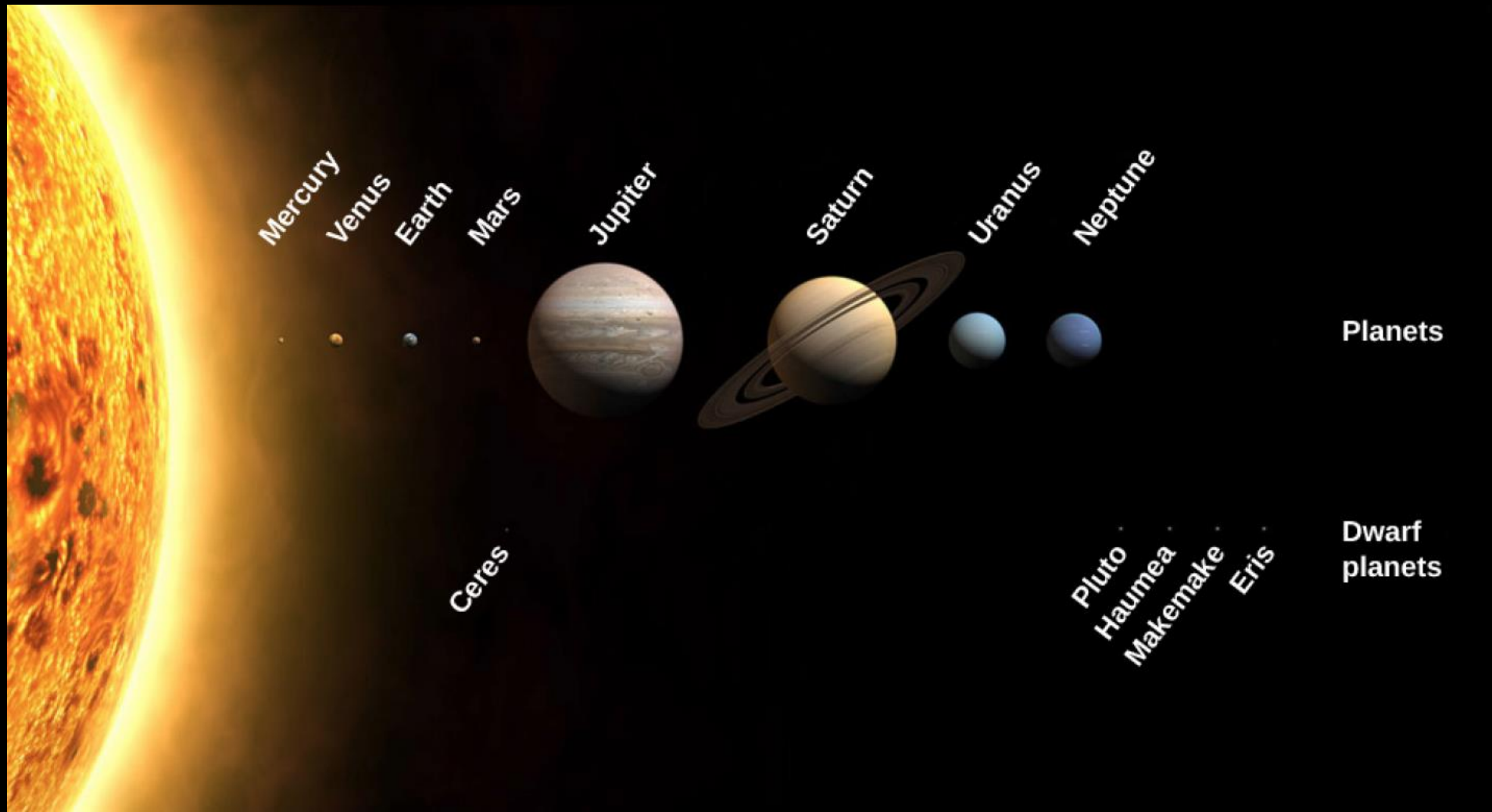
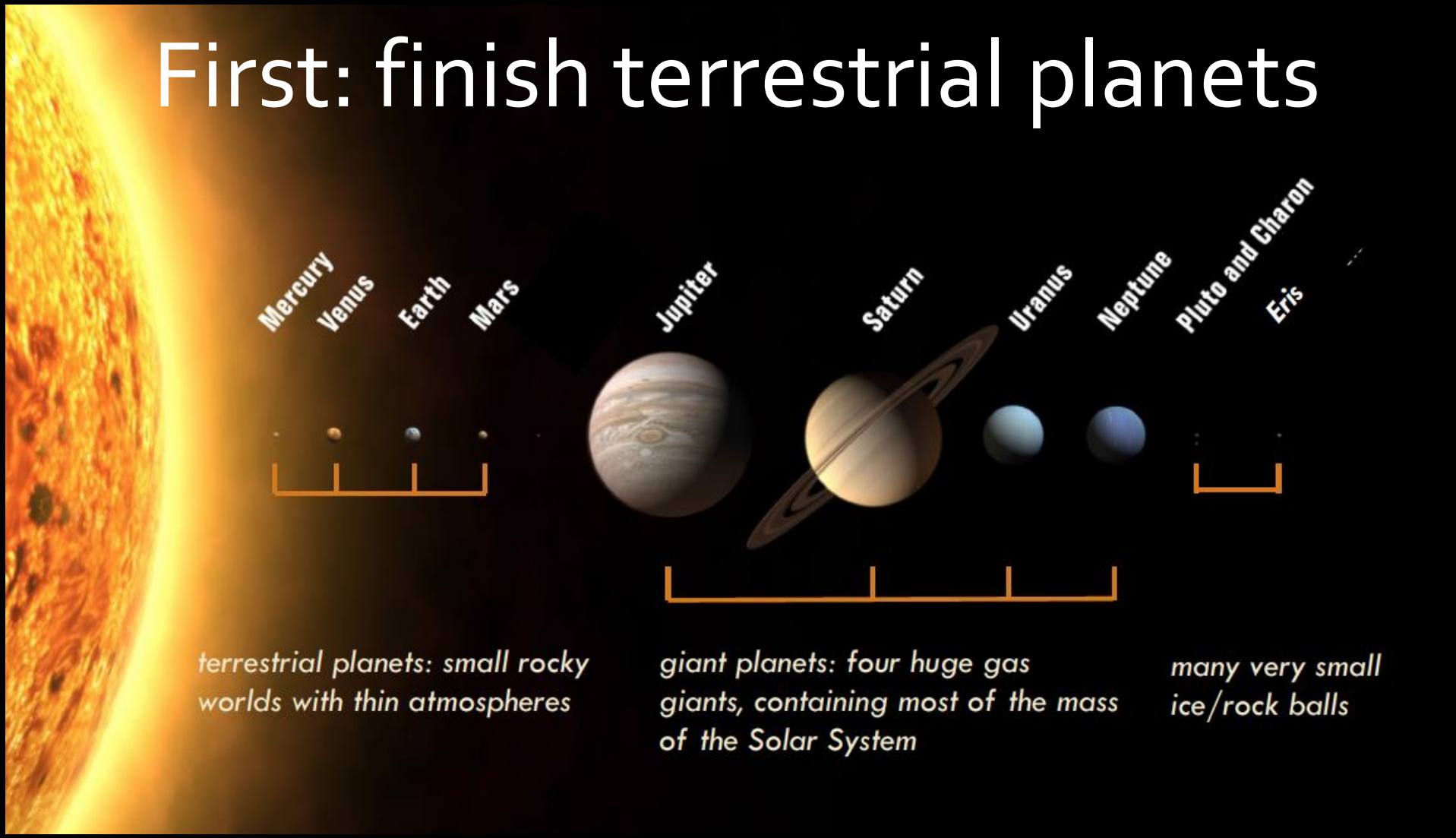
Our solar system: the giant planets and their moons

