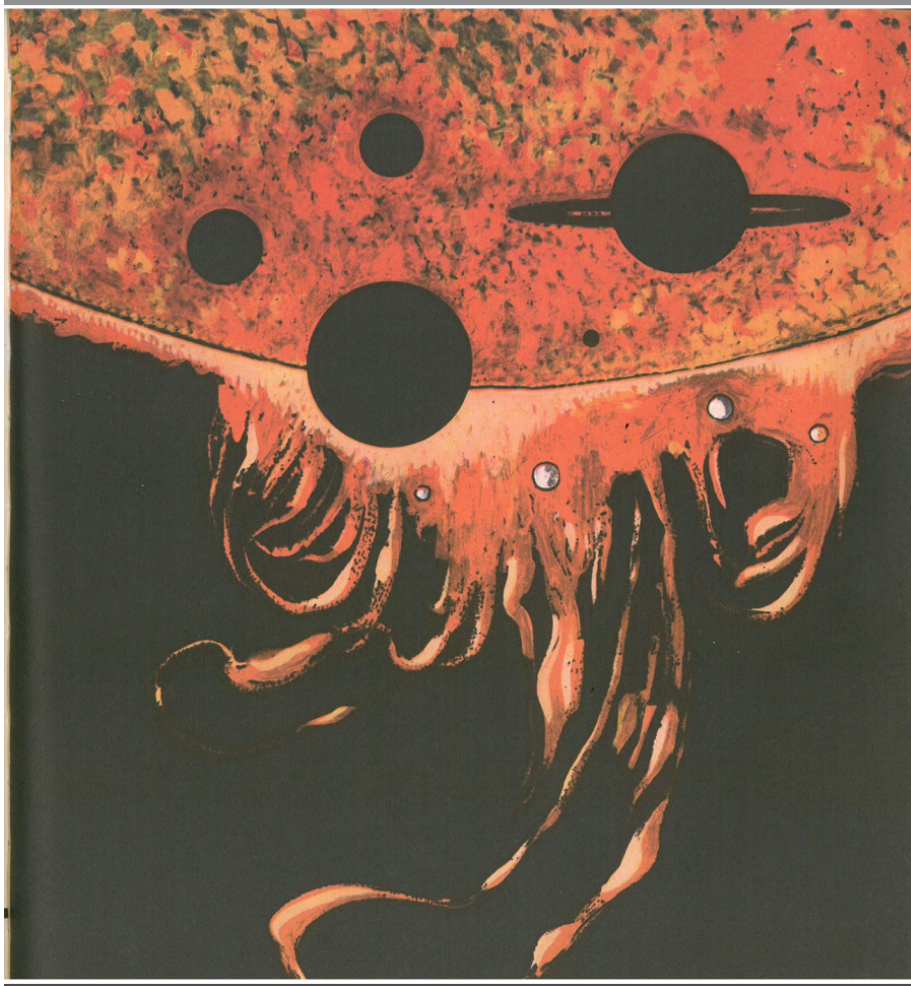


The Solar System: in school we learn about the 8 (or 9) planets that orbit the Sun



In solar system, the planets are where life is (at least in one case)

The Solar System is our best chance to study planets in detail (and learn some interesting astronomy, too)



The Earth as a Planet



Main aspects of the Earth

- Surface temperature:
about what is outside
- The atmosphere
- Liquid water



Chemical composition of the Earth's atmosphere

- Nitrogen (N₂): 78%
- Oxygen (O₂): 21%
- Argon: 1%
- Water vapor: 0 - 4% !
- Carbon dioxide (CO₂): 0.040 %



By solar system standards, the Earth's atmospheric composition is unusual; the oxygen content is extremely unusual

A measure of how “thick” an atmosphere is: atmospheric pressure

- Atmospheric pressure is weight of overlying layers of air
- In physics has **units** of Force/(unit area)= Newtons/(square meter) = Pascals
- Atmospheric pressure at sea level = 1.013E+05 Pa
- Also called “one atmosphere”

Liquid water on the surface of the Earth

The temperature and pressure at the surface of the Earth are close to the “Triple Point” of water (H₂O), conditions where water simultaneously is in equilibrium in the solid, liquid and gaseous states. This permits the hydrological cycle on Earth

The hydrological cycle and the triple point of water are almost certainly crucial for the existence of life on Earth

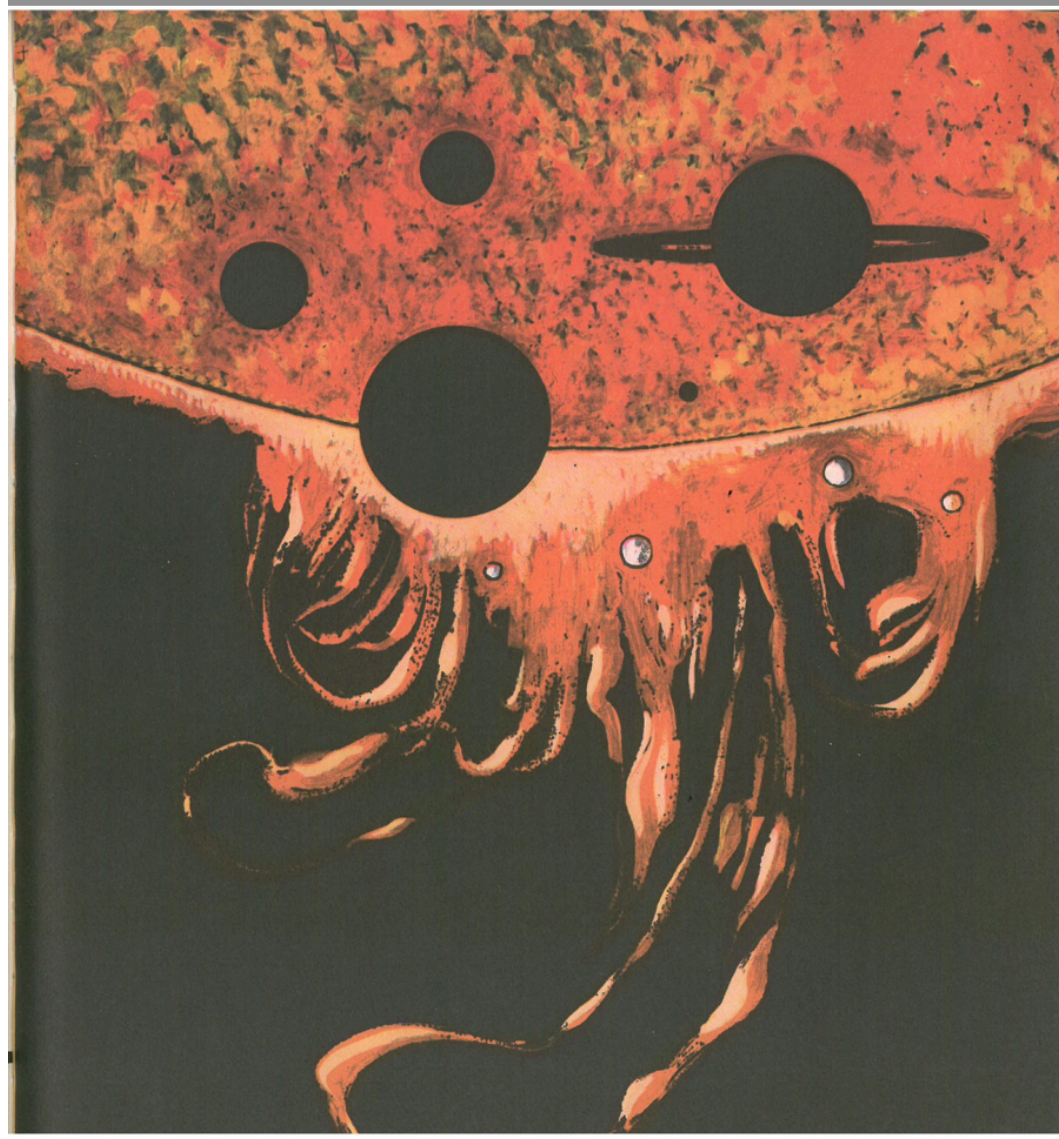
Amazingly, the Earth is not unique among solar system objects in having a “hydrological” cycle. Stay tuned.

Overall Physical Structure of the Earth (the Earth as a ball)

- Mass = $5.98E+024$ kilograms
- Diameter = 12756 kilometers (7920 miles)
- Average density = 5.52 g/cc
- Denser than almost all rocks: heavy stuff in Earth's interior

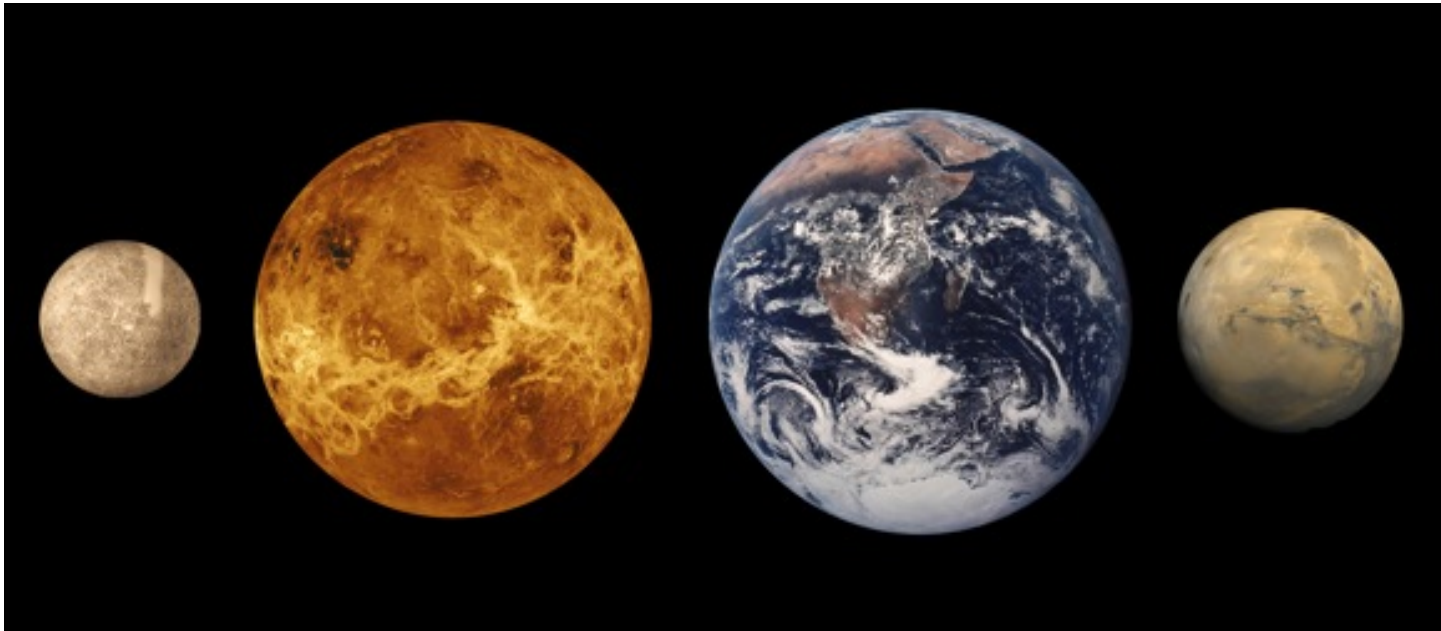


How do the other planets “stack up” next to the Earth?



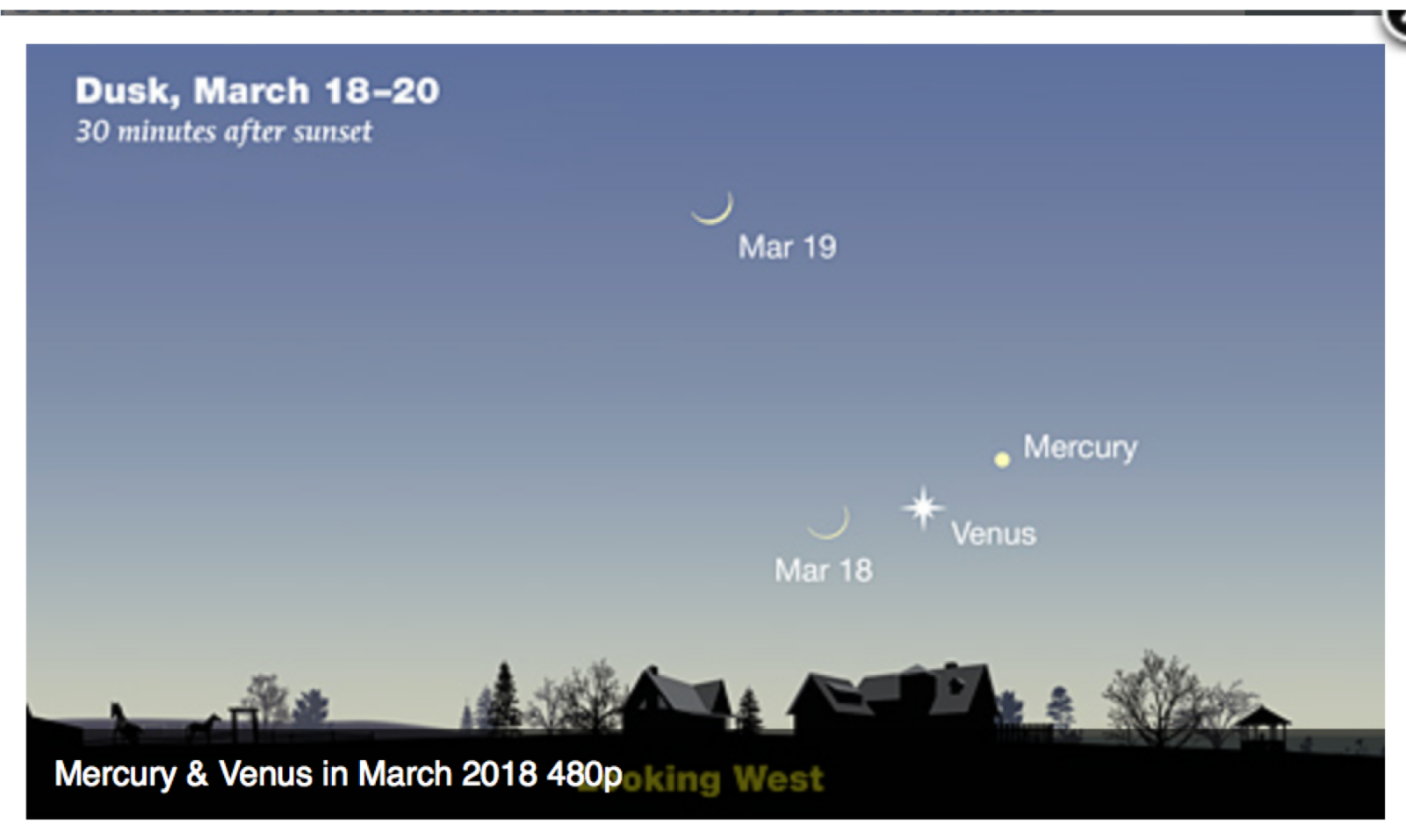
In our Solar System, the planets are so different, we have to put them in two groups

Rough sizes of the *terrestrial planets*



This picture was known 50 years ago

Where are Mercury and Venus in the night sky?



Very easy to find!

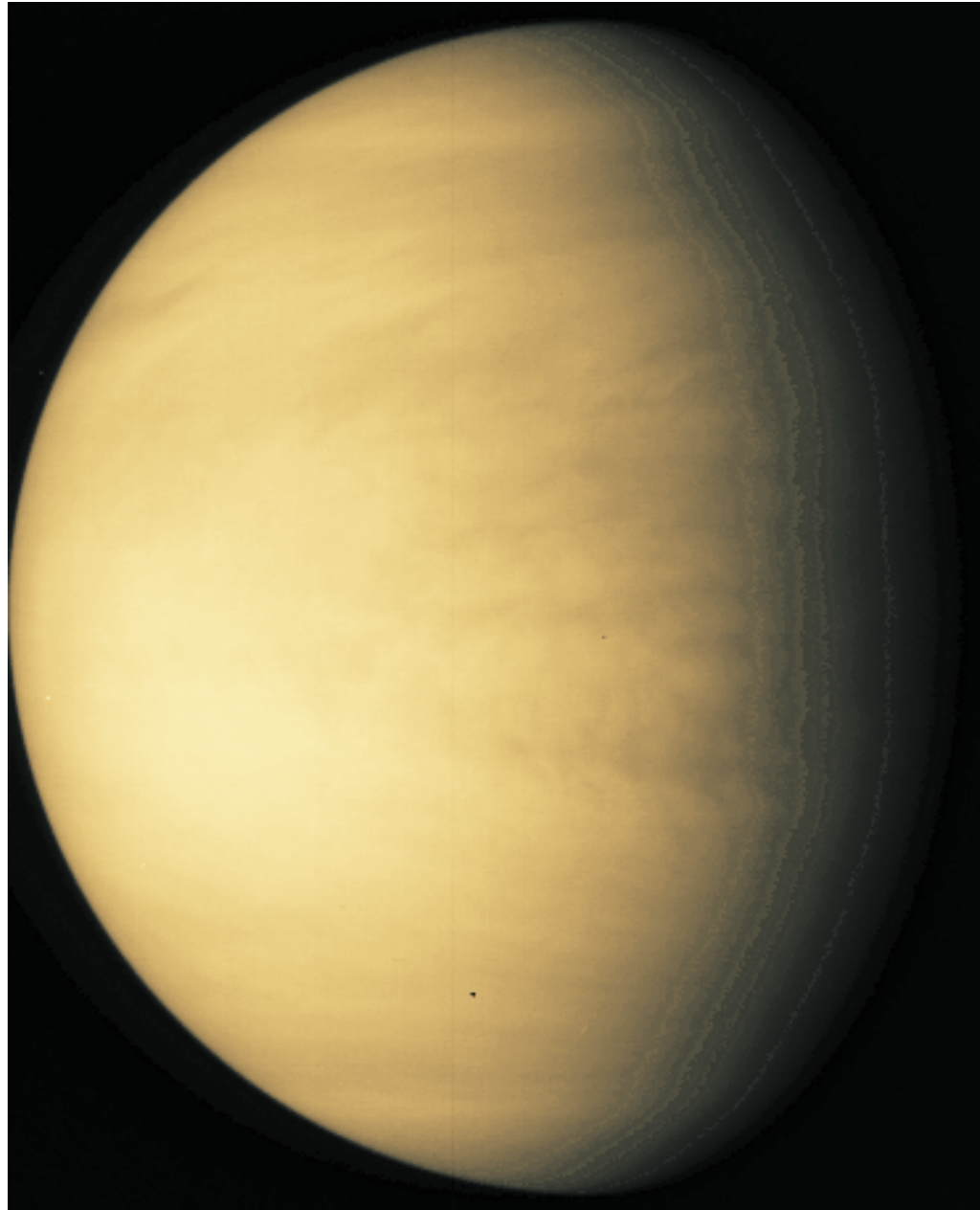
Venus...closer and bigger. Expect more to see

Venus 2004 Evening Apparition



Current distance 1.61 AU, angular diameter 10.3 arcseconds. *Why can't we see anything on the surface?*

Venus...Earth's twin



Venus is perpetually overcast. You cannot see the surface from Earth. Only the top of a cloud layer

Similarities between Earth and Venus?