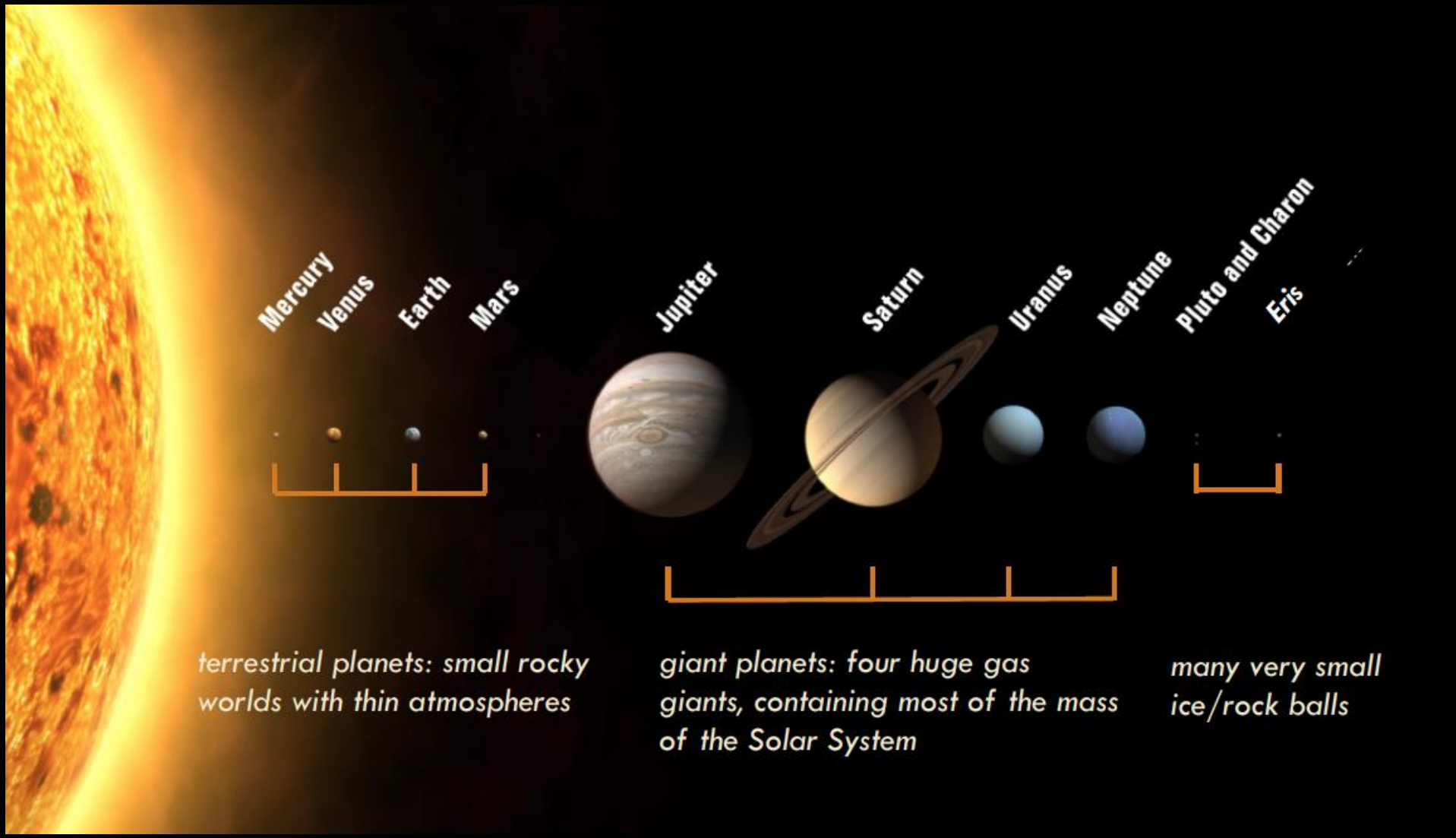


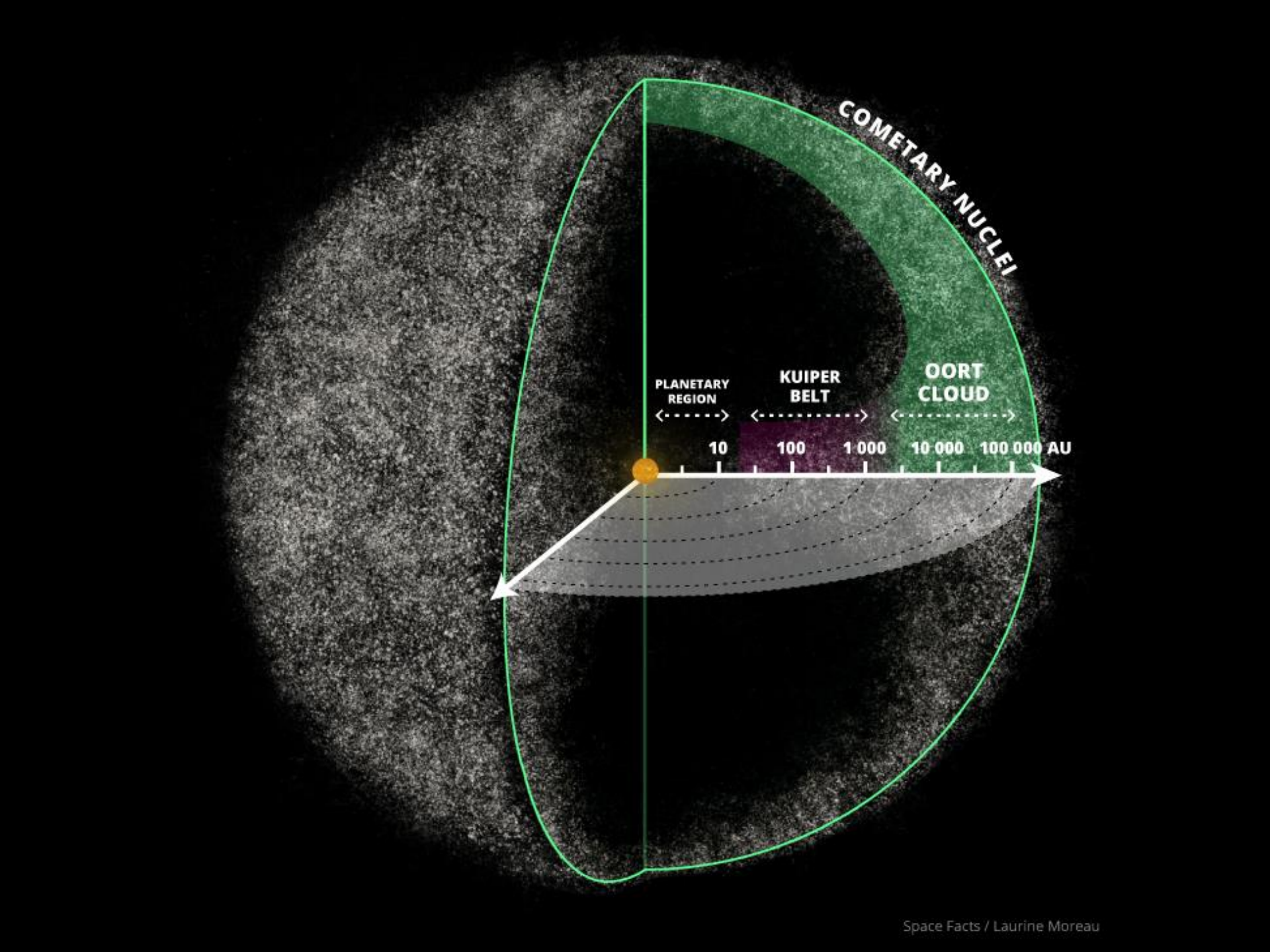
First: finish terrestrial planets



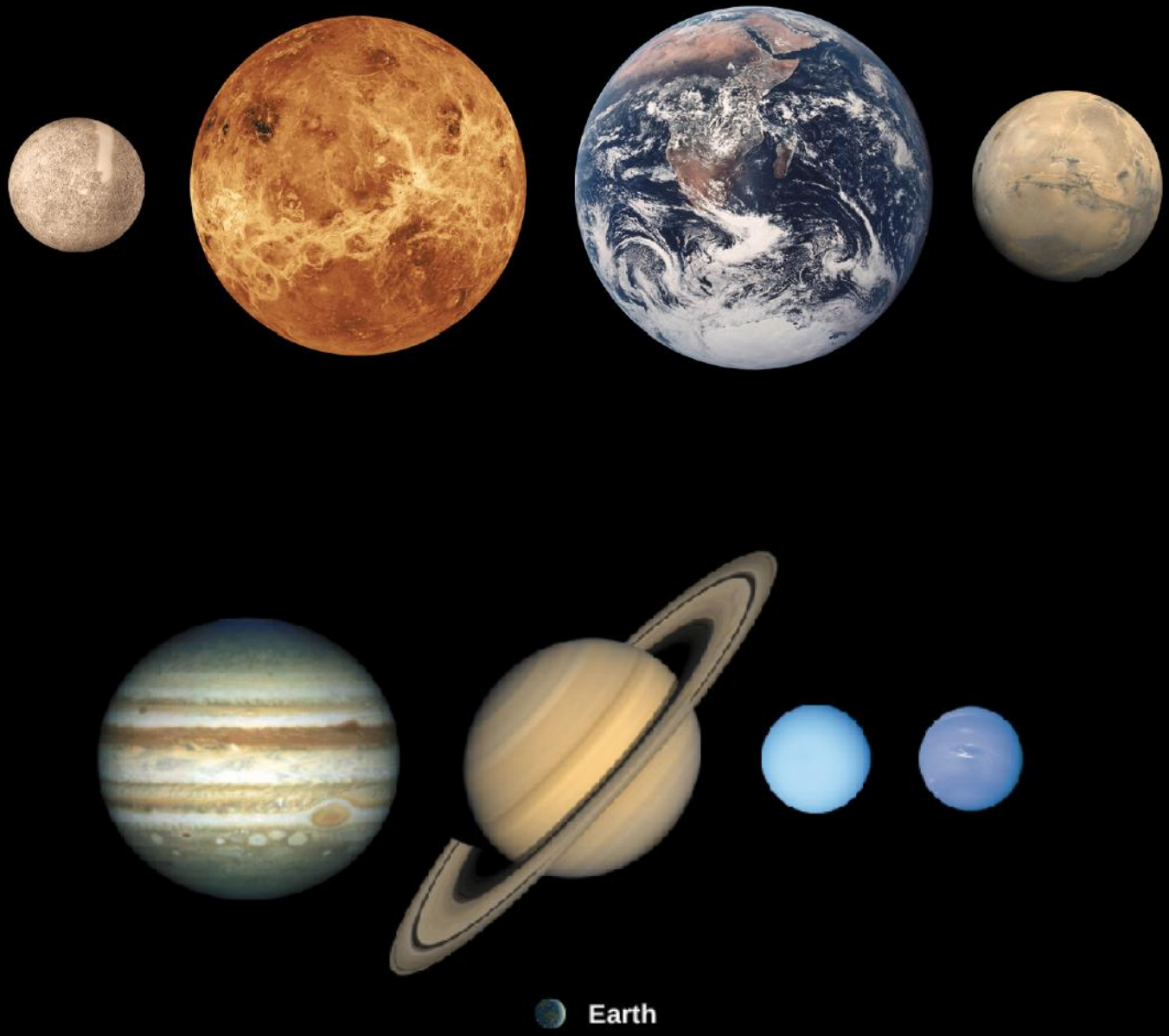
LLM policy for homework 4, project

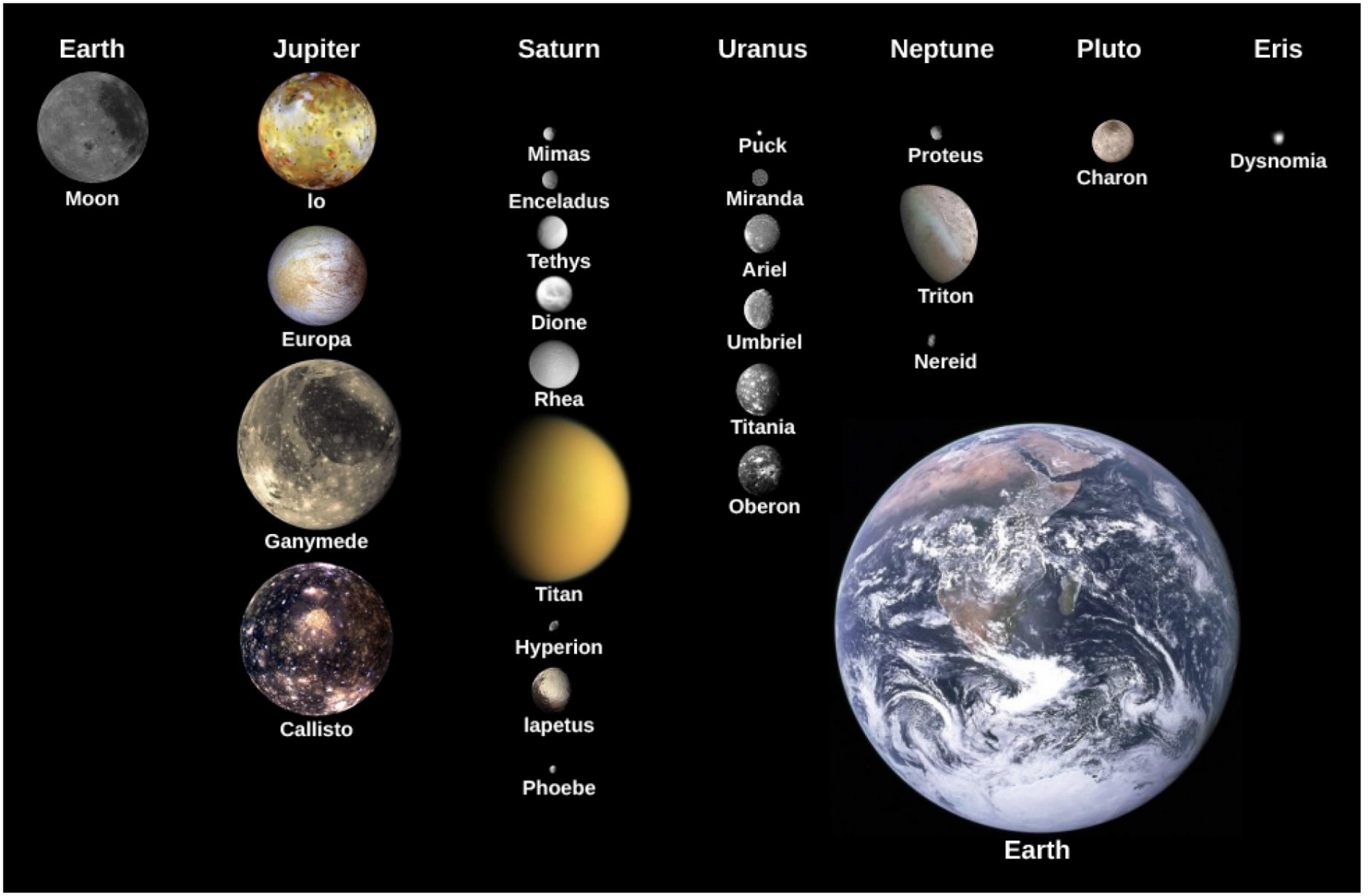
- Use LLMs (like ChatGPT) however you would like!
  - Acknowledge where you use it!
  - (obviously that acknowledgement is specific to this class; follow the syllabus for other courses and be smart about using ChatGPT – it can be obvious)
- The work you turn in must be your own
  - Points may be deducted when answers sound too much like ChatGPT.
- I think that LLMs won't help too much with the project
  - Editing/structure help
- Homework 4: added a hard question because students did so well previously
  - ChatGPT effect!

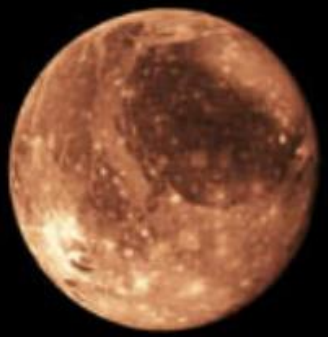

Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto and Charon
Eris
terrestrial planets: small rocky worlds with thin atmospheres
giant planets: four huge gas giants, containing most of the mass of the Solar System
many very small ice/rock balls



Space Facts / Laurine Moreau


Earth


Earth
Moon
Jupiter
Io
Europa
Ganymede
Callisto
Saturn
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
Hyperion
Iapetus
Phoebe
Uranus
Puck
Miranda
Ariel
Umbriel
Titania
Oberon
Neptune
Proteus
Triton
Nereid
Pluto
Charon
Eris
Dysnomia
Earth

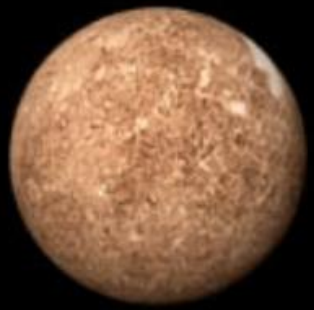


Ganymede

5262 km

Titan

5150 km

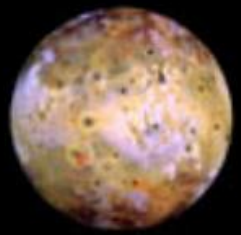


Mercury

4880 km

Callisto

4806 km



Io

3642 km

Moon

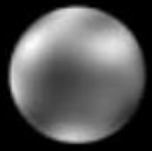
3476 km

Europa

3138 km

Triton

2706 km



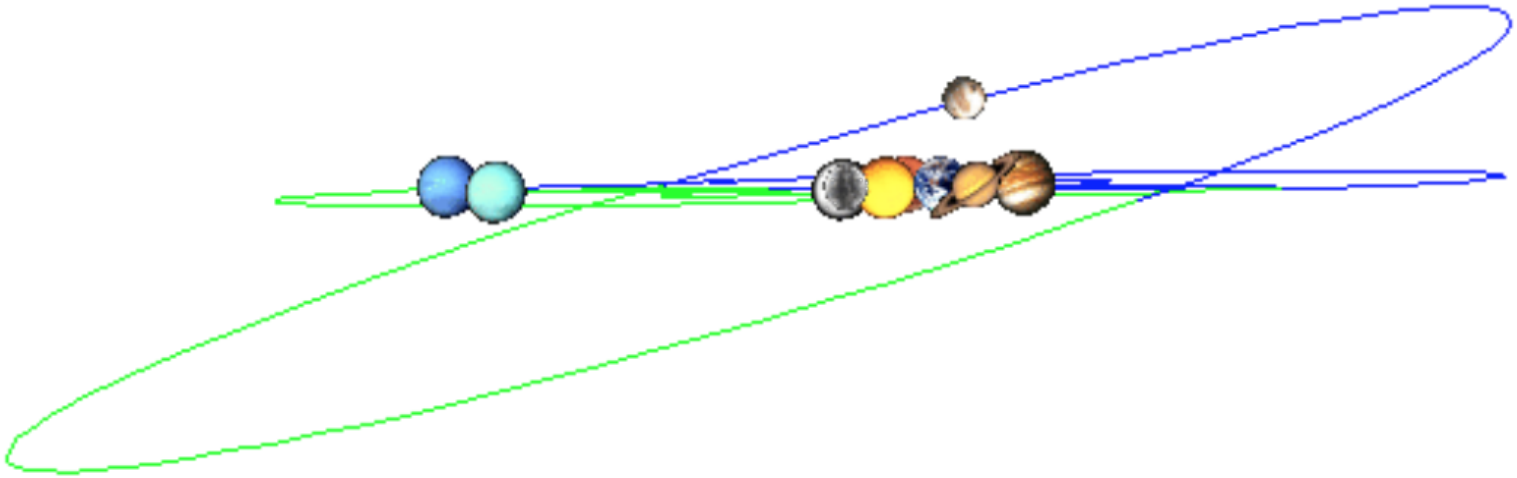
Pluto

2300 km

Titania

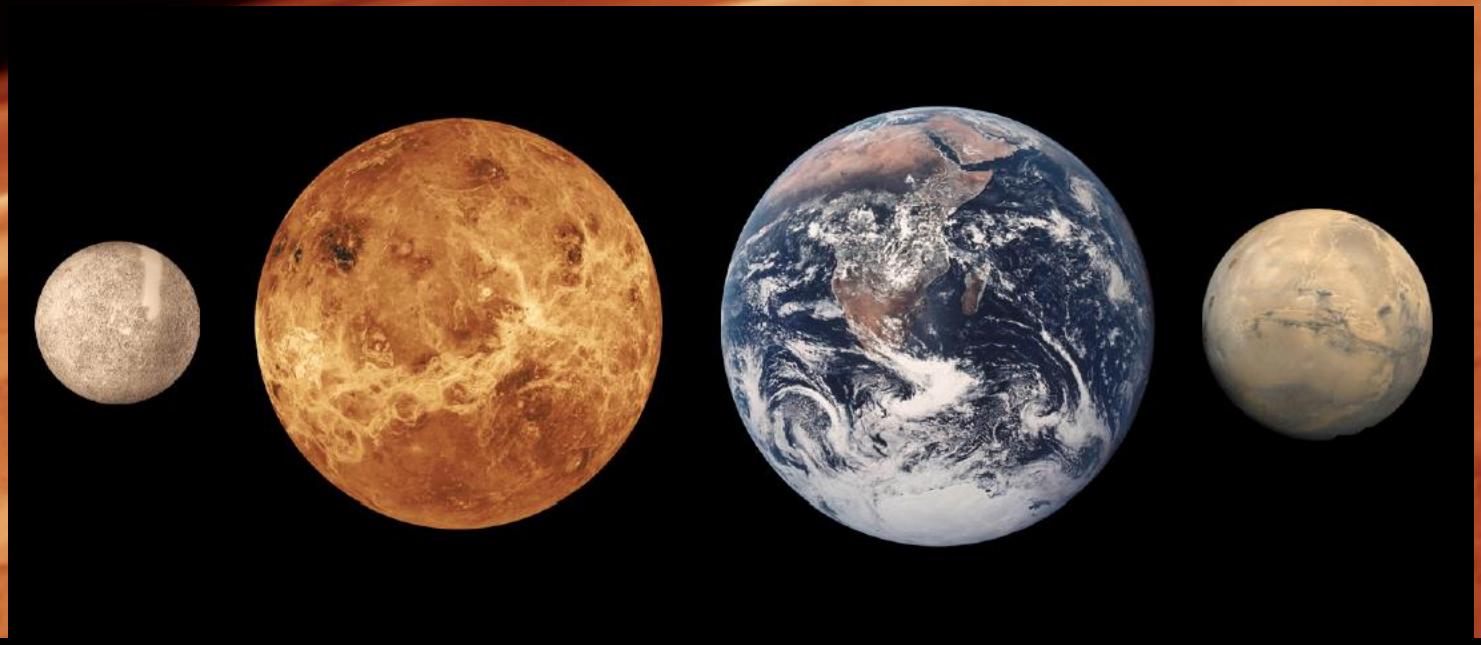
1580 km

All the planets (but not Pluto) orbit in the same direction and in the same plane: the *ecliptic* (to within 6o).