Fact that Earth and Venus are so similar in physical properties (size and mass), and that one cannot see the surface was conducive to imagination



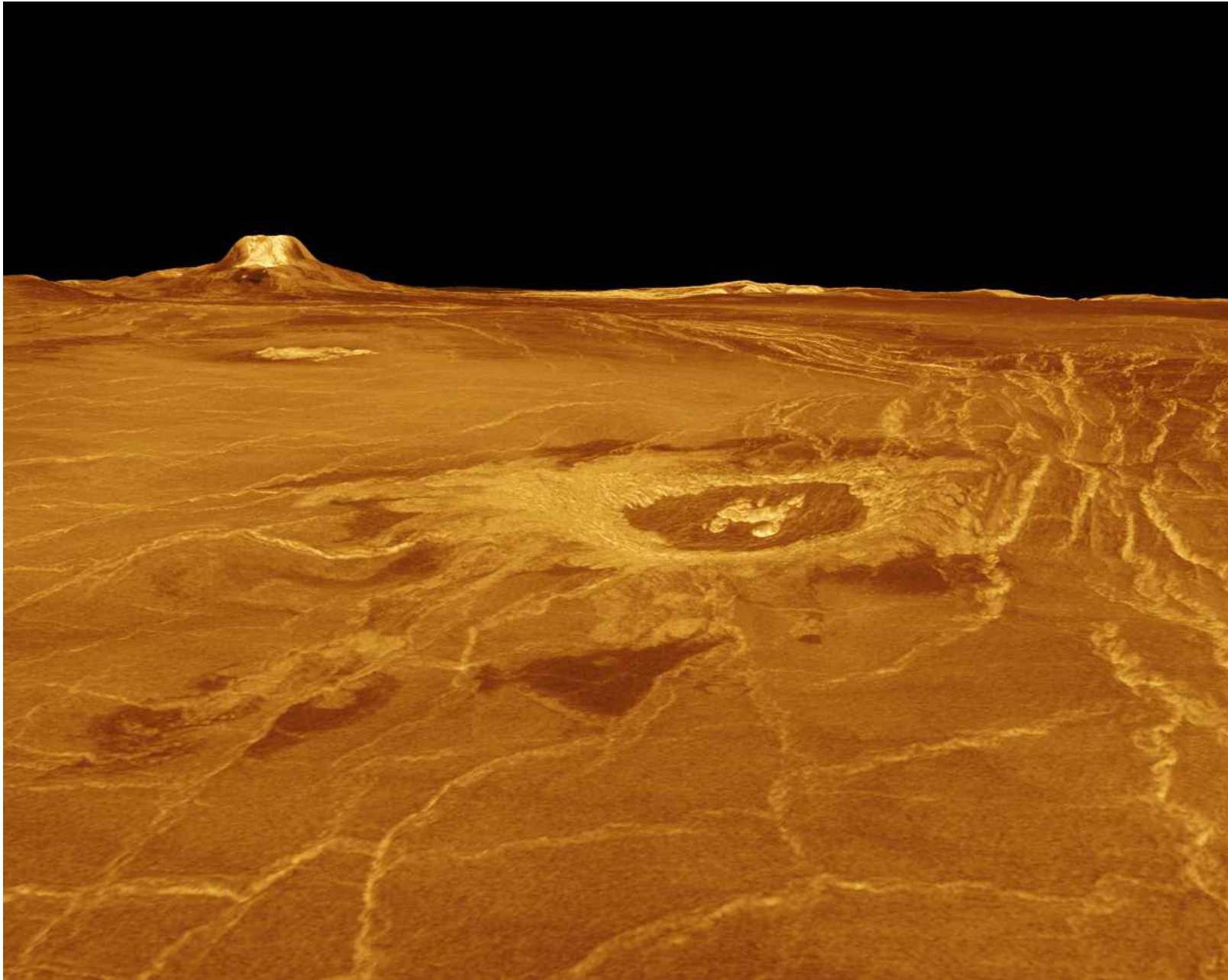
Seeing through the clouds of Venus with **Radio Astronomy!**



Radio astronomy and application of laws of physics allow us to measure the surface temperature of Venus (done first in the late 1950s)

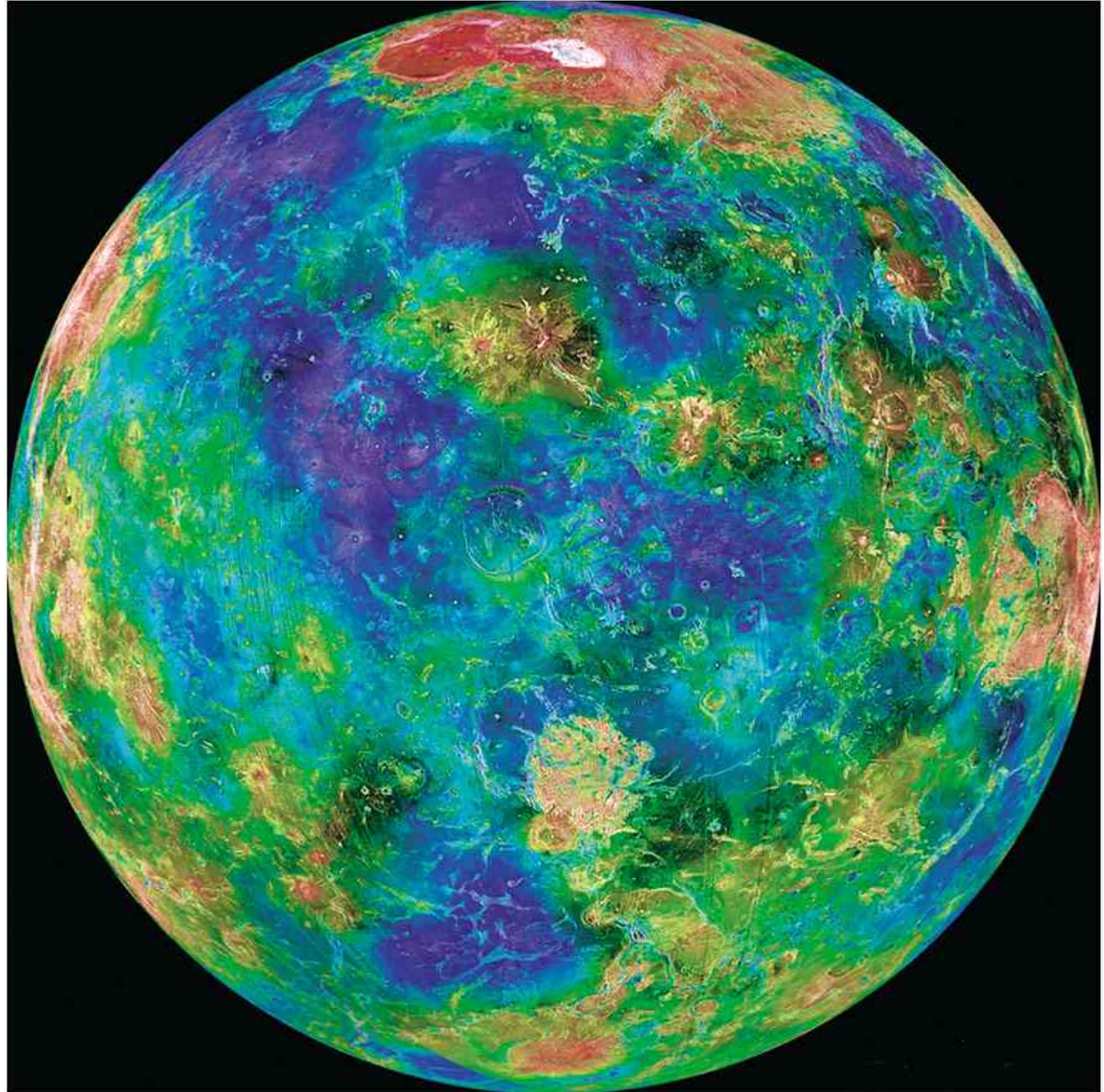
- Surface temperature is 730K
- That corresponds to 855 degrees Fahrenheit
- No longer “Earth’s twin”
- What is responsible for this sort of temperature?
- Physics tells us!

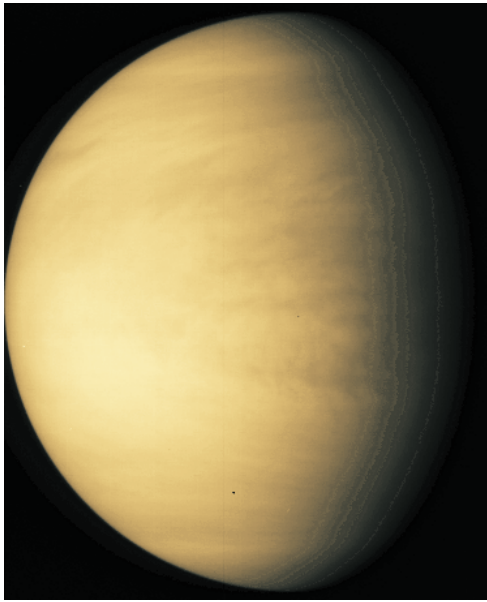
What the surface of Venus looks like



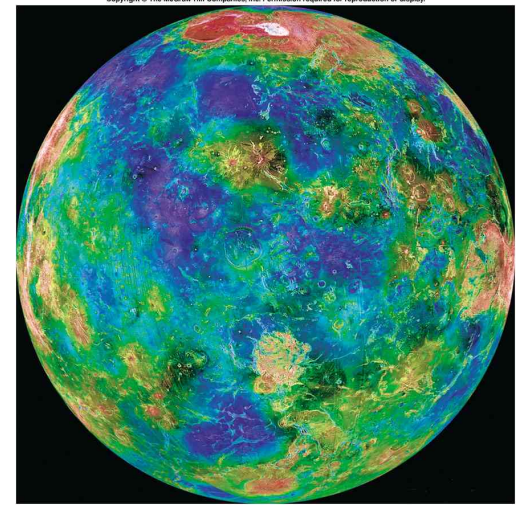
And now, a similar view of Venus, thanks to the
Magellan orbiter

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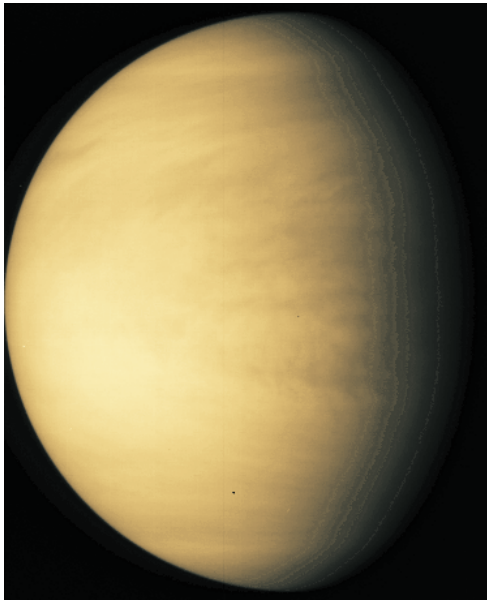




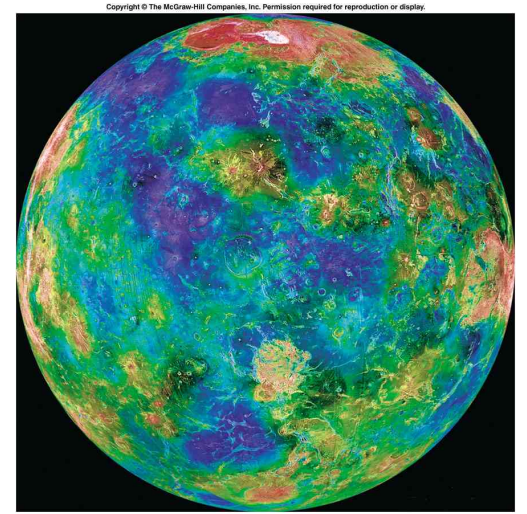
Remaining questions about Venus



- Why is the surface temperature so high?
- **Hint:** it has a dense, carbon dioxide atmosphere
- Did Venus ever have oceans like the Earth?
- If it did have them, where did they go? (See article from *Sky and Telescope*, April 2008)

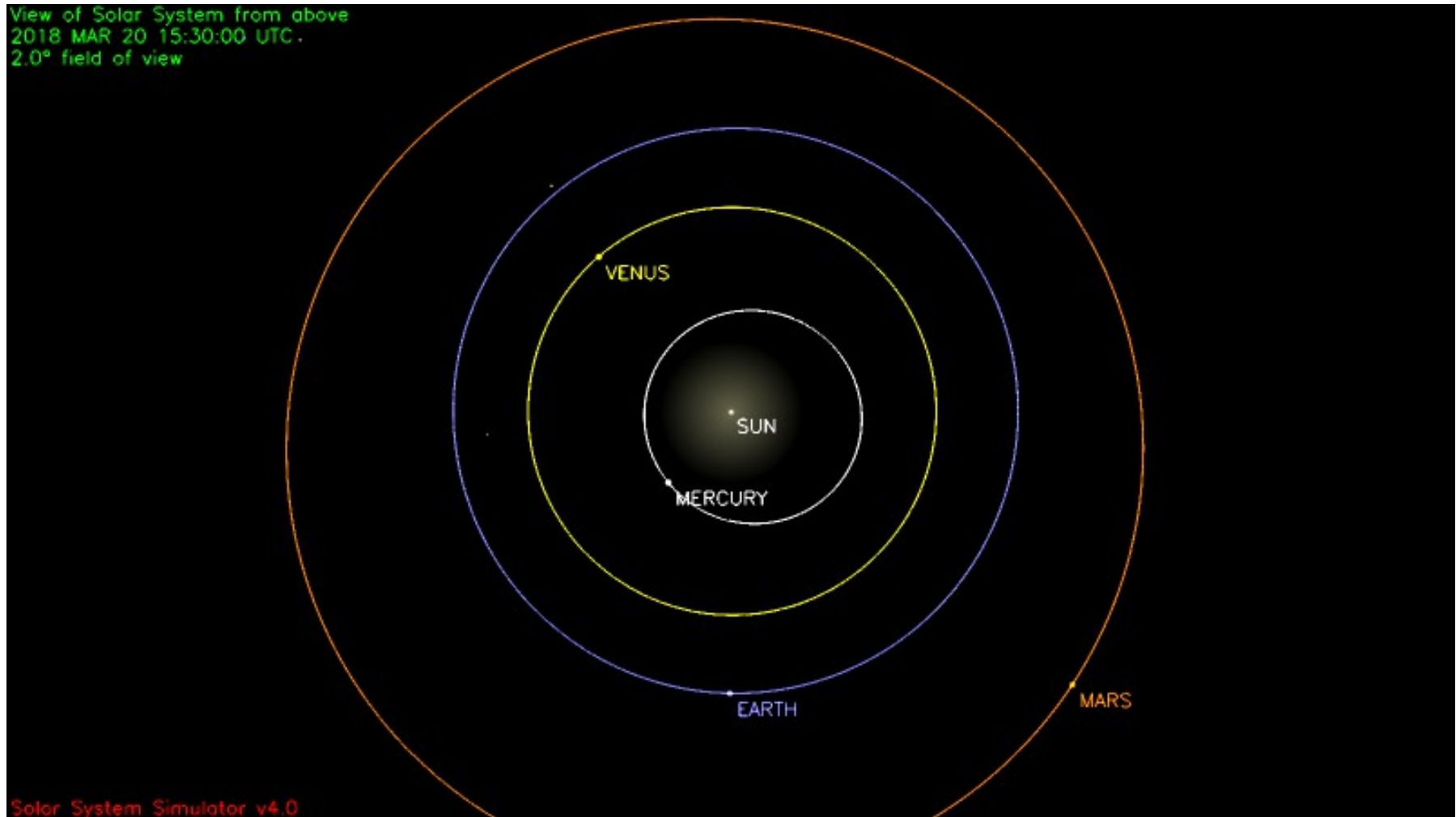


Lessons of Venus for exoplanet studies



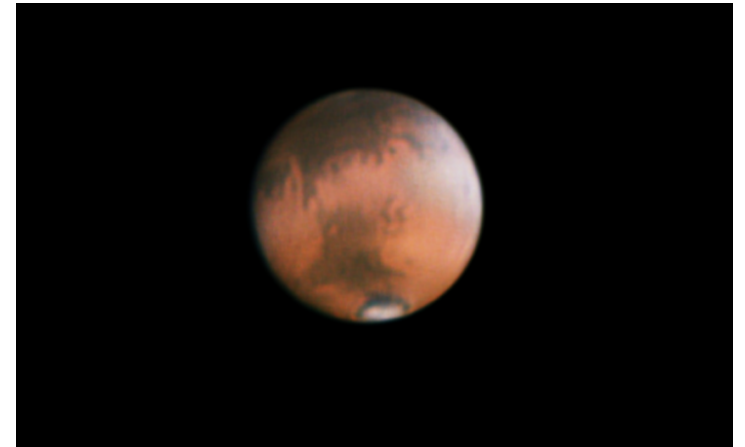
- A planet can be the “right size”, and *nearly* in the “right place”, but still be completely unsuitable for life