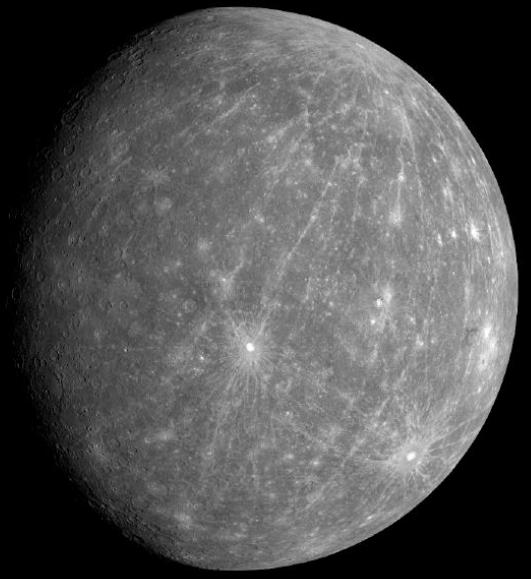


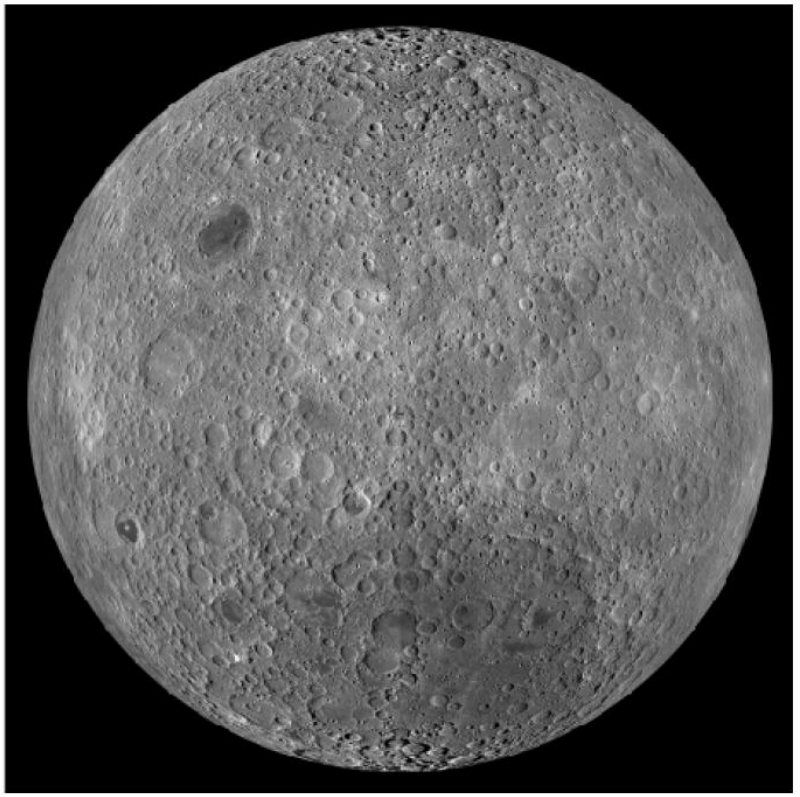
The terrestrial planets

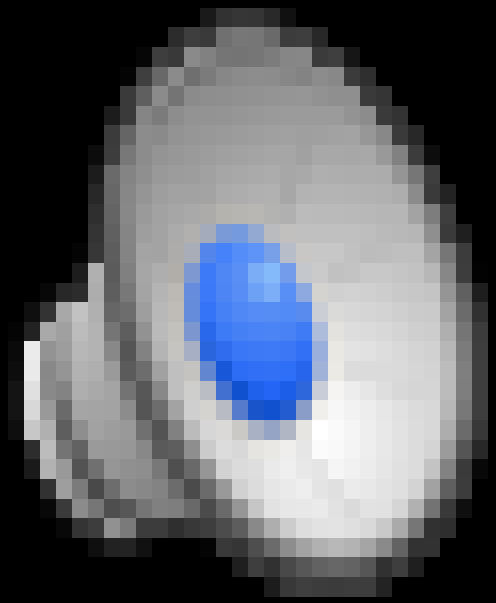
– rocky worlds



The moon and Mercury





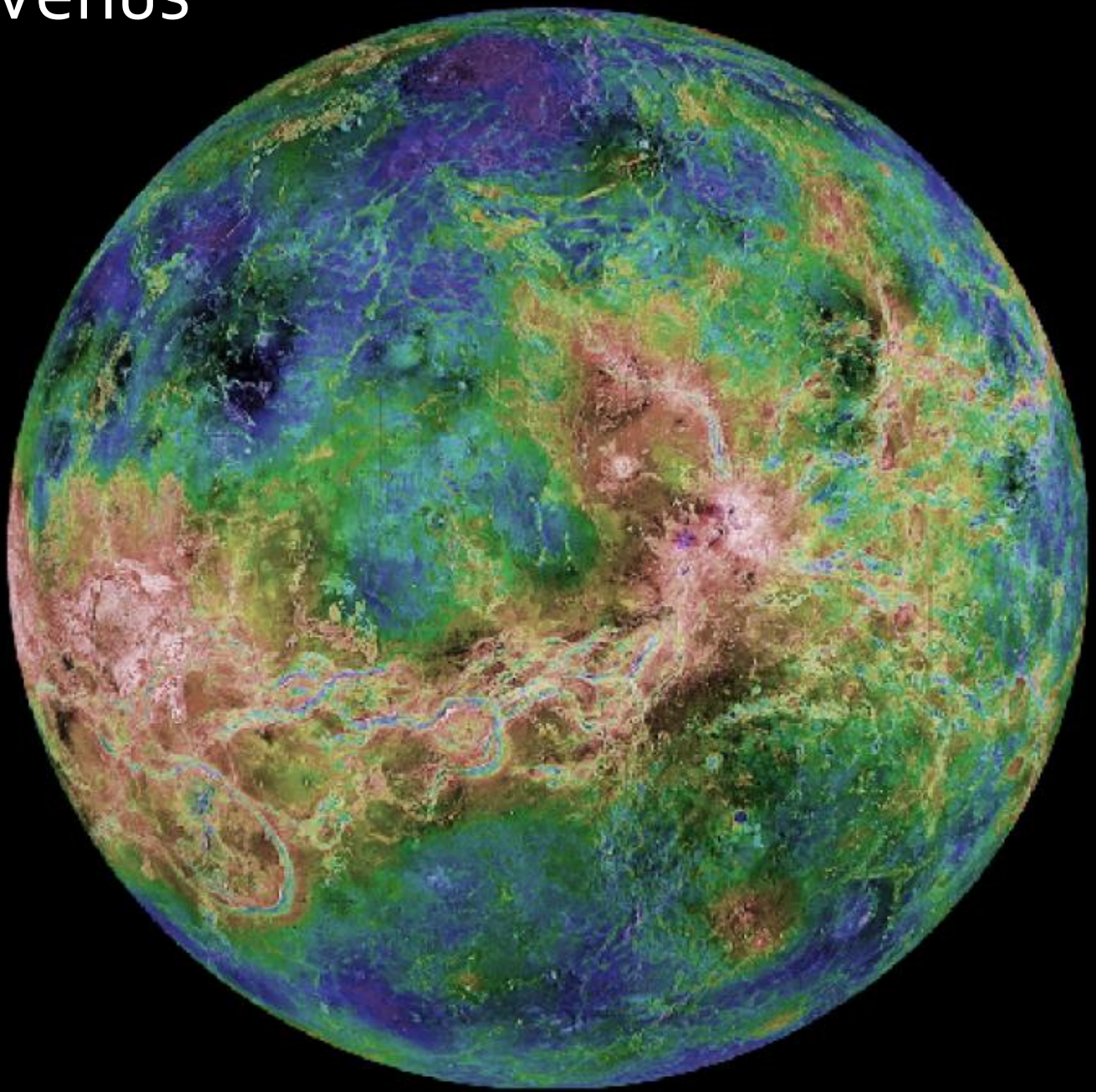


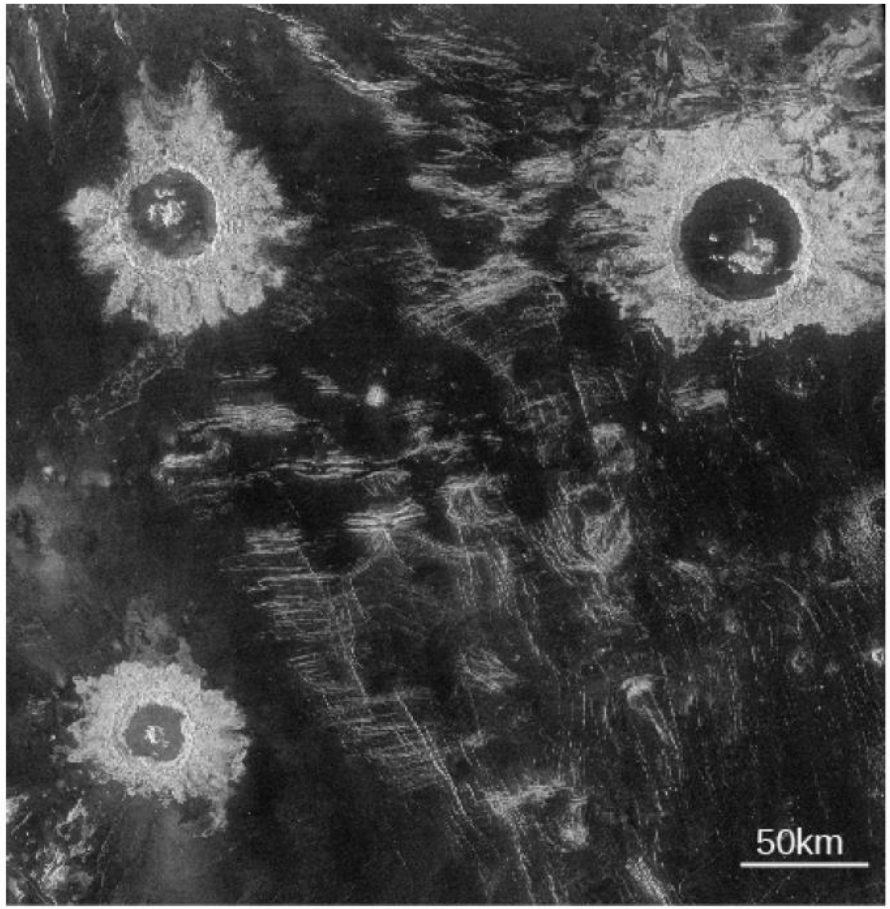
Properties of Earth, Venus, and Mars

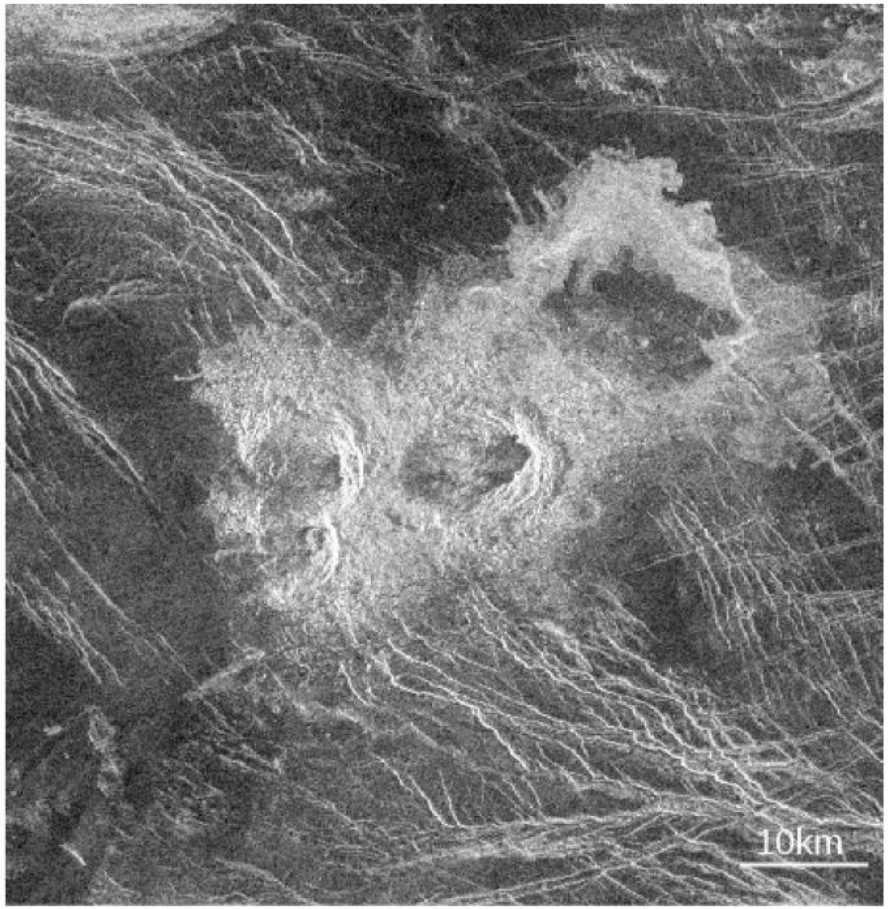
Property	Earth	Venus	Mars
Semimajor axis (AU)	1.00	0.72	1.52
Period (year)	1.00	0.61	1.88
Mass (Earth = 1)	1.00	0.82	0.11
Diameter (km)	12,756	12,102	6,790
Density (g/cm^3)	5.5	5.3	3.9
Surface gravity (Earth = 1)	1.00	0.91	0.38
Escape velocity (km/s)	11.2	10.4	5.0
Rotation period (hours or days)	23.9 h	243 d	24.6 h
Surface area (Earth = 1)	1.00	0.90	0.28
Atmospheric pressure (bar)	1.00	90	0.007