Moving out in the solar system...Mars

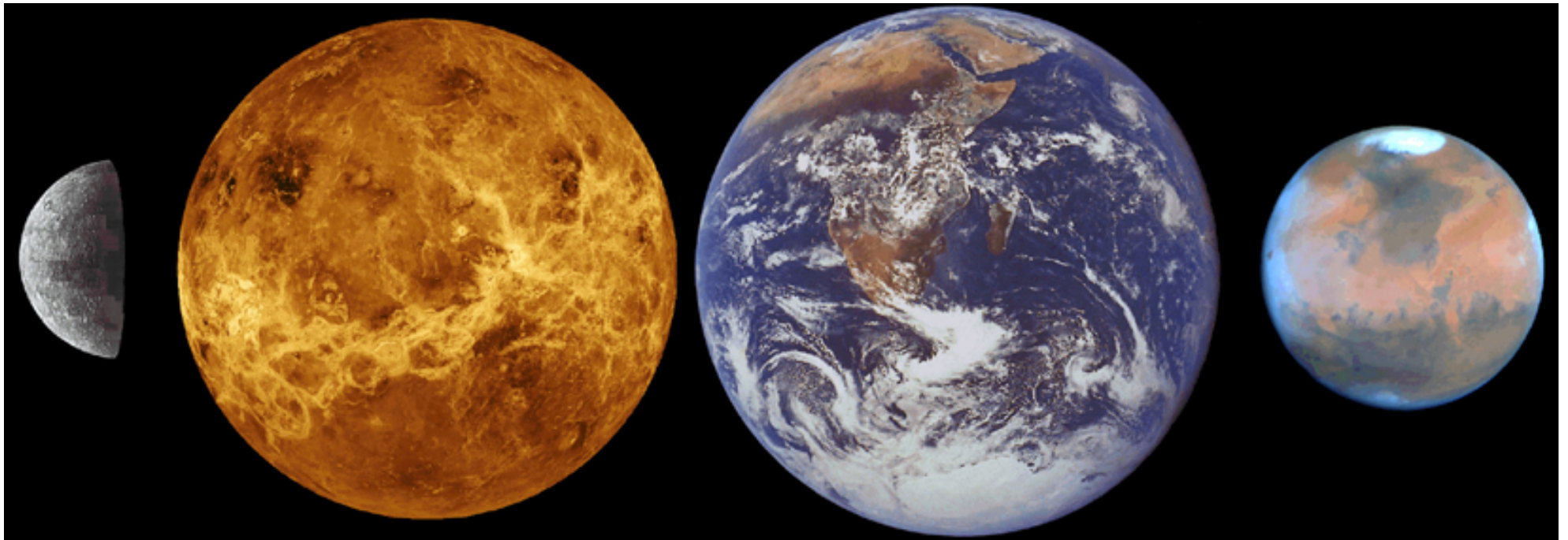


Mars...start with the orbital parameters

- Semimajor axis: 1.524 AU
- Orbital Period: 1.88 years
- Eccentricity: 0.093
- Best *opposition* since 2003
this summer (late July);
take advantage of the
chance to see Mars
through a telescope

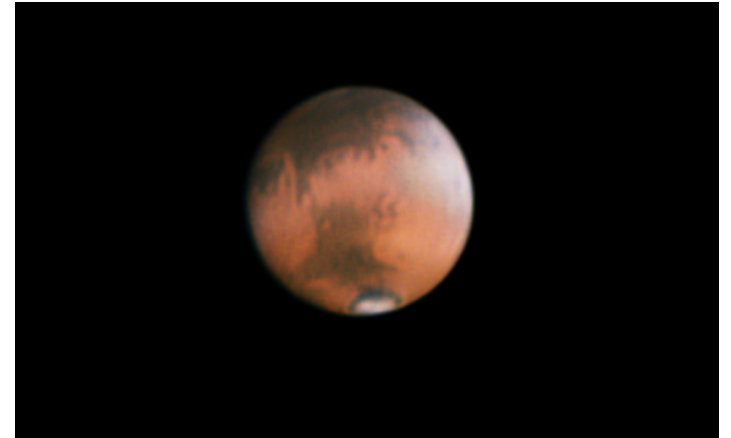


Average physical characteristics of Mars



By the 1960s it was known that the circa-1900 view of an Earth-like Mars with higher life forms could not be right; the atmosphere on the surface of Mars is about 0.7 % the sea-level pressure on Earth. Water cannot exist in liquid form under those conditions.

The average surface temperature on Mars is also about 100 degrees Fahrenheit below.



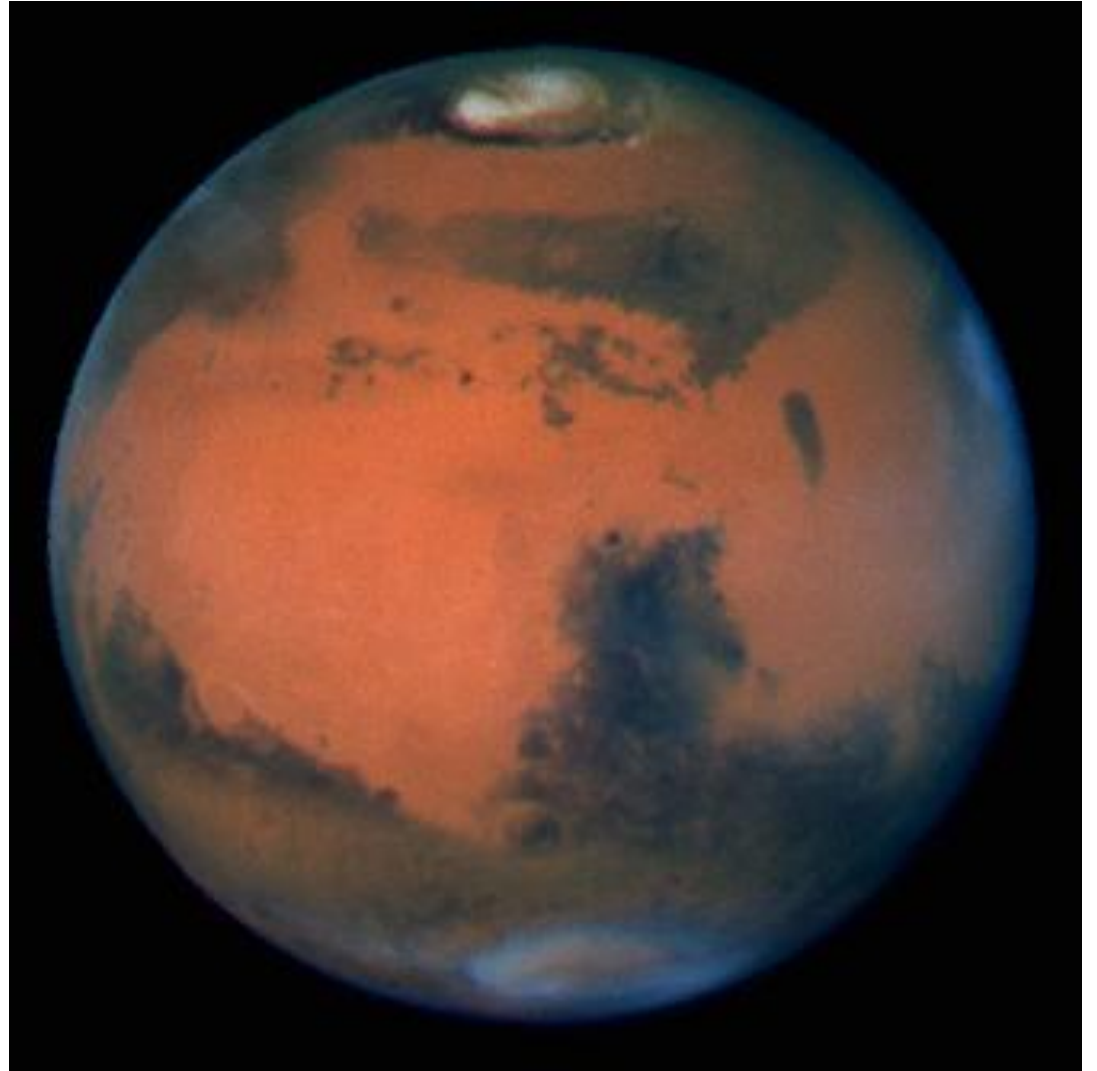
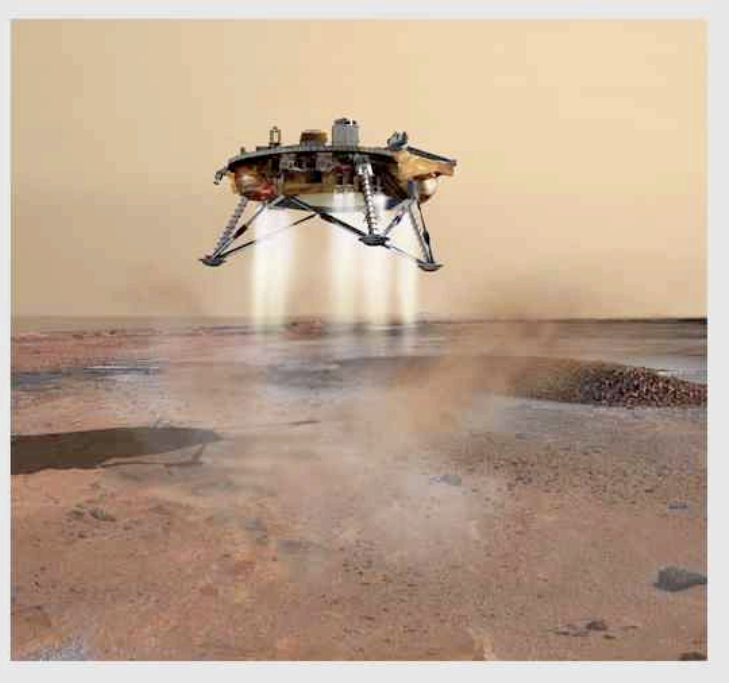
The atmosphere of Mars: 95% CO₂

Most of the rest is nitrogen (diatomic molecular)

The chemical composition of Martian atmosphere is like Venus, not the current Earth

(But like the early Earth)

Robotic Exploration of Mars



We have learned an incredible amount about Mars in the past few decades

An illustration of the fascinating results brought to us by
robot spacecraft



A major result: apparent ancient water channels



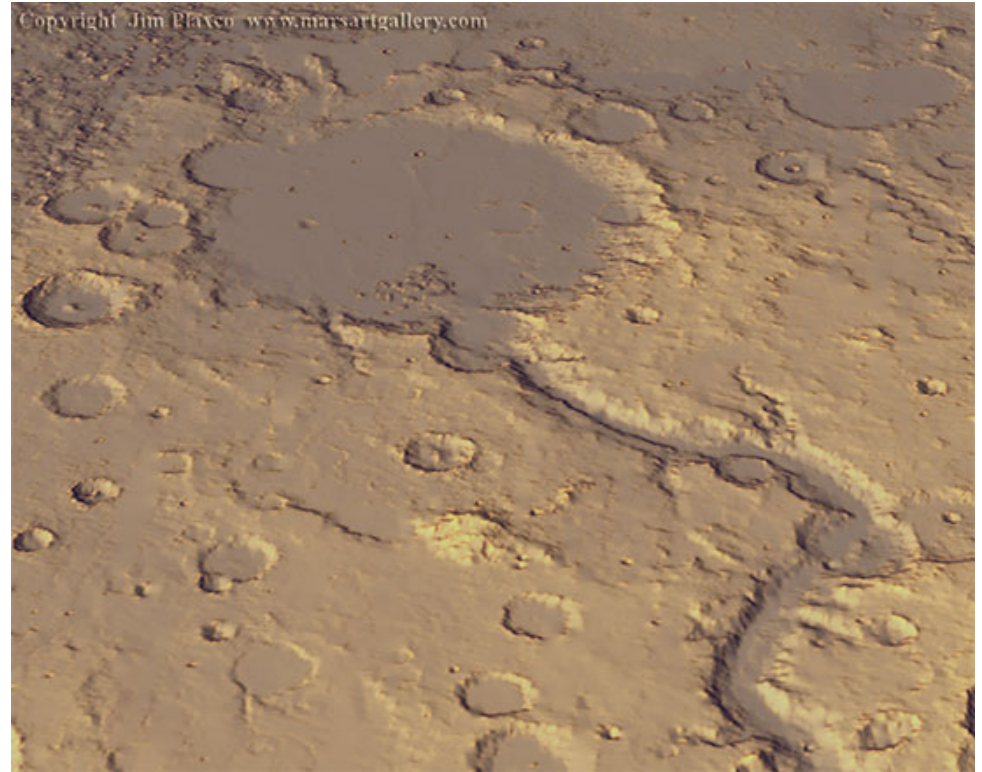
Determining the Ancient History of Mars

What its present surface tells us



The central mystery of Mars since the 1970s

- The present climate of Mars is such that liquid water cannot last long
- Orbiting spacecraft show apparent evidence of flowing water channels (rivers and larger) in landscapes that formed 3 – 4 billion years ago
- How are these two (apparently) contradictory results to be reconciled?

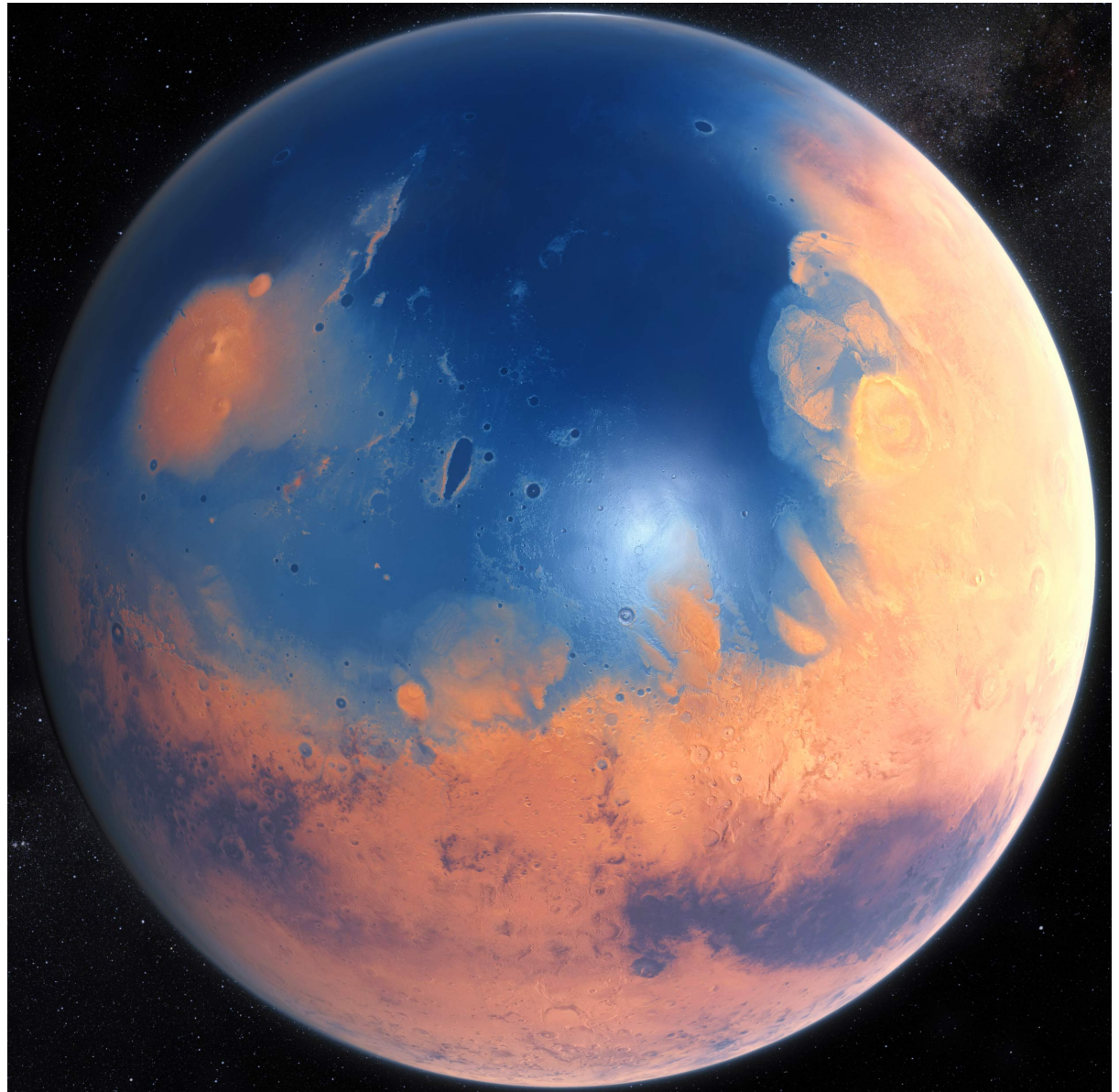


These observations led to the idea of the “Warm, Wet Mars”

Mars 3.8 billion years ago?



Since 1990s,
clear that the
key is to land
on the surface,
do geology



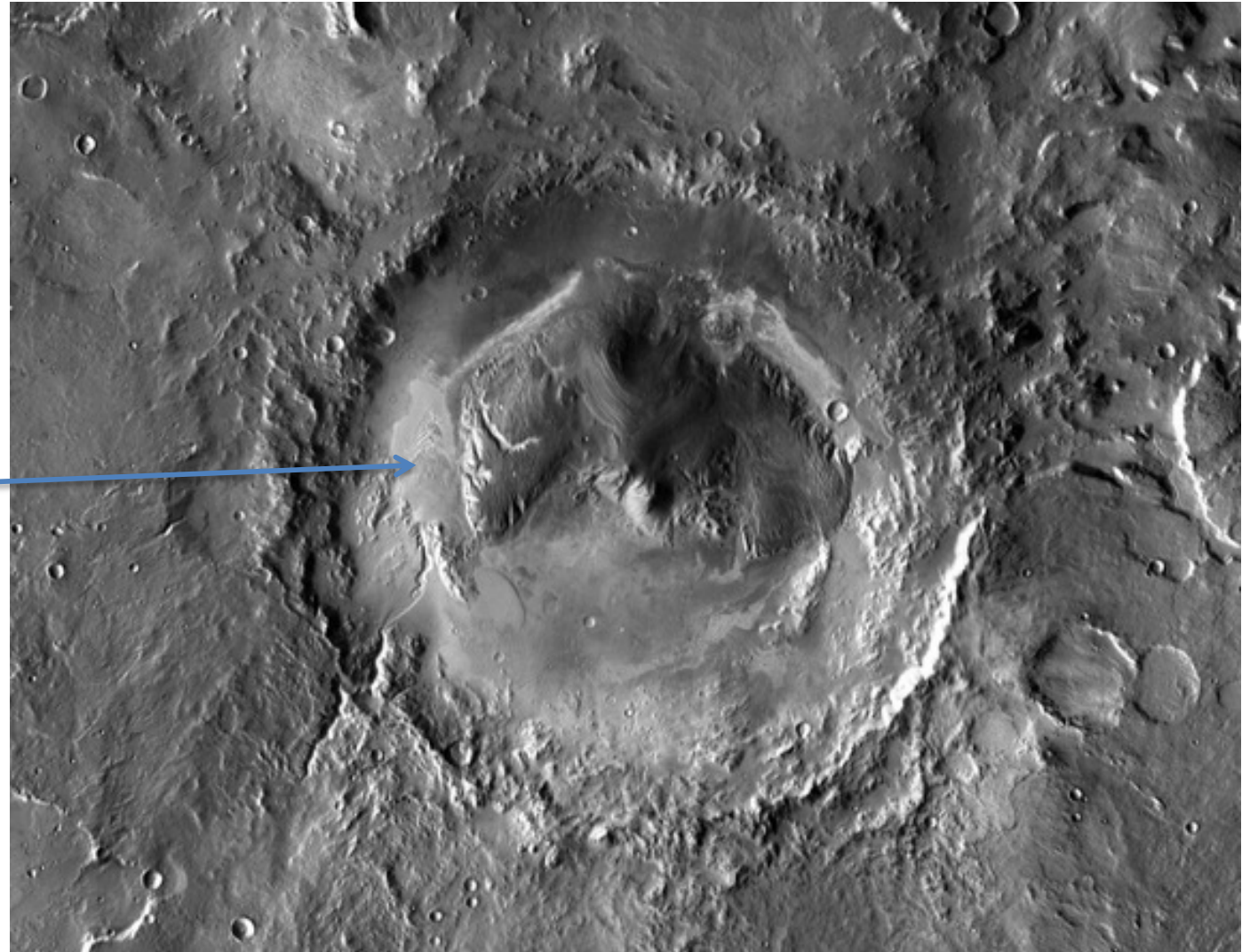
The key to
determining the
ancient climate of
Mars (and implications
for life); robot
geological
laboratories

Curiosity 

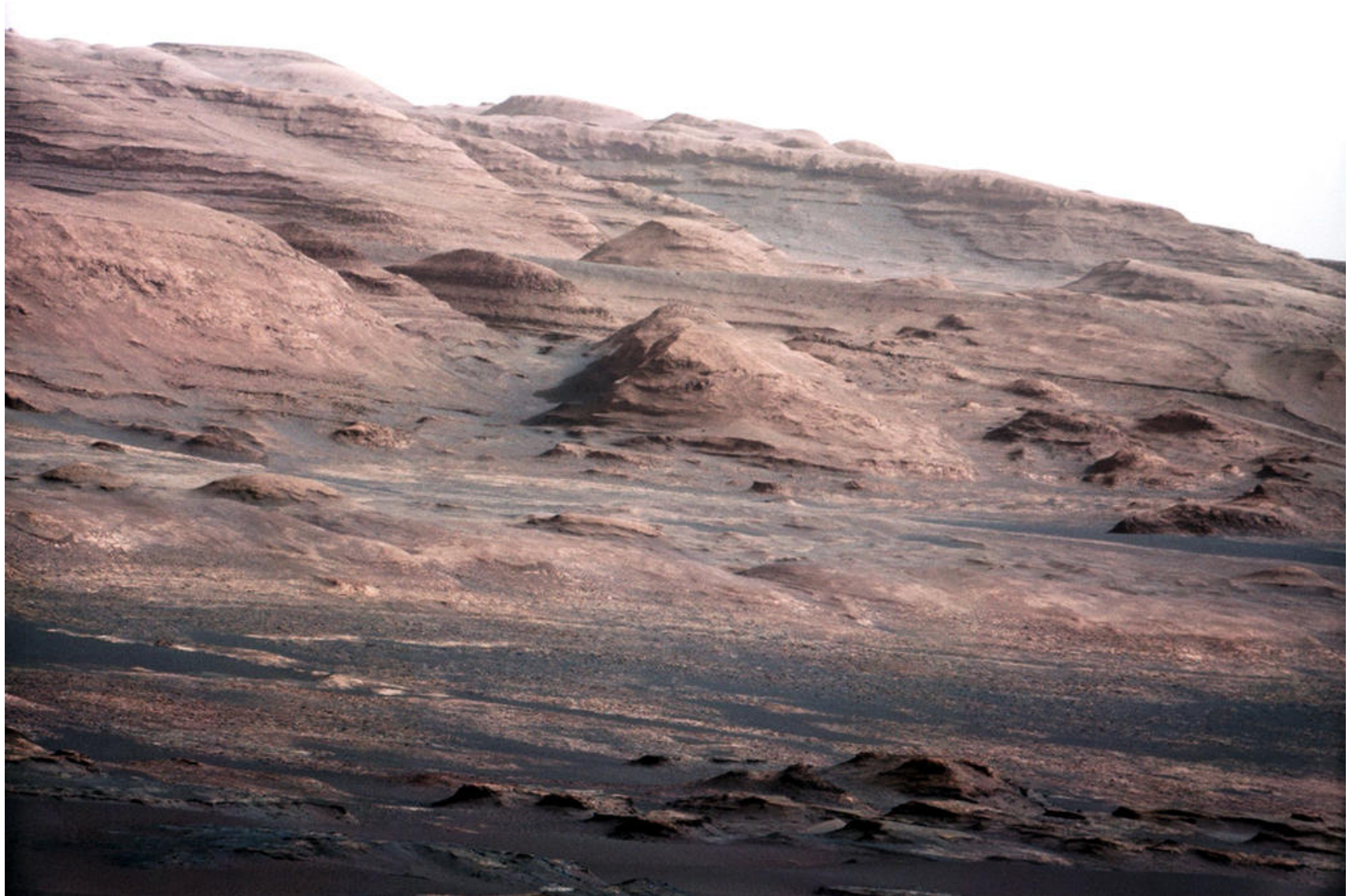


The Mars Science Laboratory and Gale Crater

Clay
deposits at
bottom of
central
mountain



The destination for “Curiosity”

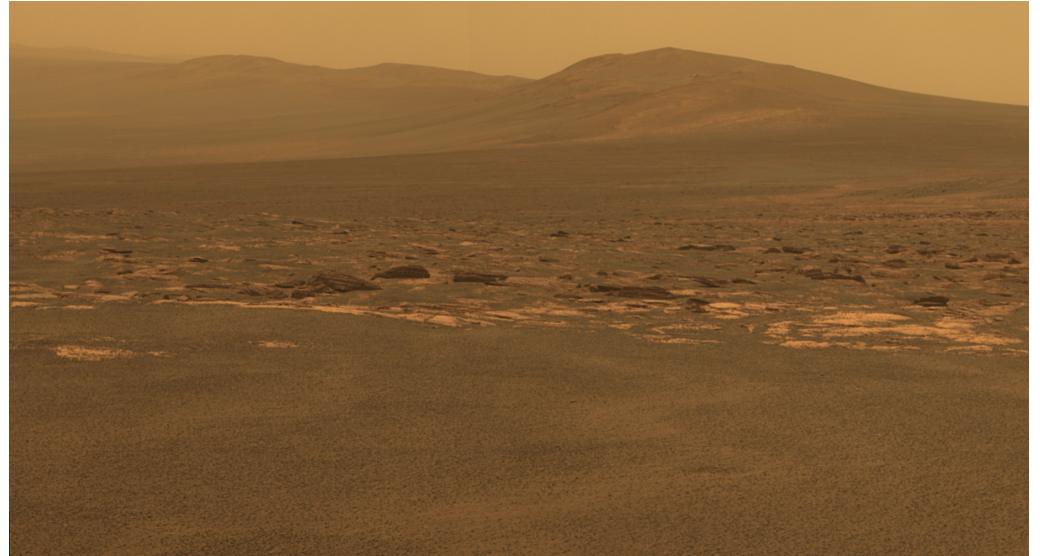


What have we learned from the MERs, “Mars Phoenix”, and Mars Science Laboratory

- It now seems clear that there were standing bodies of water for long periods of time early in Martian history
- Evidence is presence of hematite, jarosite, and other minerals that form in lakes or oceans
- Relative absence of carbonate rocks is due to alternative chemistry in acidic water
- **But**, apparently oldest rock strata do contain carbonate rocks and clay (montmorillonite)
- Mars Science Laboratory has found abundant mineralogical evidence for water in Gale Crater
- *Apparently* there were liquid water bodies on Mars in at least some locations (Gale Crater) long enough for life to have developed.

What happened to the atmosphere?

- The rocks found on the Martian surface required higher atmospheric pressures than presently exist
- Mars must have lost its atmosphere
- Can we find independent evidence for this? **Yes!** Finding of the *Maven* spacecraft
- How long did it take to lose its atmosphere?---We'll have to wait for the answer



The El Dorado of future missions: Mars Sample Return

Stay tuned

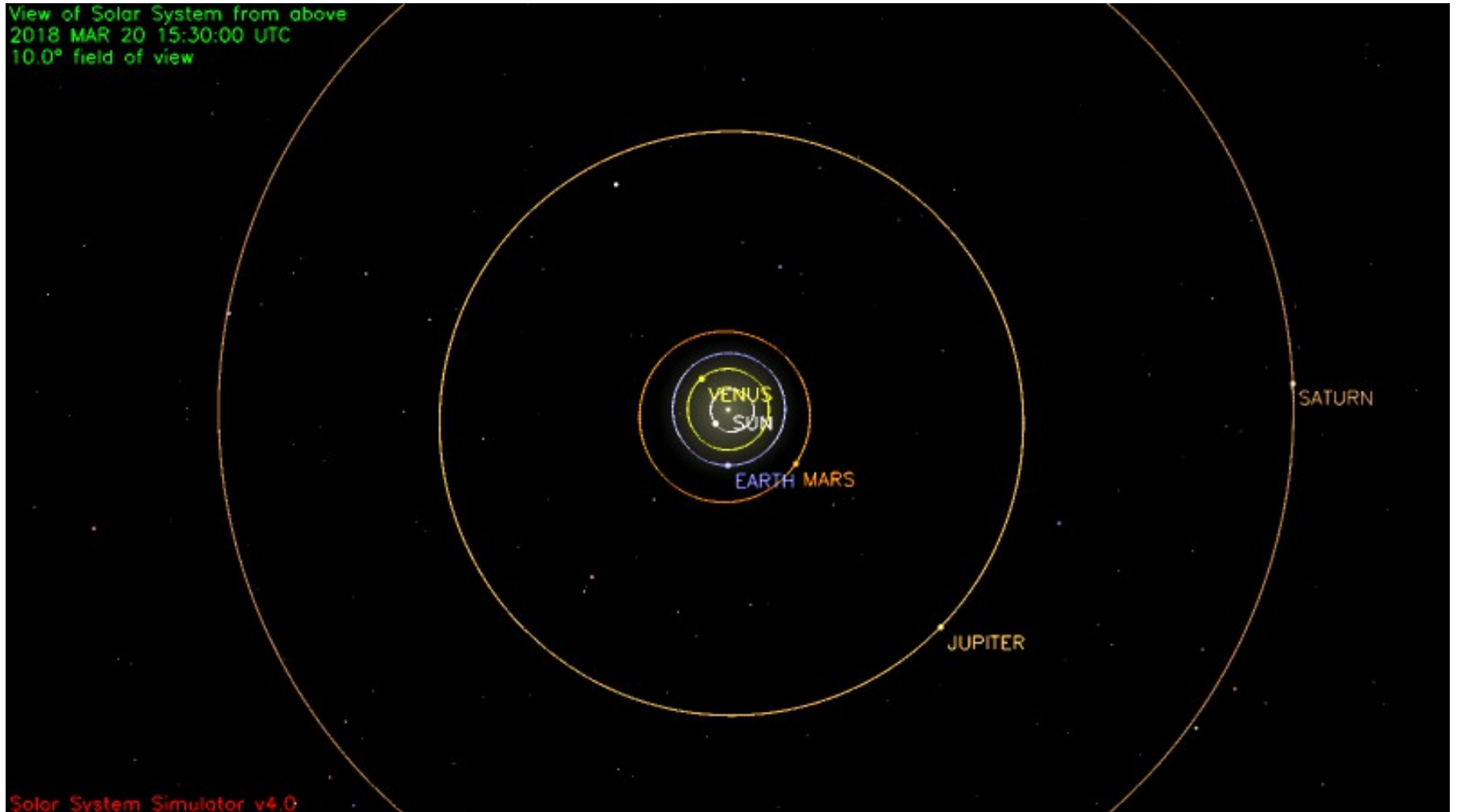


What about the
more distant
planets in the Solar
System?

What can they
tell us about how
planets formed,
the nature of
other solar
systems?