Venus
Thick atmosphere

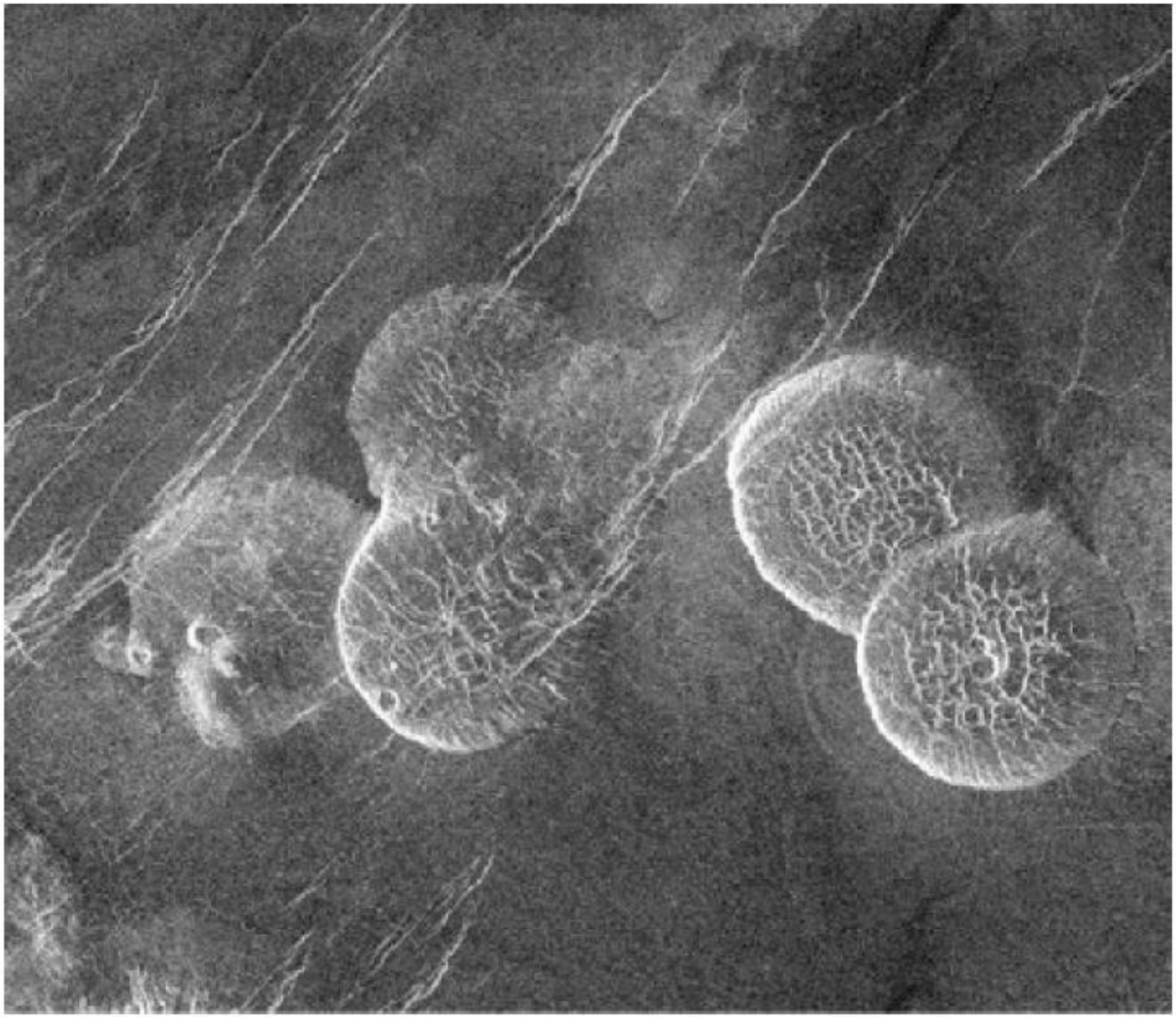
Venus

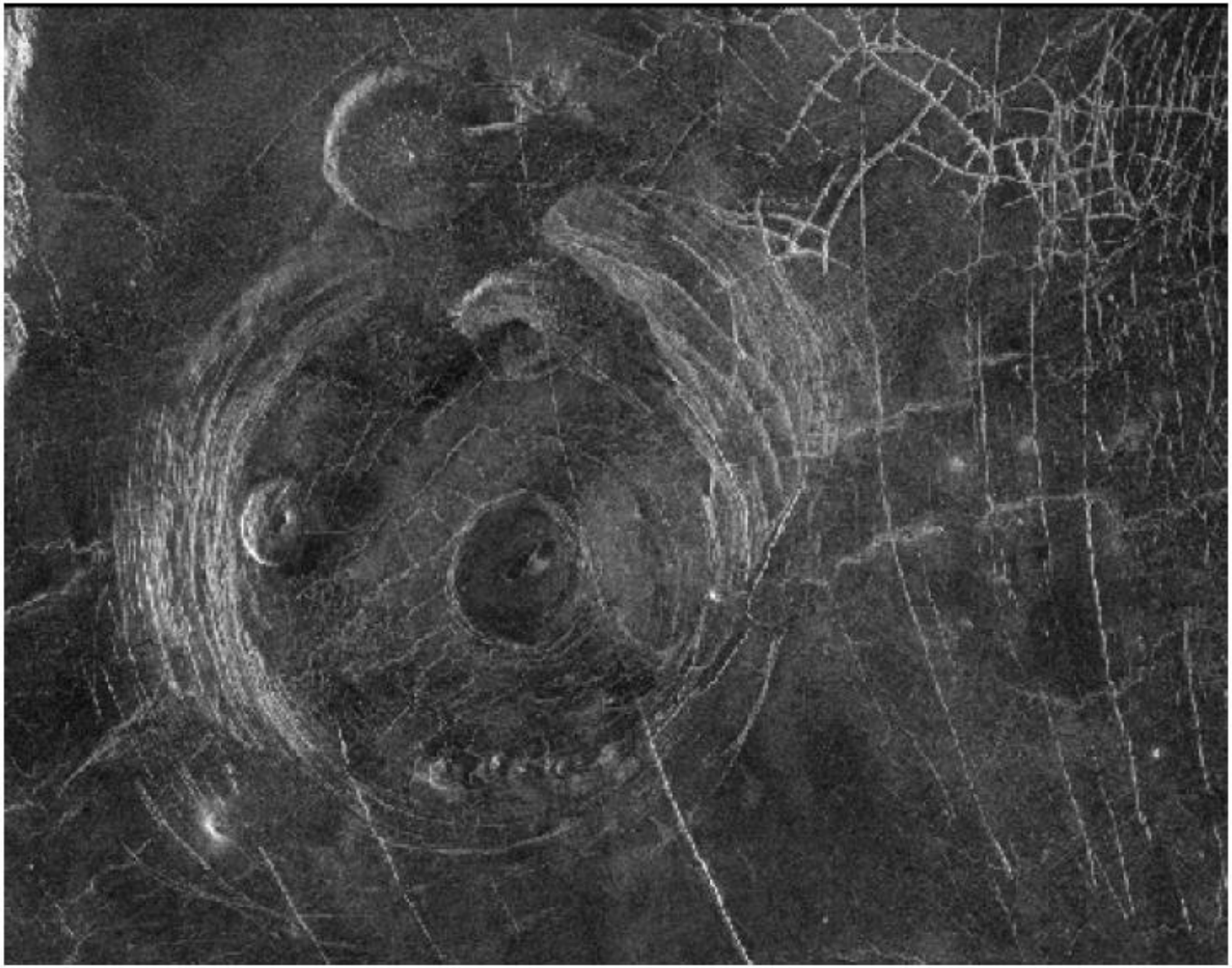


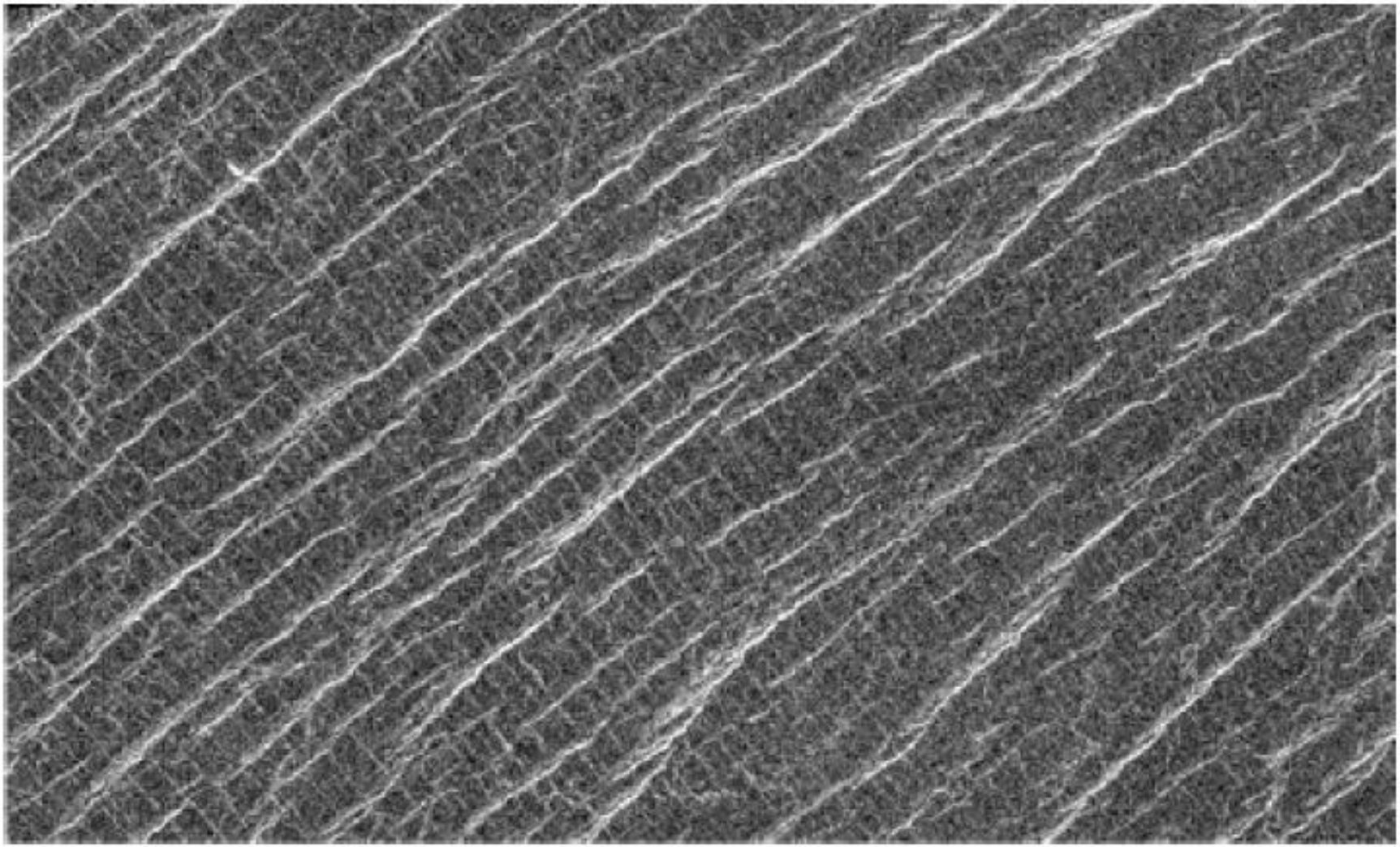


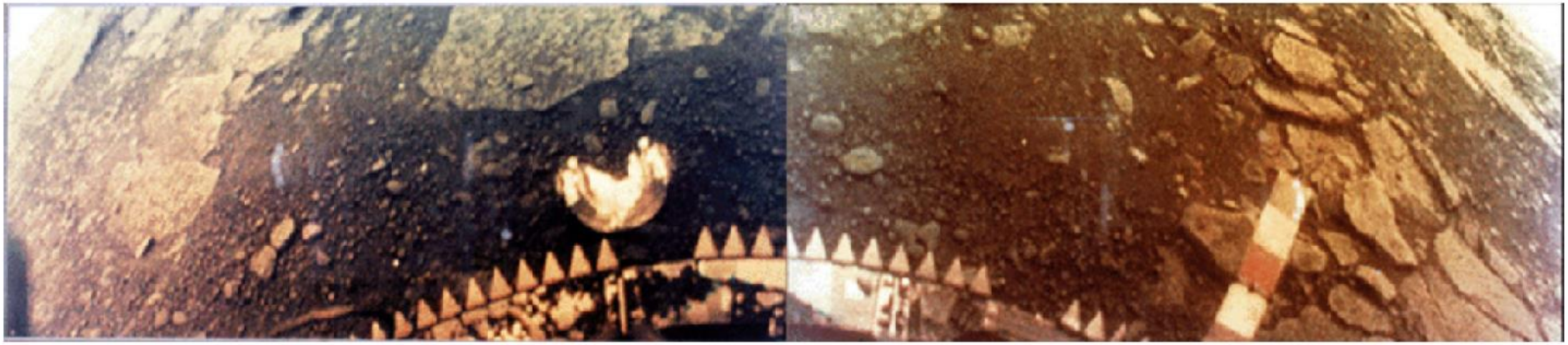


Only a few landers
(all Soviet Union)



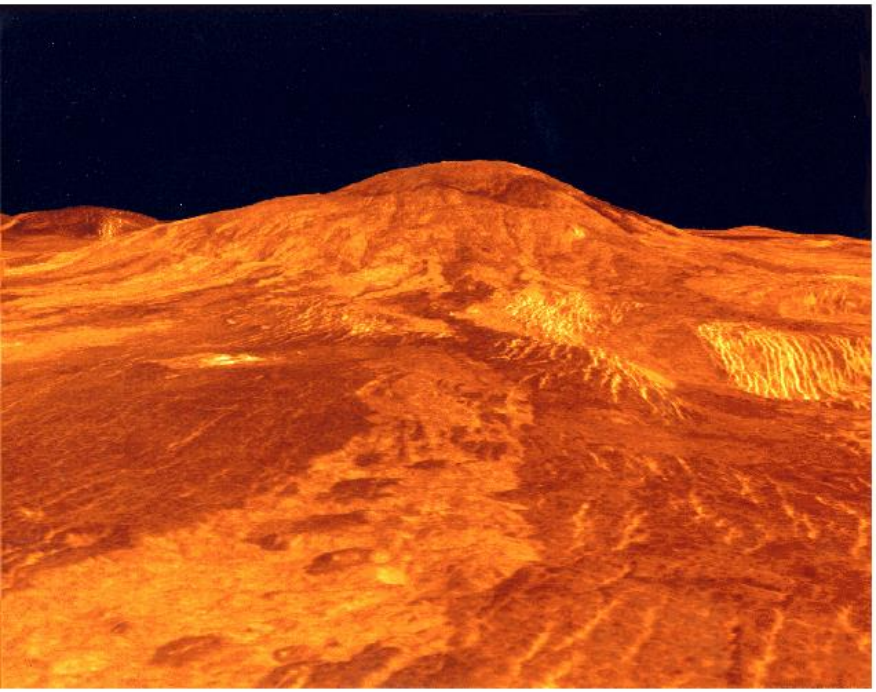