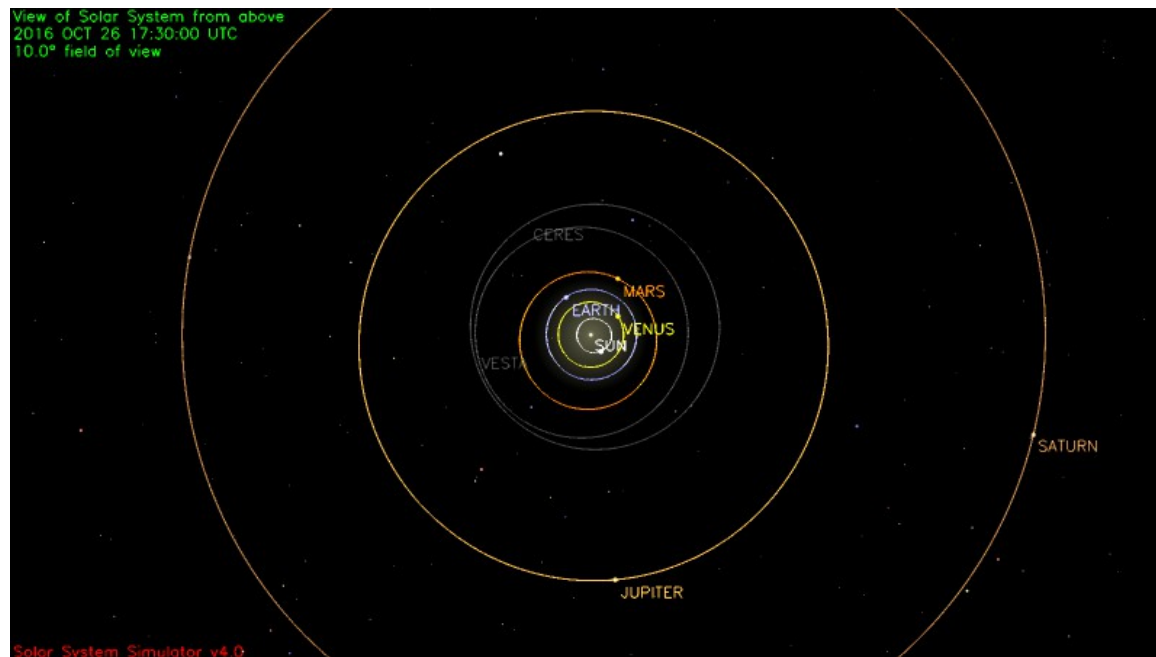
Exploring further out in the Solar System



Jupiter, Saturn, and friends

Jupiter and Saturn: orbital characteristics

Planet	a (AU)	P (yrs)	ecc	Incl (deg)
Jupiter	5.20	11.9	0.049	1.3
Saturn	9.58	29.4	0.057	2.5



What do they look like? Let's start with Jupiter

Jupiter...largest planet in the solar system



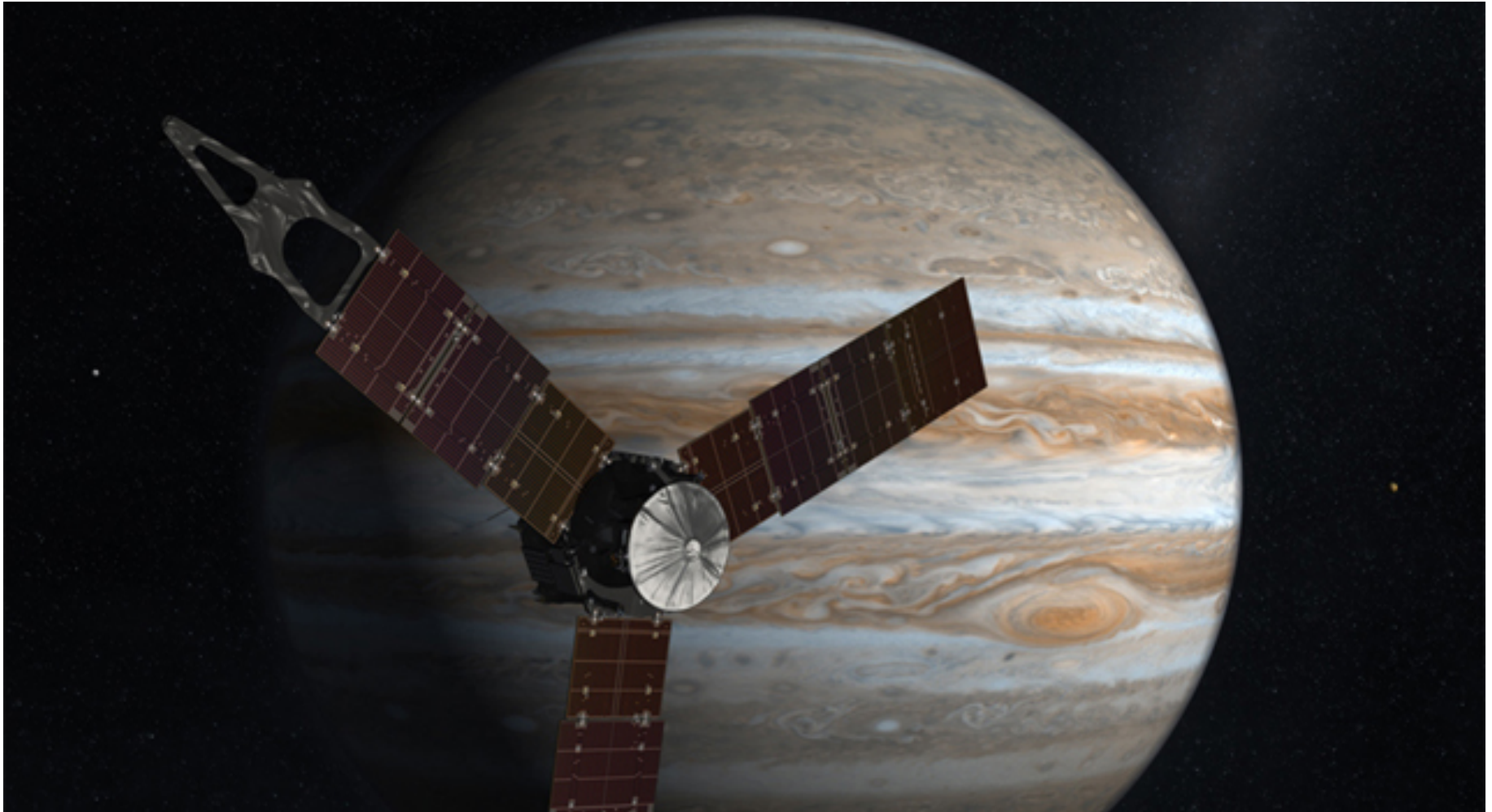
Basic properties of Jupiter and Saturn

- Jupiter: 11.2 X diameter of Earth and 318 X mass
- Saturn: 9.5 X diameter of Earth and 95 X the mass
- Jupiter and Saturn: the “giant planets”
- Jupiter and Saturn are “all atmosphere”, and mainly hydrogen and helium

Jupiter and the Earth



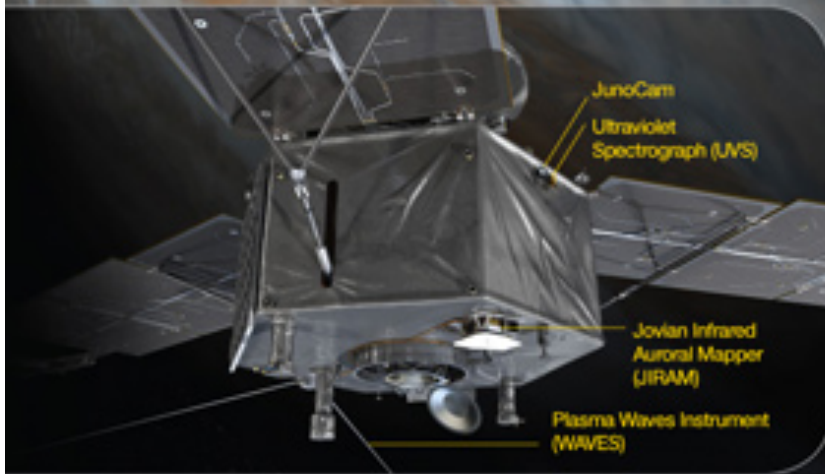
The future exploration of Jupiter... Juno (arrived last summer)



Launch: August 5, 2011... Arrival at Jupiter: July 4, 2016



Juno Spacecraft



SPACECRAFT DIMENSIONS

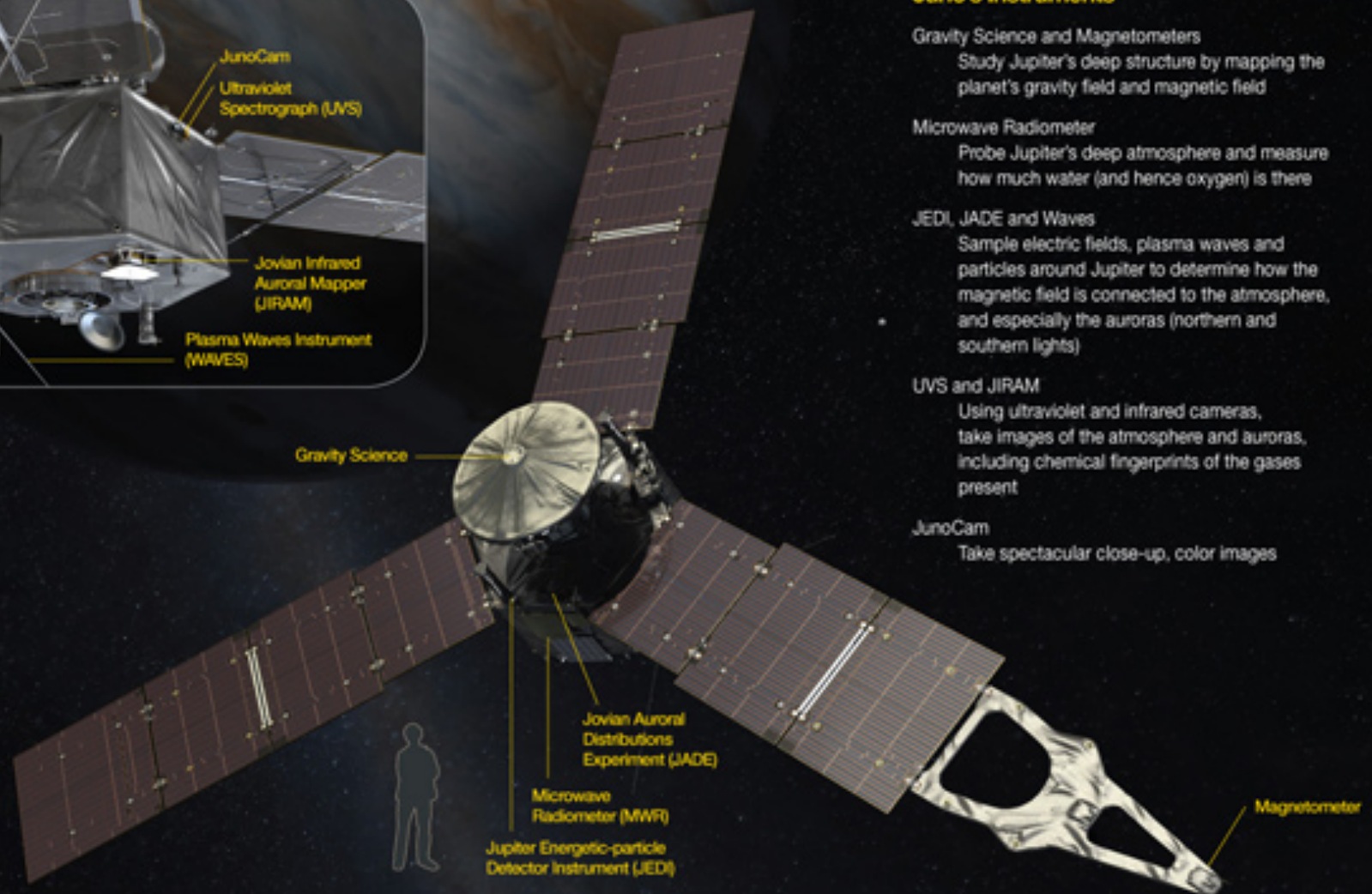
Diameter: 66 feet (20 meters)
Height: 15 feet (4.5 meters)

For more information:
missionjuno.swri.edu &
www.nasa.gov/juno

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov



Juno's Instruments

Gravity Science and Magnetometers

Study Jupiter's deep structure by mapping the planet's gravity field and magnetic field

Microwave Radiometer

Probe Jupiter's deep atmosphere and measure how much water (and hence oxygen) is there

JEDI, JADE and Waves

Sample electric fields, plasma waves and particles around Jupiter to determine how the magnetic field is connected to the atmosphere, and especially the auroras (northern and southern lights)

UVS and JIRAM

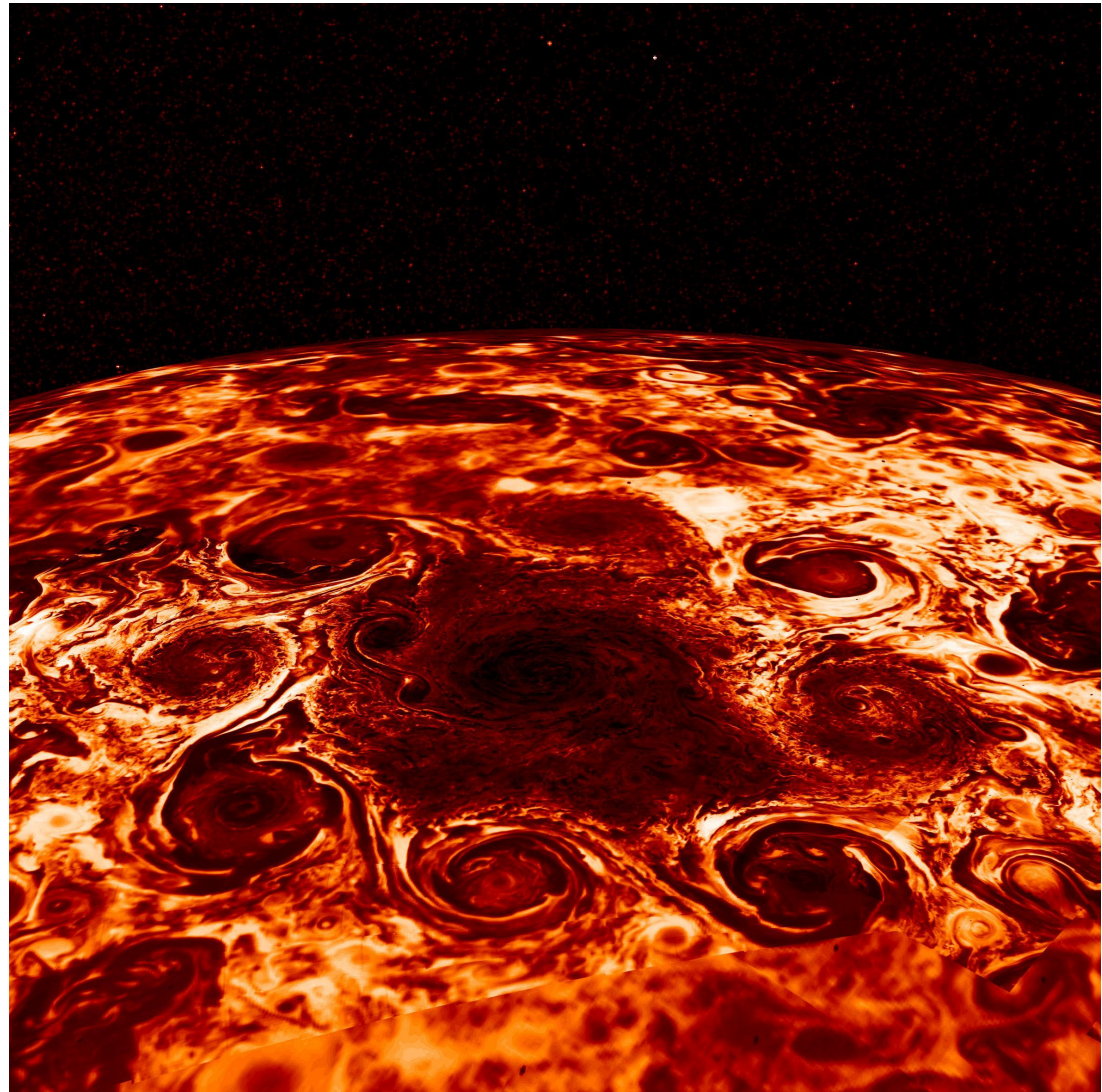
Using ultraviolet and infrared cameras, take images of the atmosphere and auroras, including chemical fingerprints of the gases present

JunoCam

Take spectacular close-up, color images

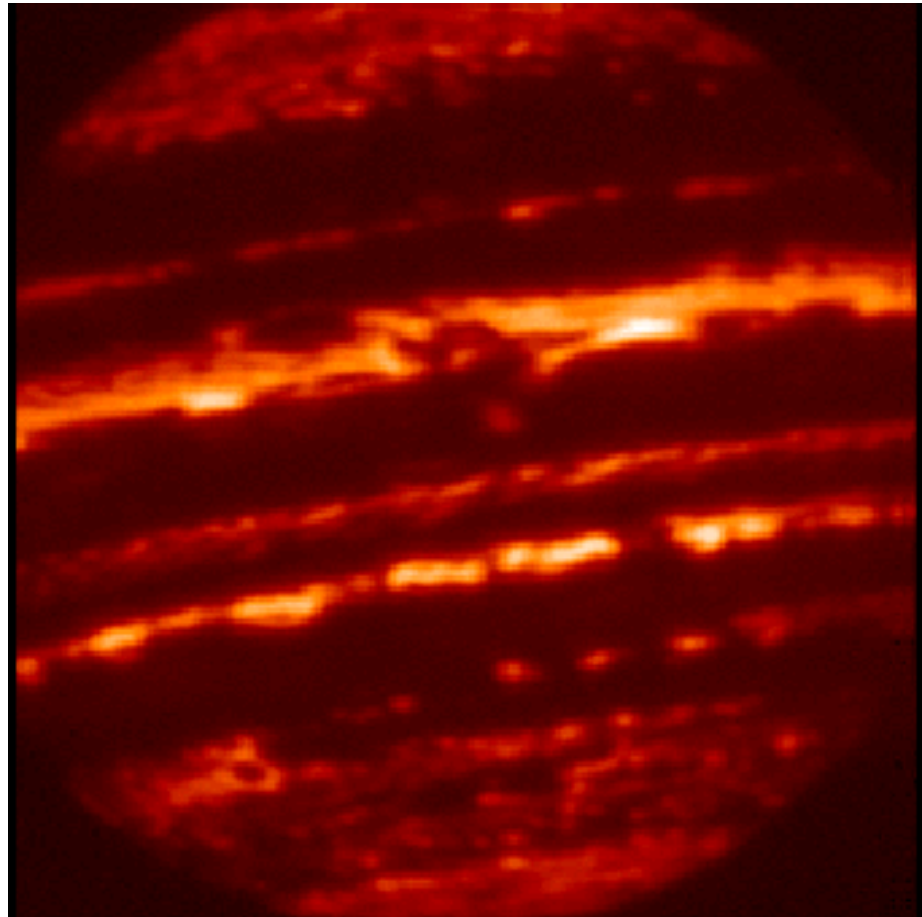
The Juno spacecraft is giving us new insights into Jupiter

There is really no surface on Jupiter; the gas density and pressure get larger and larger, matter weirder and weirder



Are Jupiter and Saturn planets or stars?

Jupiter as
seen at
infrared
wavelengths



Jupiter emits 70% more radiation to space than it receives from the Sun. It has an “engine” inside

The Moons of Jupiter



Jupiter has many moons

- 12 when I started studying astronomy
- A standard textbook lists 38
- Most important are the 4 **Galilean** satellites, Io, Europa, Ganymede, Callisto



From Earth, it is difficult to learn too much about the Galilean satellites

At **opposition** of Jupiter, the angular diameter of Ganymede is 1.7 arcseconds

Pre space-age telescope observations revealed a little bit about size, reflectivity (albedo), and surface features

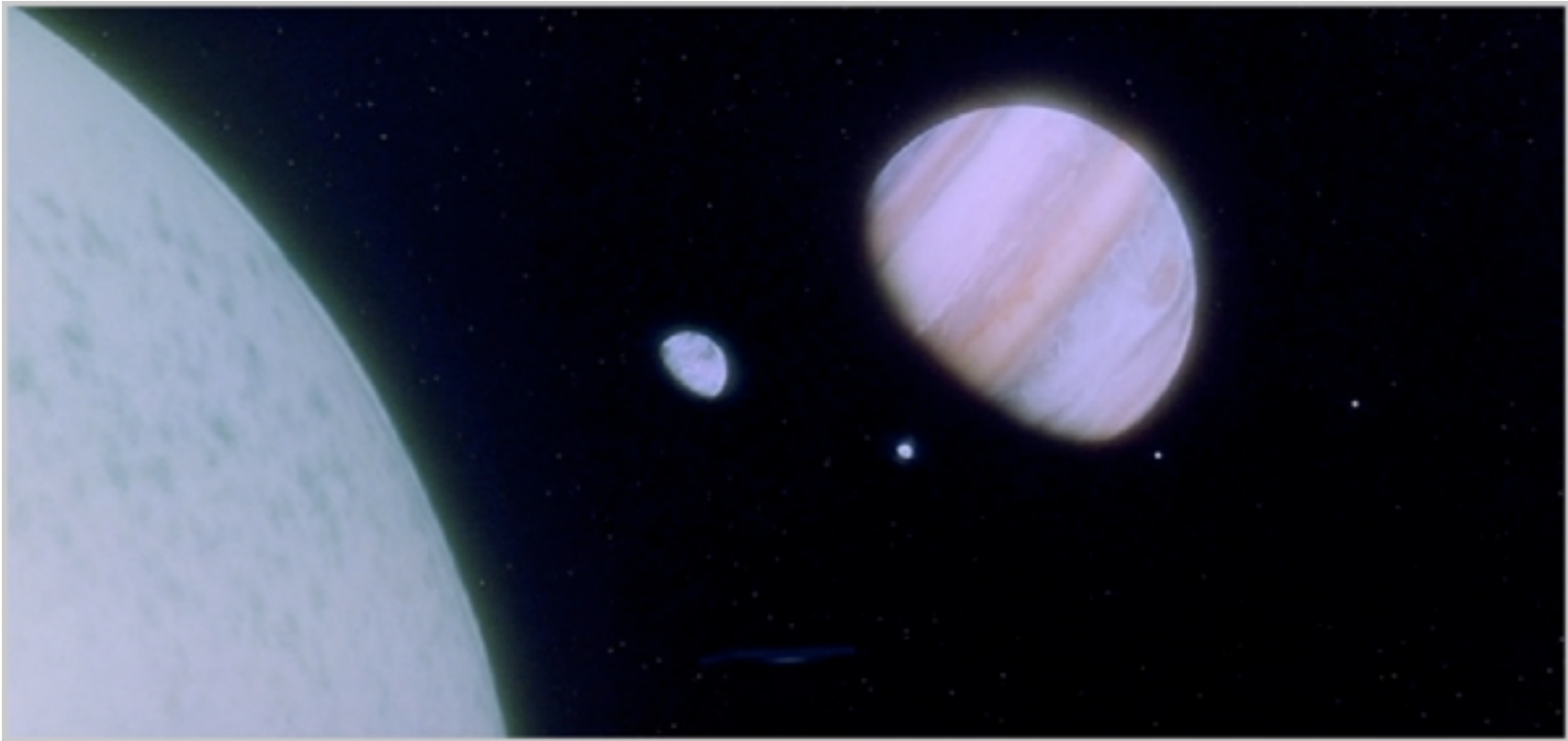


Basic data on the Galilean satellites

moon	a (km)	P (days)	D (km)
Io	422,000	1.769	3630
Europa	671,000	3.551	3130
Ganymede	1,071,000	7.155	5280
Callisto	1,884,000	16.689	4840
MOON	384,000	27.32	3476

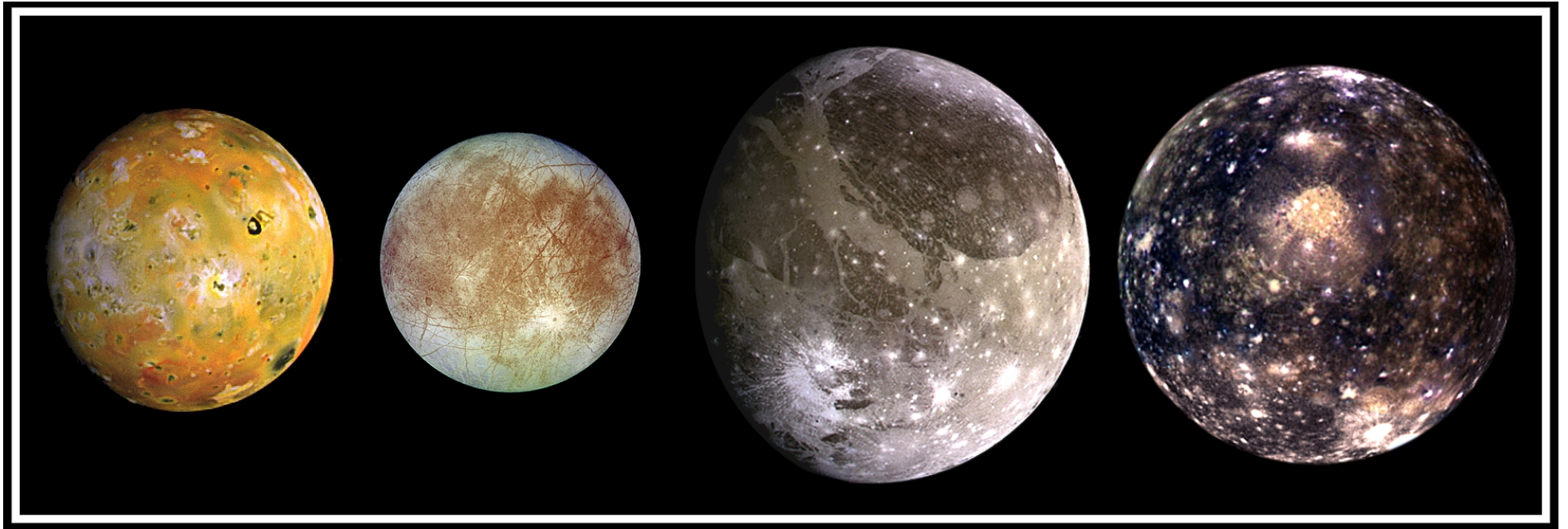
The largest Moon, Ganymede, has a diameter about 50 percent larger than our Moon

What are the moons of Jupiter like? Would do they look like “up close”?



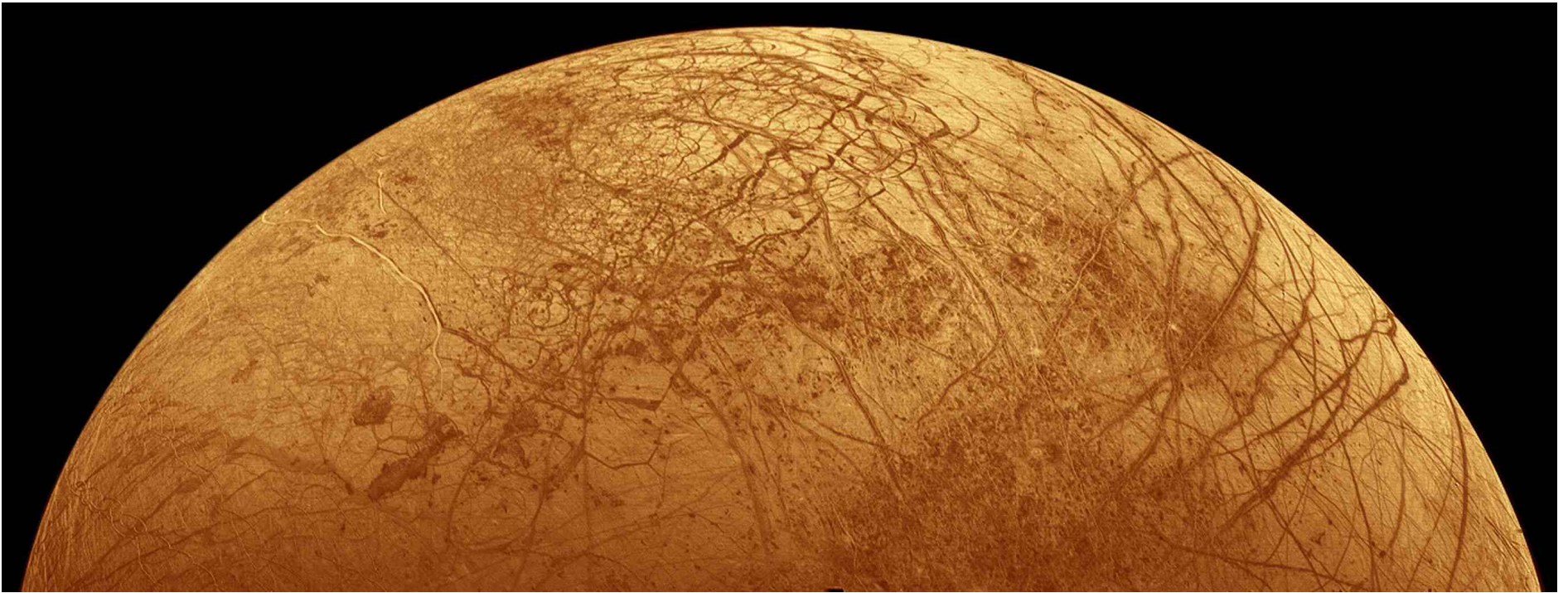
The 1968 movie “2001 A Space Odyssey” has them similar and looking like our Moon

All of them together (sibling portrait)



Images scaled to give correct relative sizes

Exploring Europa



What is under its ice-covered plains?

Europa is slightly smaller and less massive than our Moon. It is of interest because the entire moon is encased in ice. There are cracks and other features that hint at liquid water at some point below the surface,