Venus has hardly any impact craters; the surface density of craters indicates most of the surface is only 600 million years old; but craters do not appear to be eroding. Where are all the older craters?

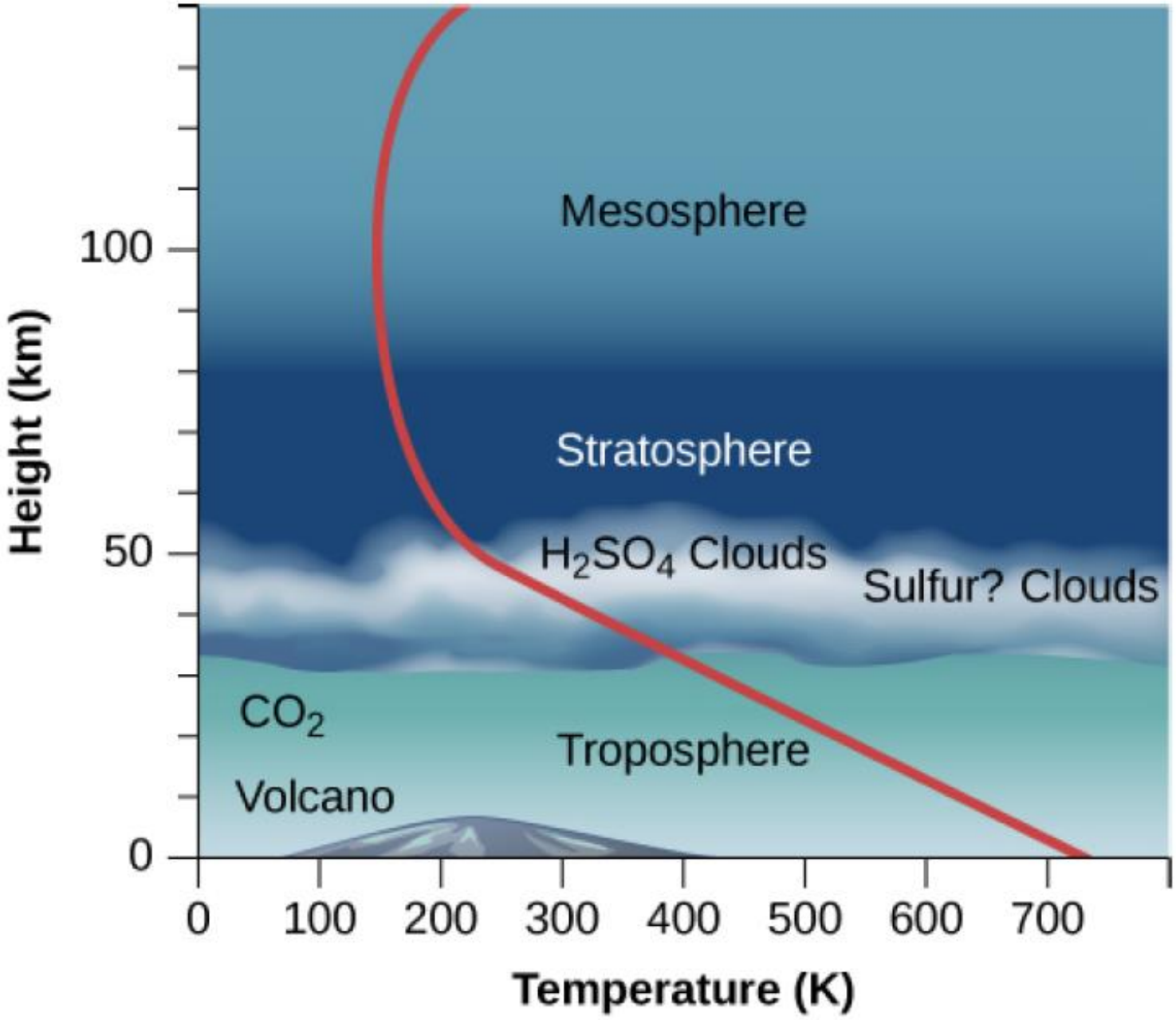
Perhaps Venus undergoes periodic *catastrophic resurfacing*. The last such event would have taken place about 600 million years ago.