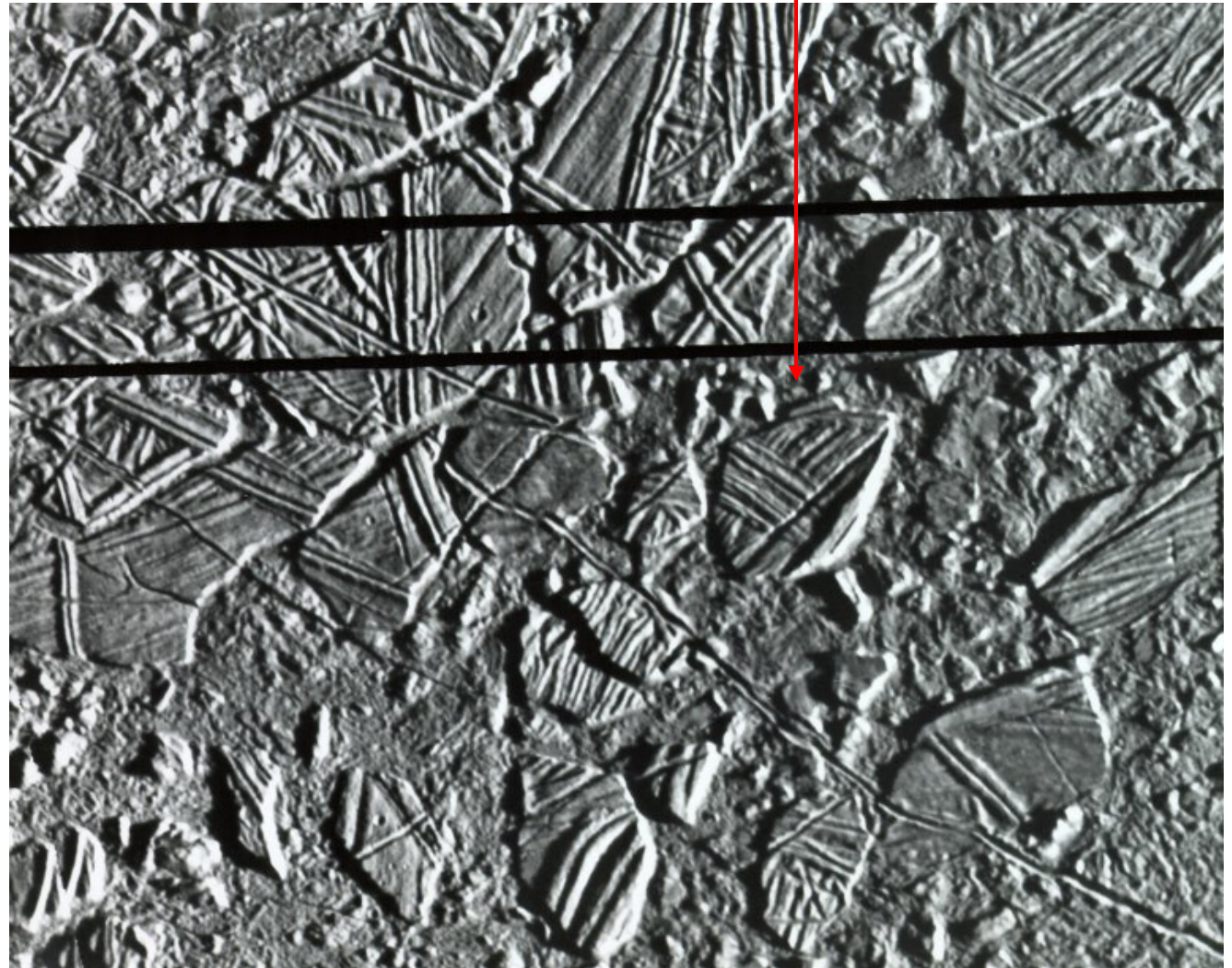
Views of the cracks from Galileo



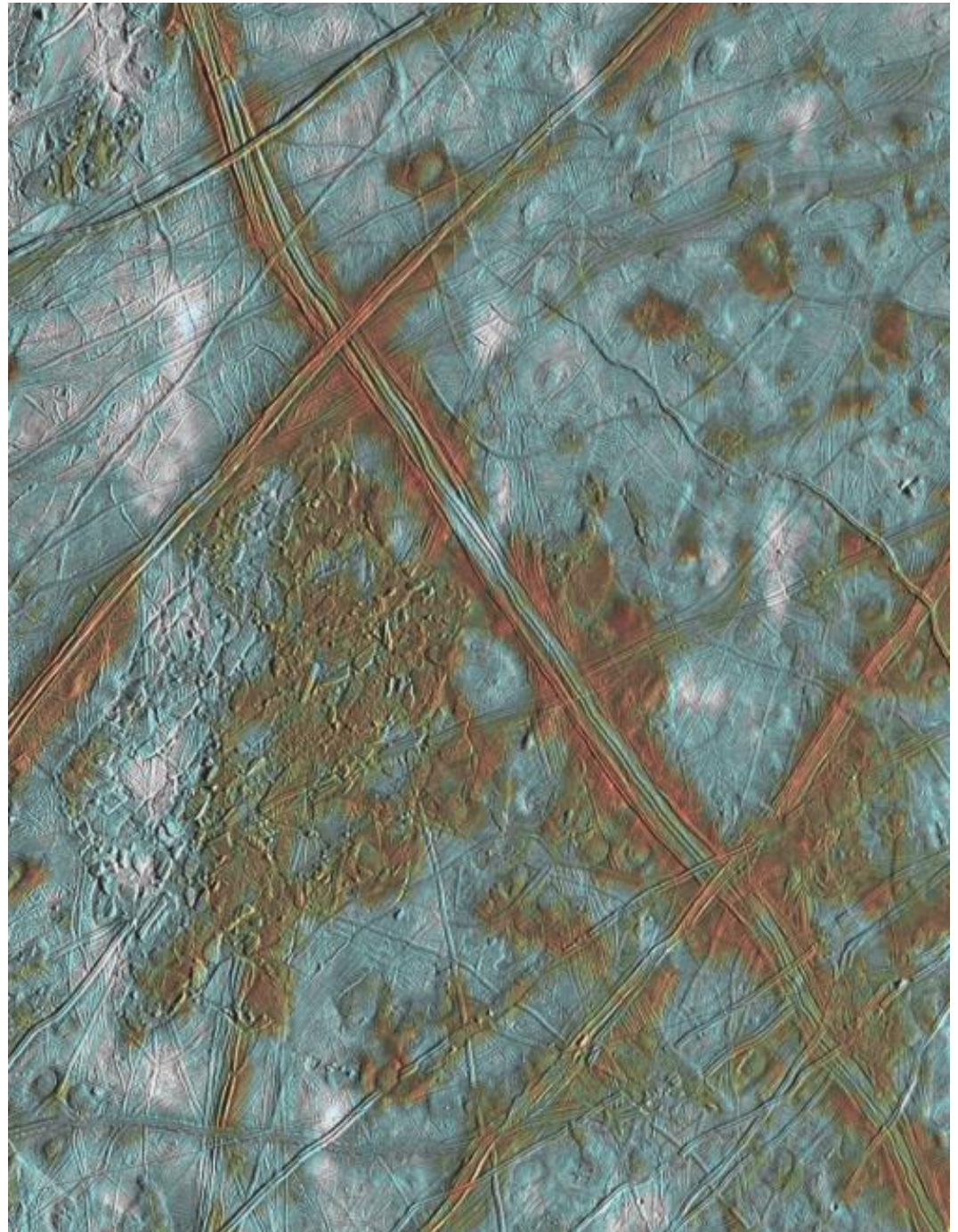
Picture
about 100
miles on a
side

A related phenomenon. The ice rafts of Europa

Similar features seen in arctic ocean and are due to flows of ocean underneath



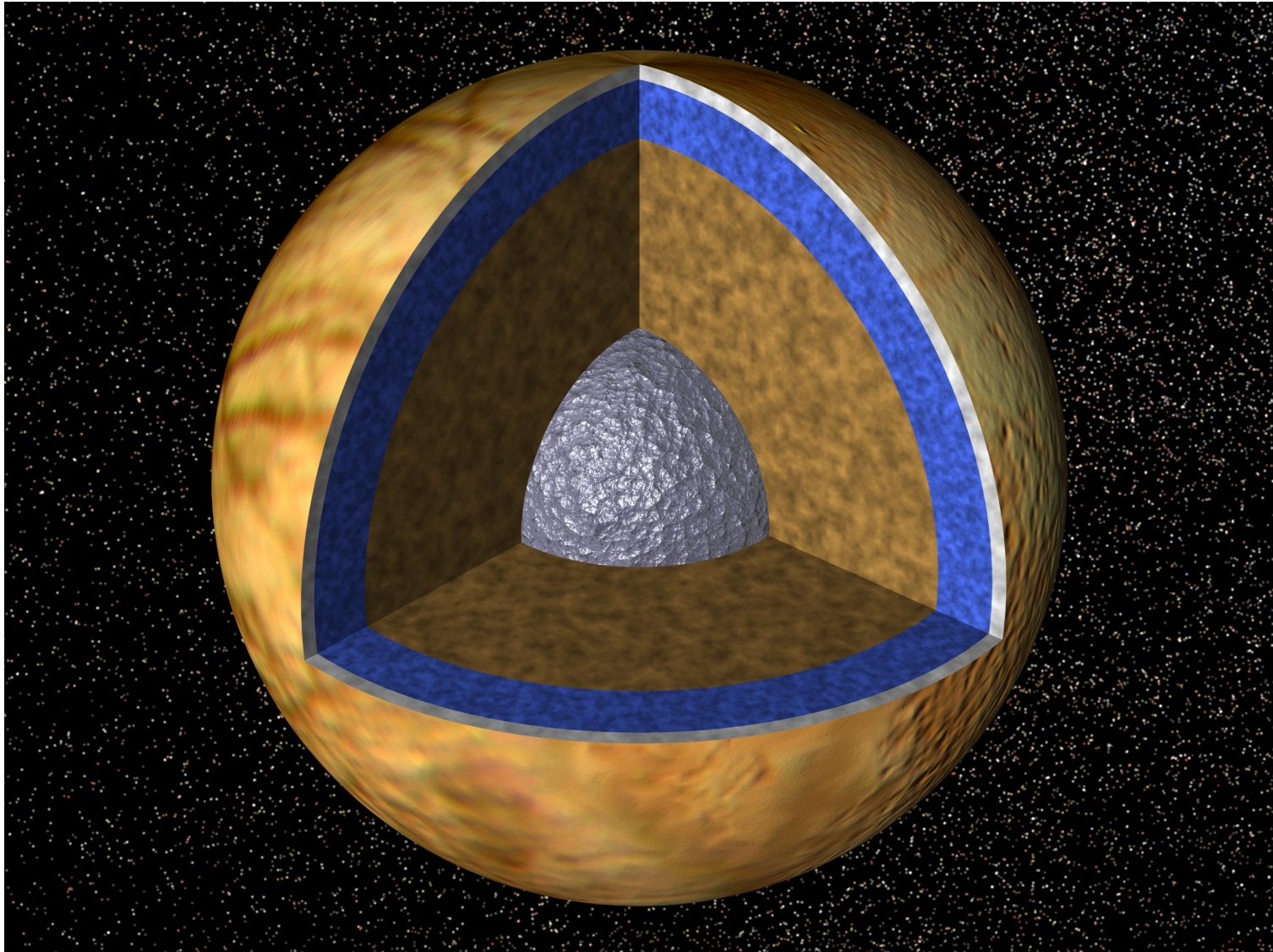
Evidence for flows
from beneath the
surface of Europa



There is evidence (circumstantial) for liquid water under the surface, but how far down is it? What is below the water?

Spacecraft missions to Europa over the next few decades might tell us

Speculations on interior structure of Europa



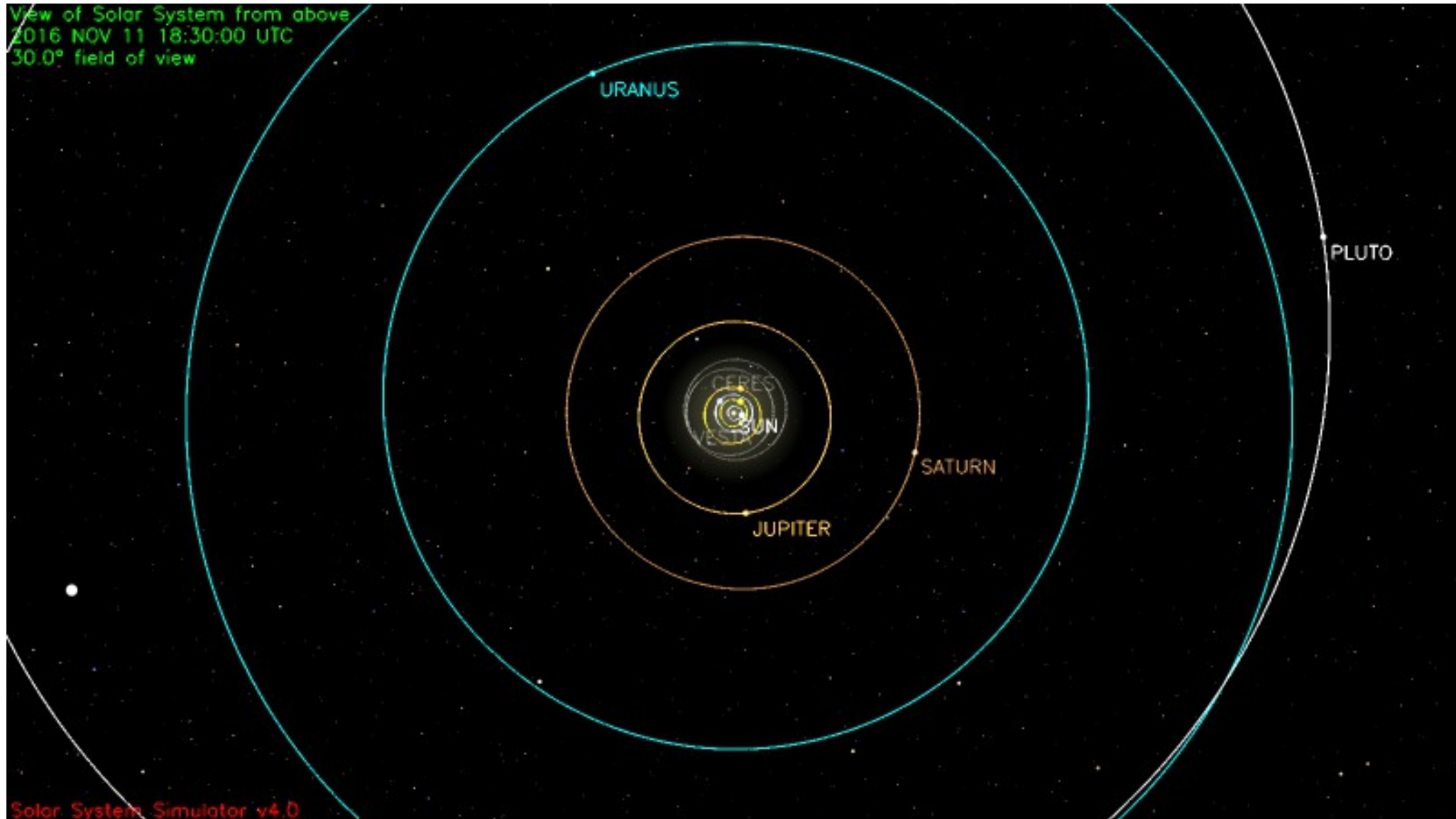
A summary of what we know about Europa

- Slightly smaller in mass and diameter than the Moon
- Surface covered with water ice casing
- Evidence for surface “activity” from cracks and grooves, and ice rafts
- Small numbers of craters implies surface has reformed in last 100 million years
- Estimates that liquid layer, “sealed ocean” is between 10 - 50 kilometers below the surface, with possible rocky sea floor

A future Europa Lander could tell us much about the possible subsurface ocean of Europa



Further out...to the edge of the Solar System



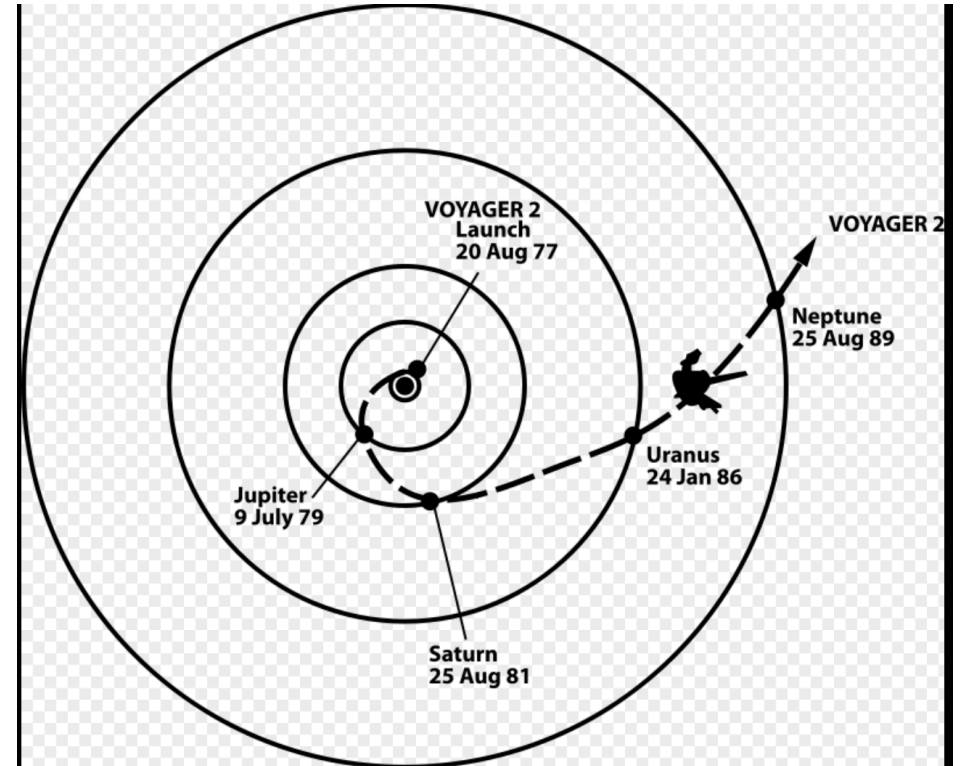
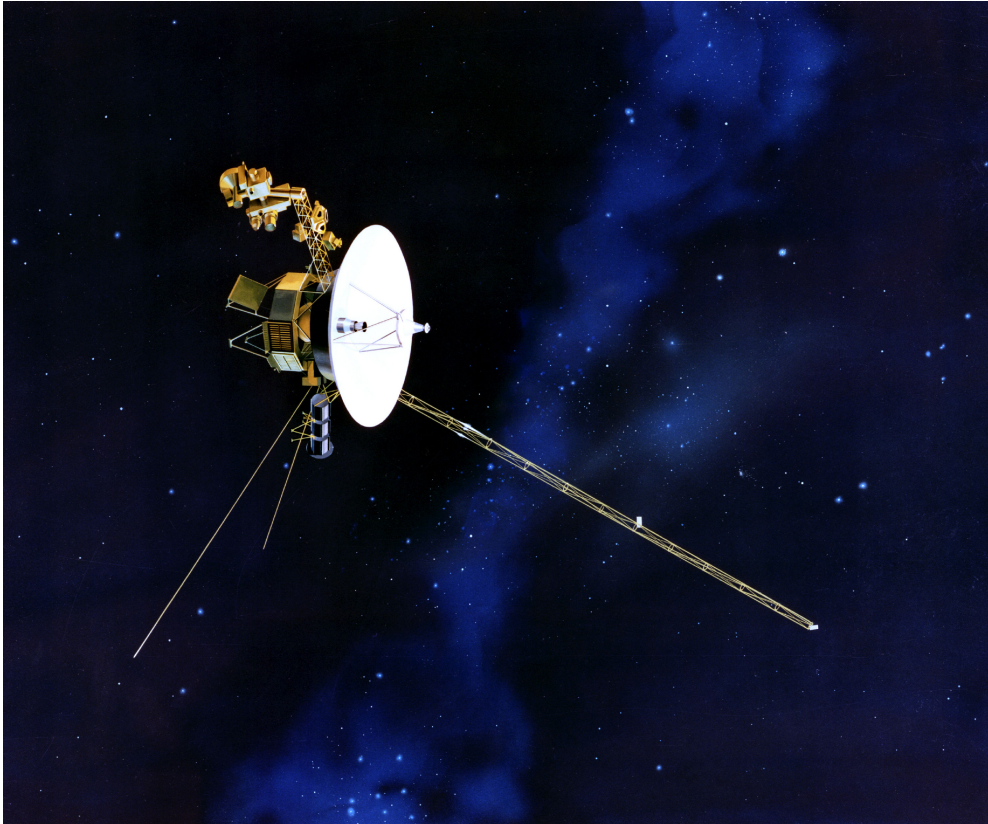
Uranus and Neptune... where are they? Let's look at a **Table!**

Planet	a (AU)	P(yr)	ecc	Incl (degrees)
Uranus	19.20	83.7	0.046	0.8
Neptune	30.5	163.7	0.011	1.8

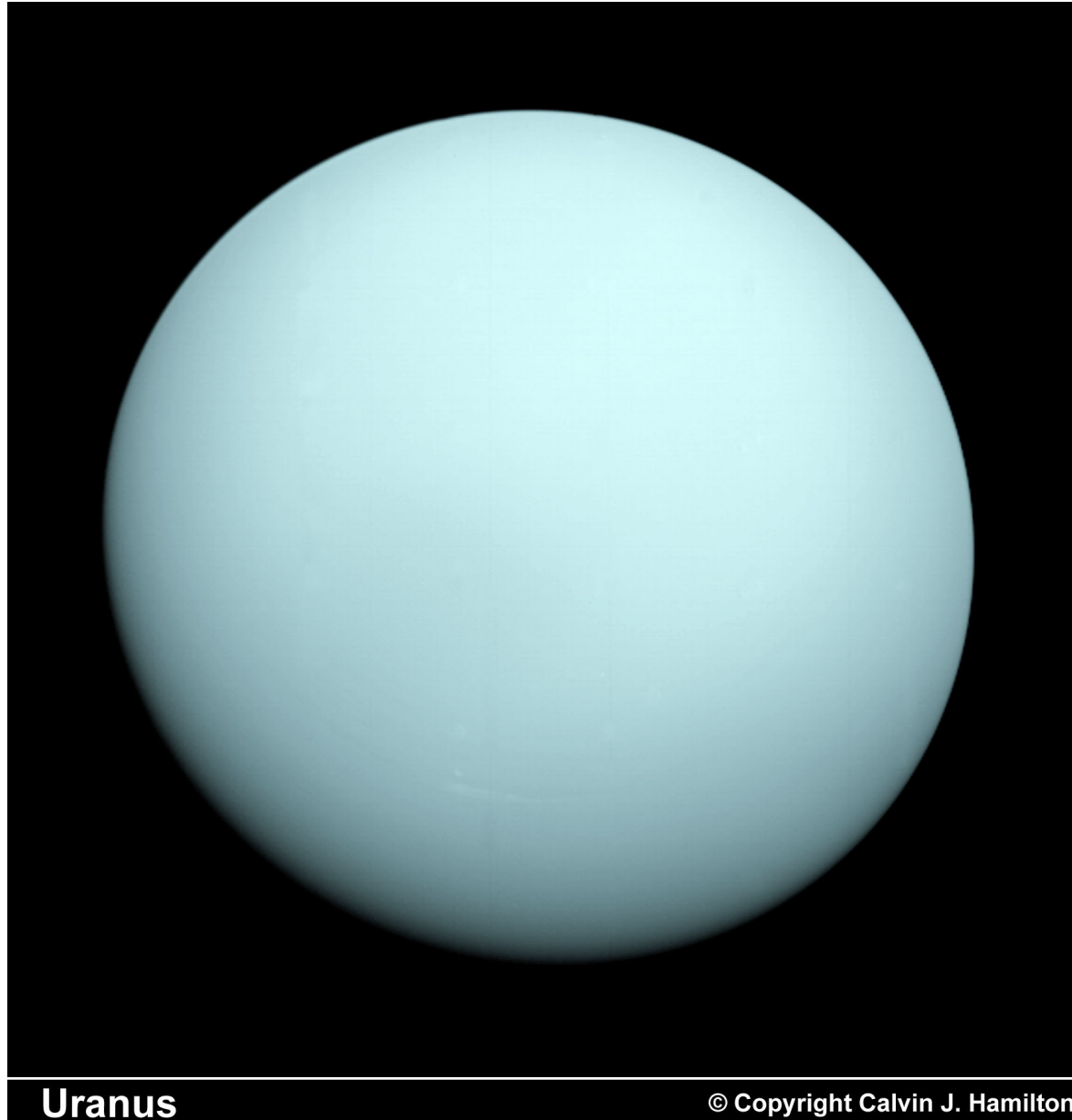
Current locations: Uranus: Pisces;
Neptune: Aquarius.

What do they look like?

Our best views (and scientific information) come from visits (flybys) of the Voyager 2 spacecraft



Uranus as seen by Voyager 2

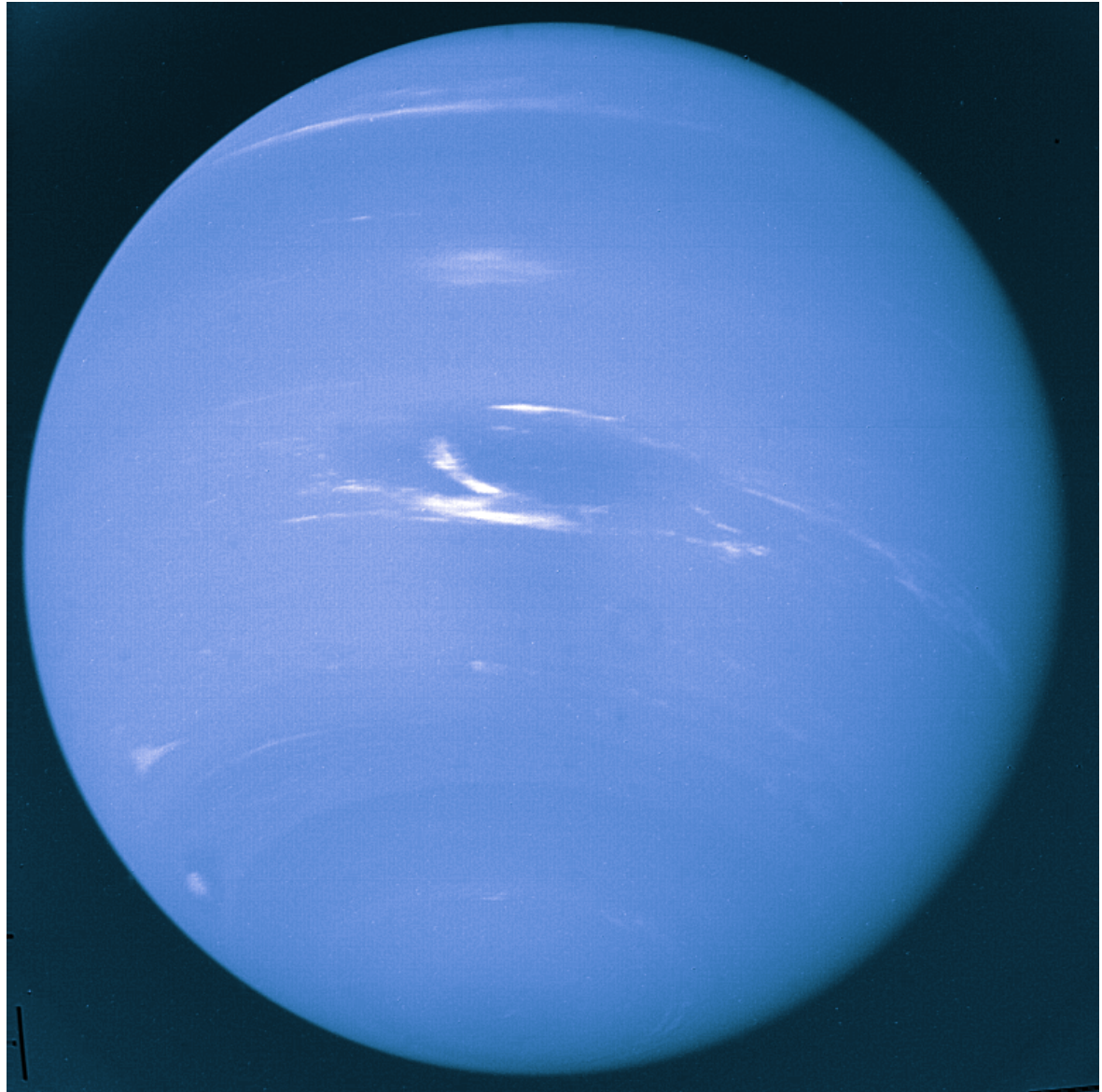


Uranus

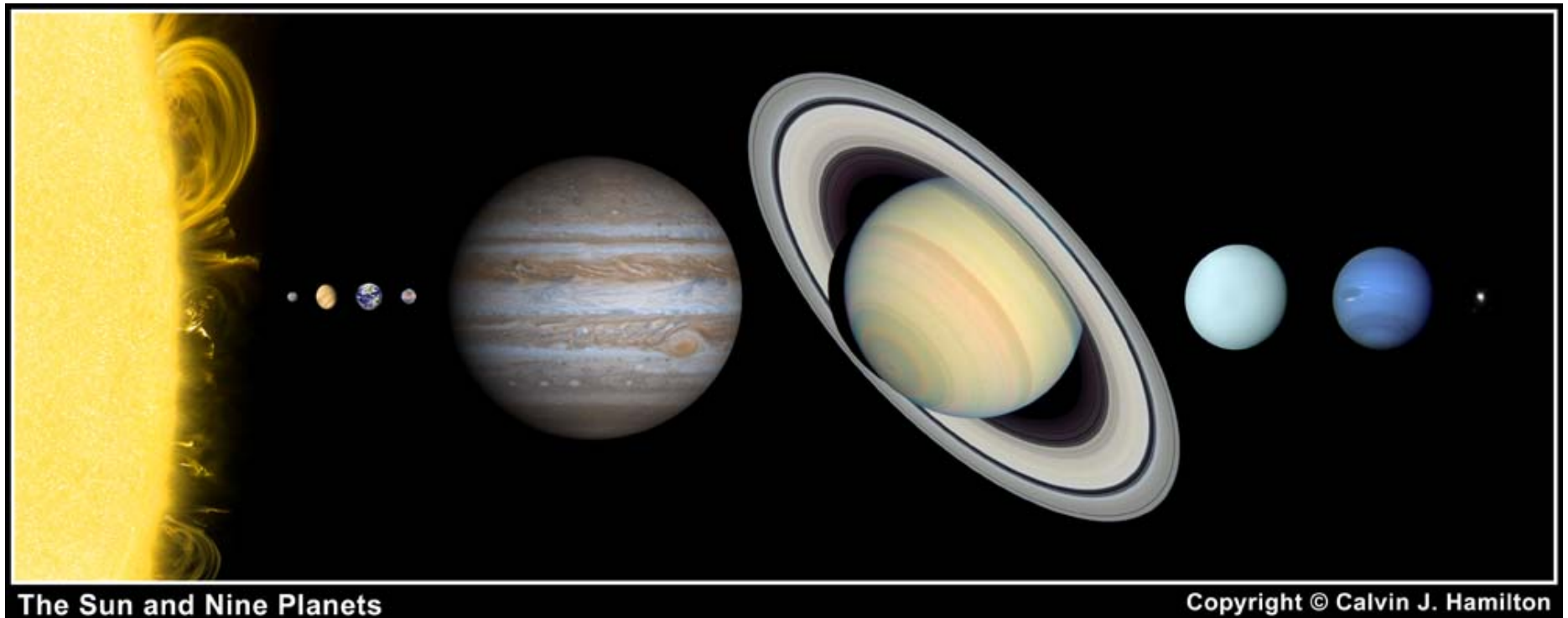
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Neptune as seen by Voyager 2

They look like
“blue Jupiters”

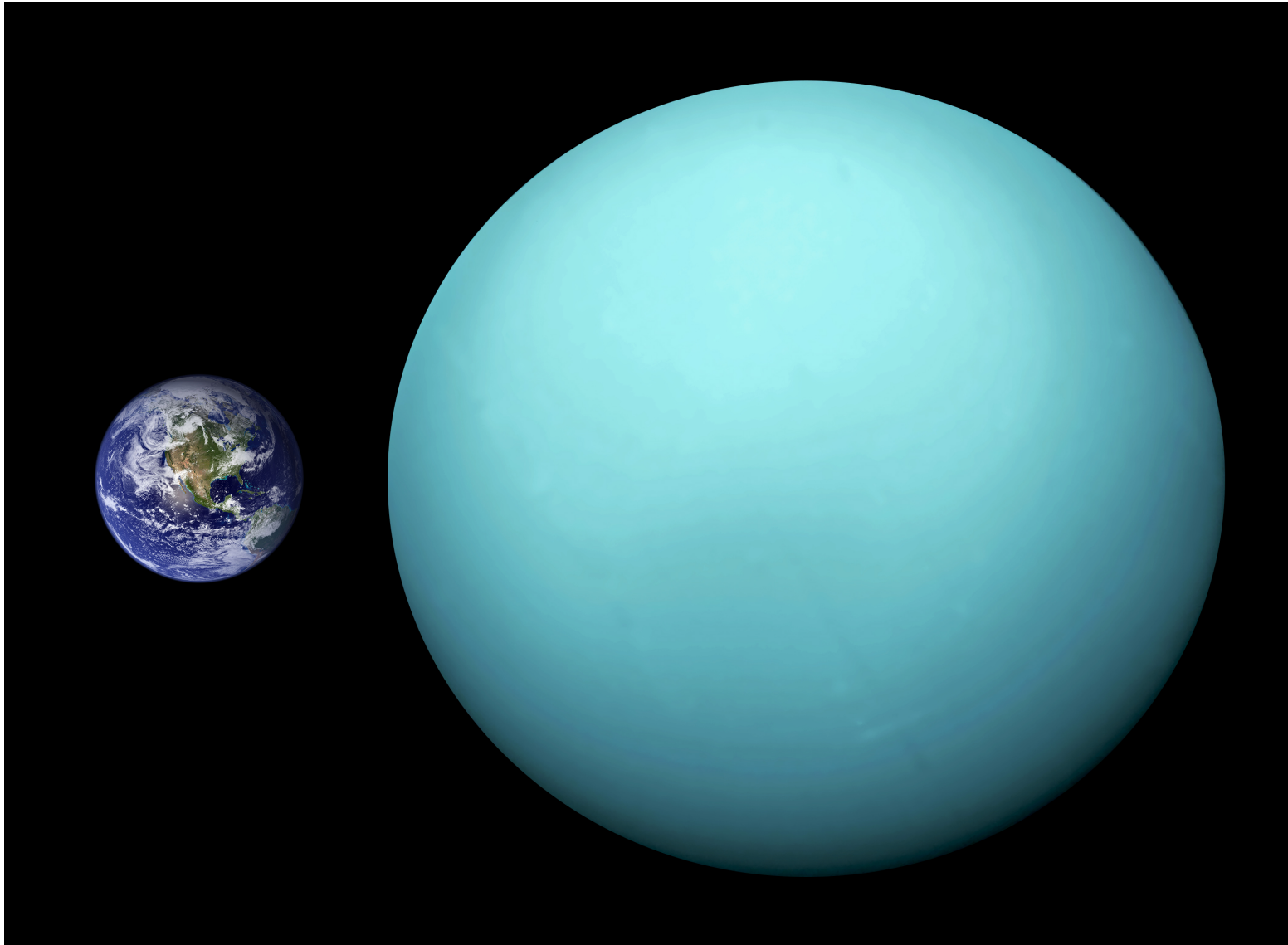


How do they match up to Jupiter and Saturn?

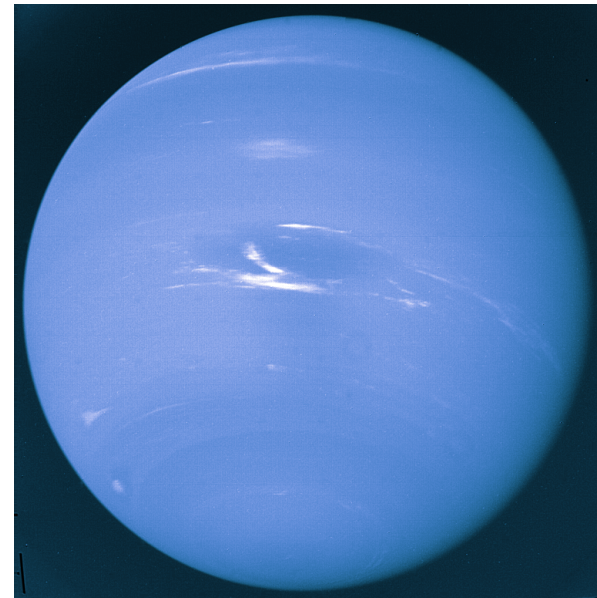
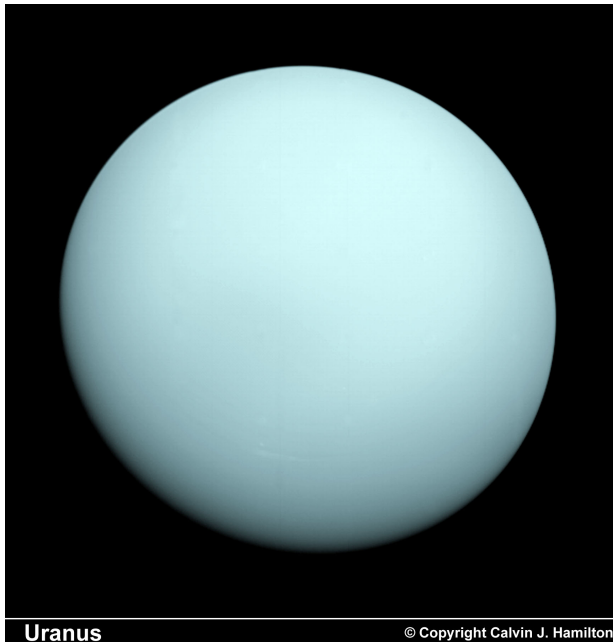


Smaller than Jupiter and Saturn; much bigger than the Earth

Uranus (and Neptune) substantially larger than Earth



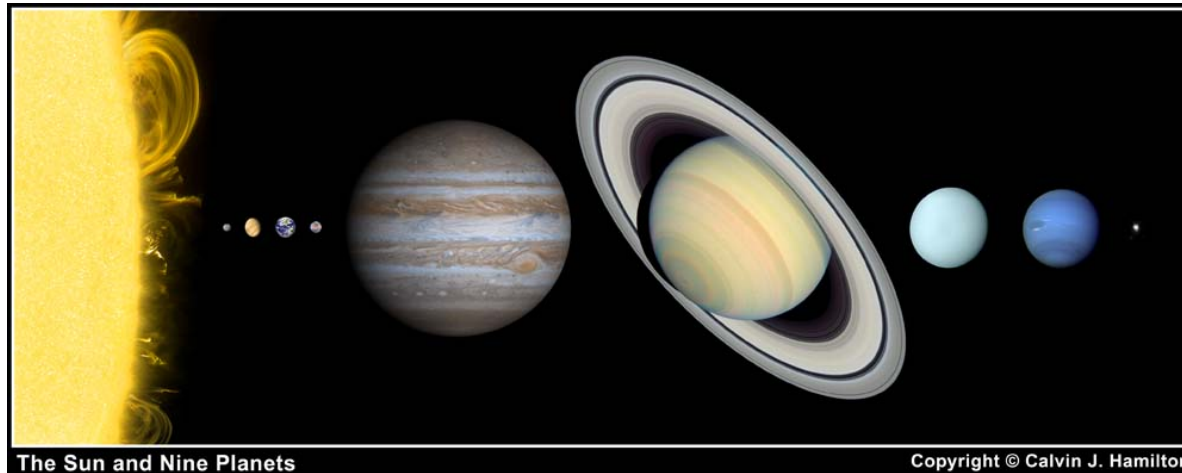
Uranus and Neptune (just the facts, Ma'am)



planet	D (rel to Earth)	M (rel to Earth)
Uranus	4.01	14.5
Neptune	3.88	17.1

Uranus and Neptune are relevant in the exoplanet context

How do we summarize all of this?



- The small rock planets are in close to the Sun
- The big, gaseous planets are way out, far from the Sun
- Mars *may have* had habitable conditions on its surface billions of years ago
- Moons of the outer planets (Europa, Titan) may be promising locations for life