The volcano Sif Mons. is about 2 km high and nearly 300 km across. There appear to be recent lava flows at the front of the image: these flows are about 120 km long, which suggests that these lavas were also very fluid.

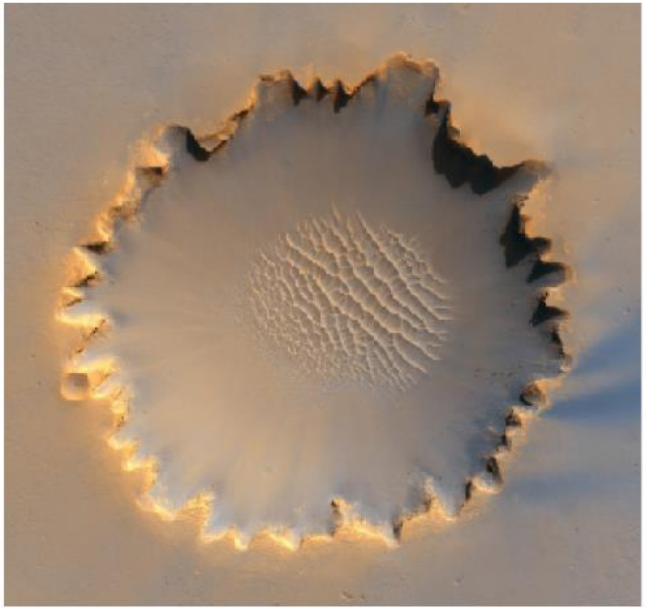
Atmospheric Composition of Earth, Venus, and Mars

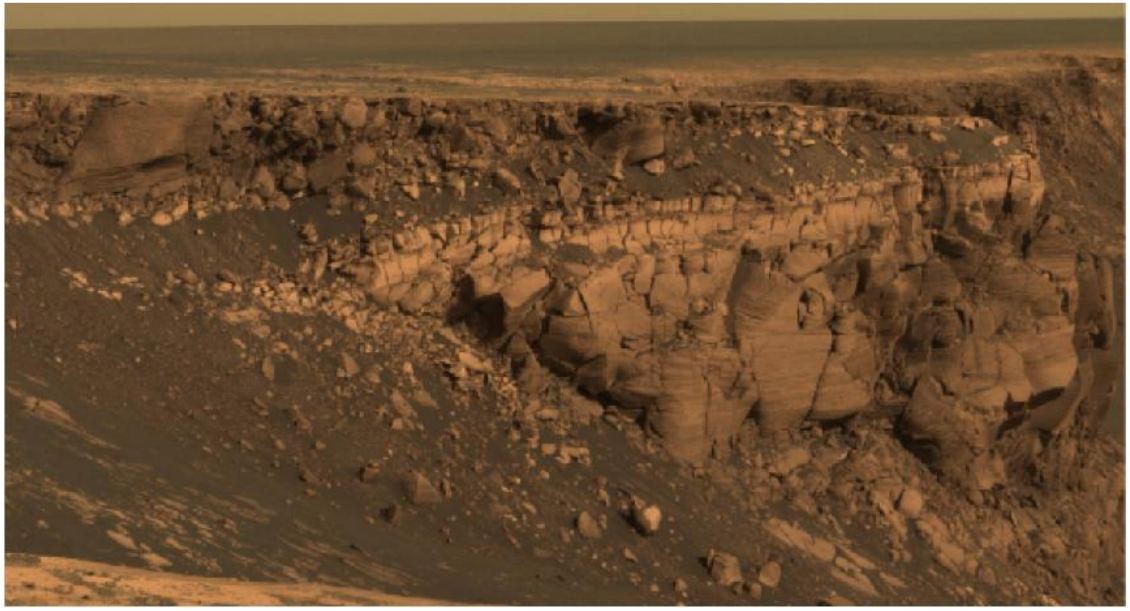
Gas	Earth	Venus	Mars
Carbon dioxide (CO_2)	0.03%	96%	95.3%
Nitrogen (N_2)	78.1%	3.5%	2.7%
Argon (Ar)	0.93%	0.006%	1.6%
Oxygen (O_2)	21.0%	0.003%	0.15%
Neon (Ne)	0.002%	0.001%	0.0003%

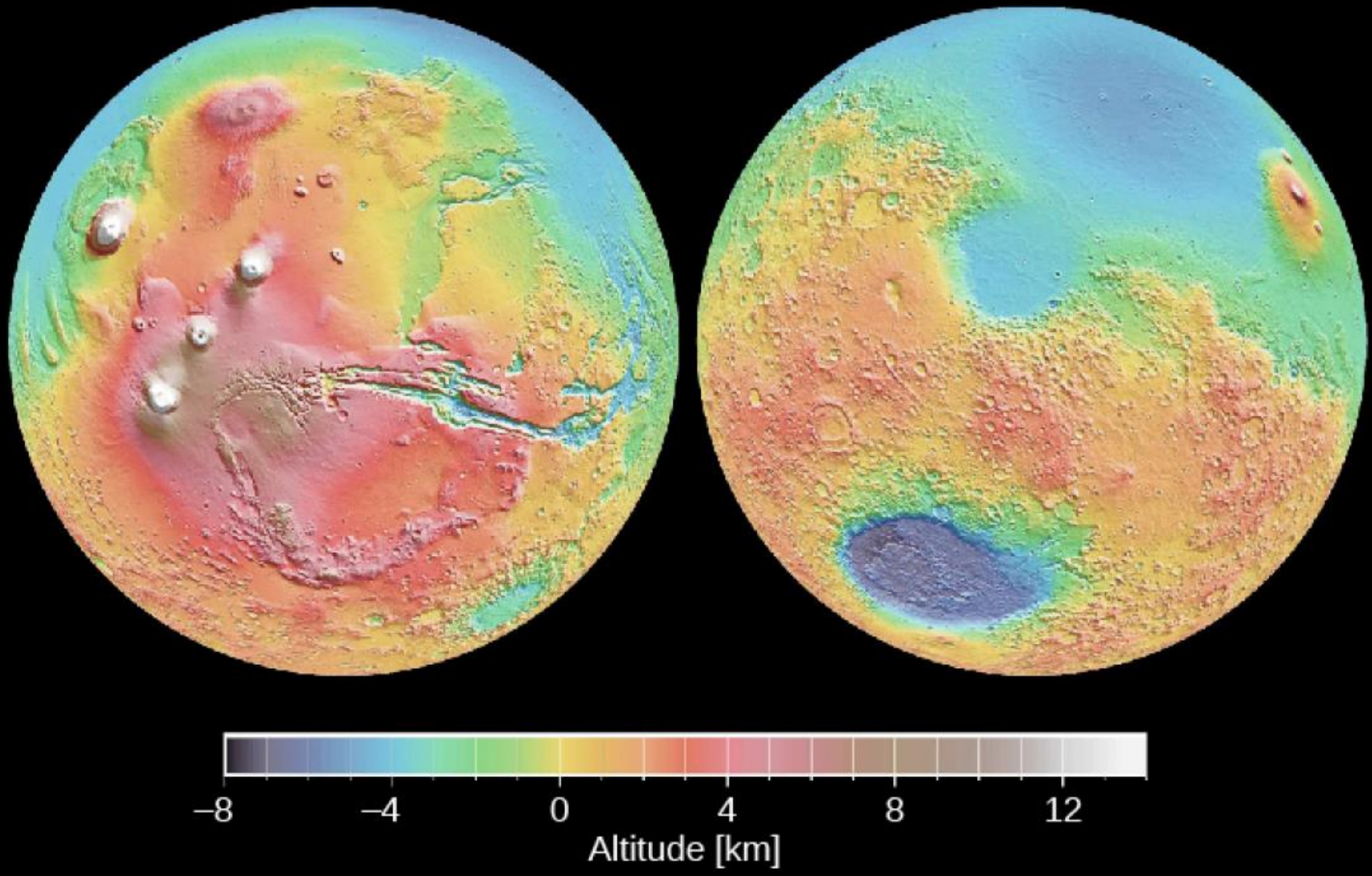

Mesosphere
Stratosphere
H_2SO_4 Clouds
Sulfur? Clouds
CO_2
Troposphere
Volcano
Height (km)
100
50
0
0
100
200
300
400
500
600
700
Temperature (K)

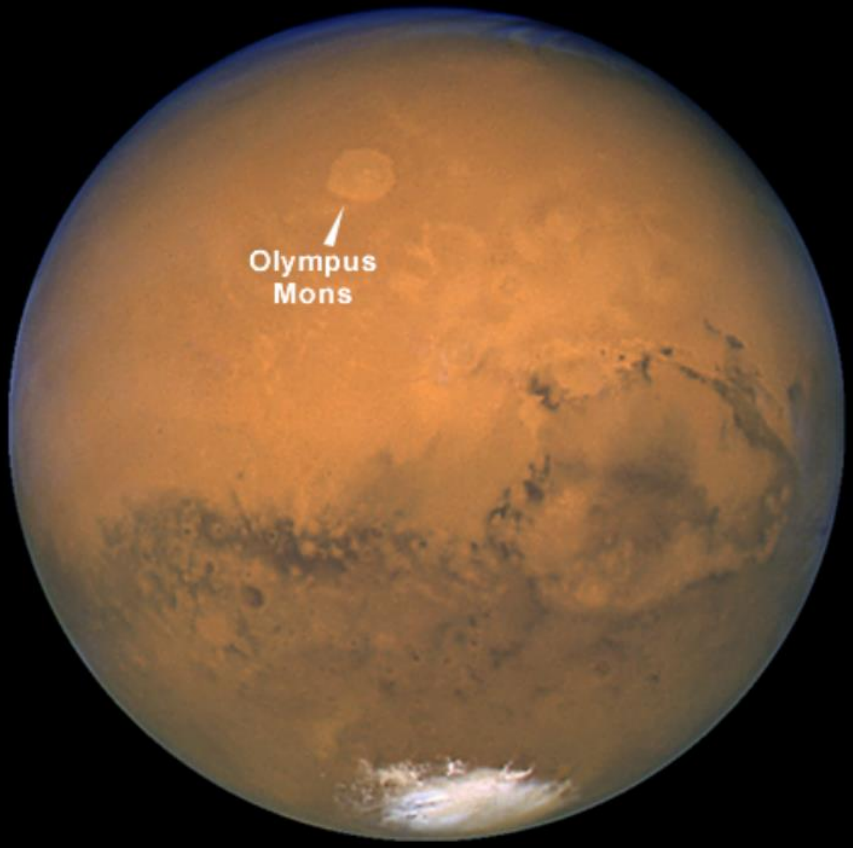
Mars

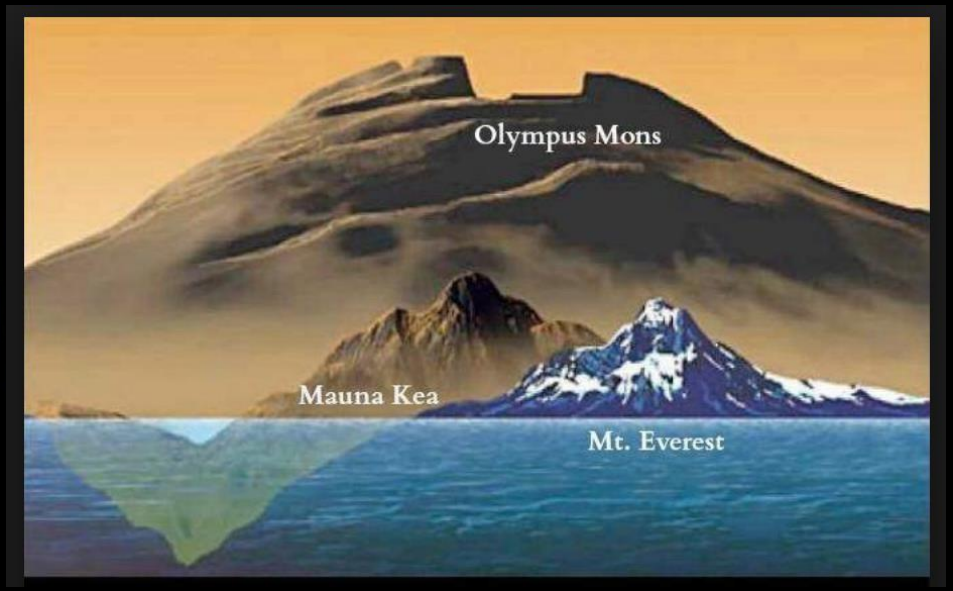
Mars rock from Antarctica!

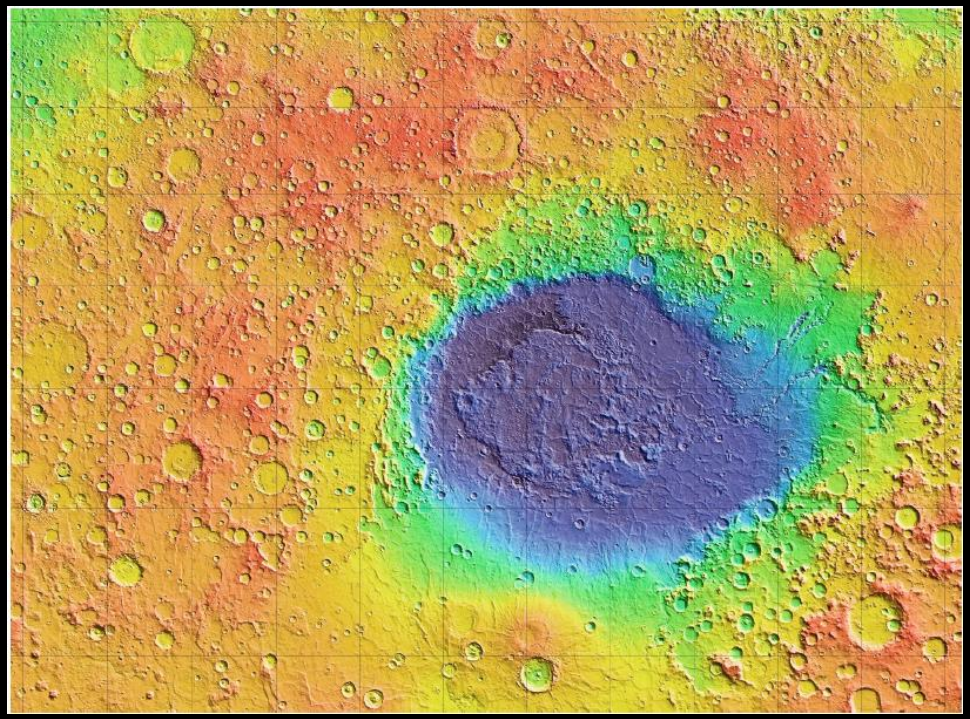


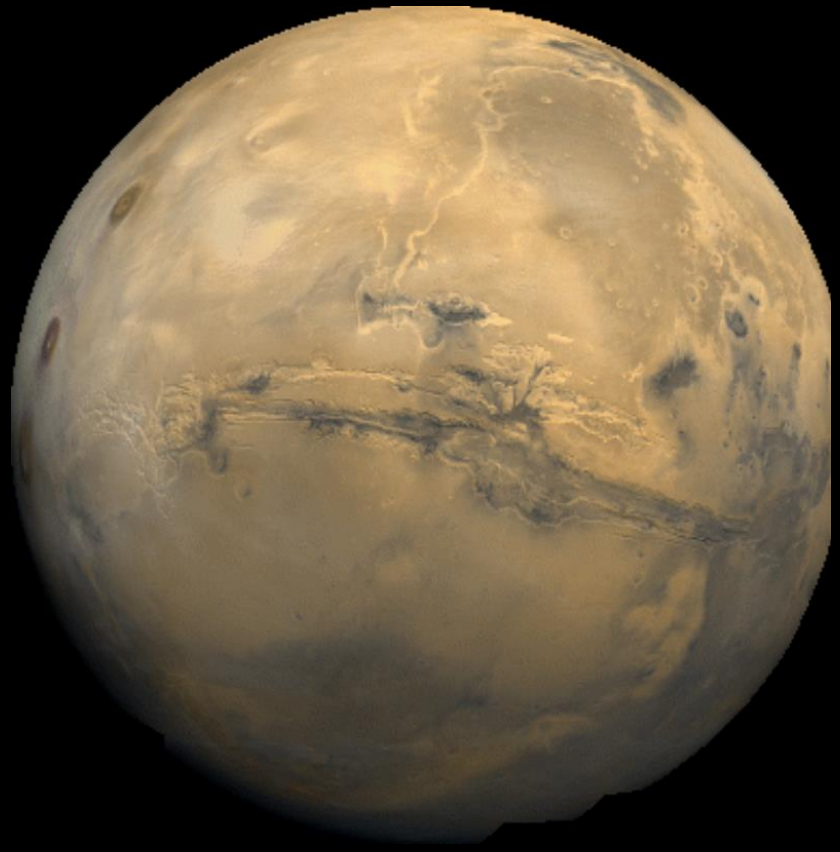


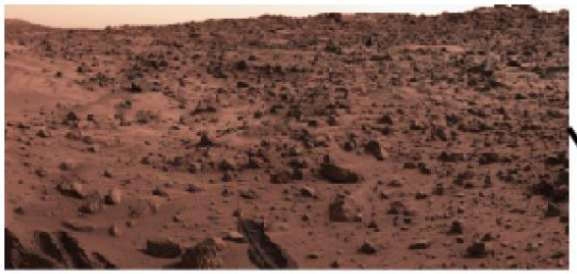

–8
–4
0
4
8
12
Altitude [km]

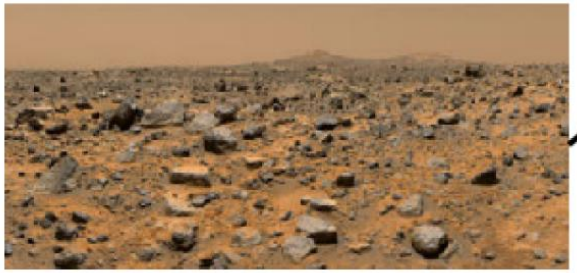

Olympus
Mons


Olympus Mons
Mauna Kea
Mt. Everest



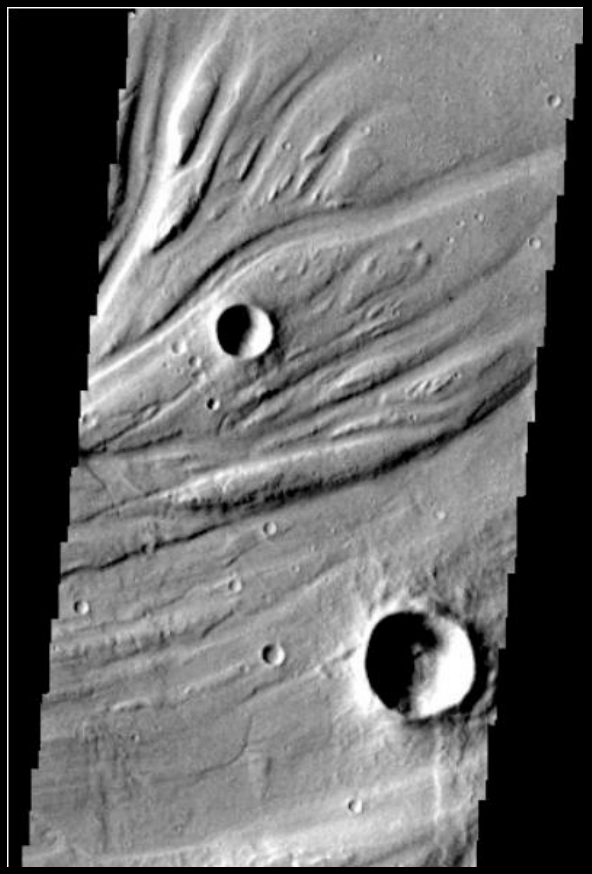


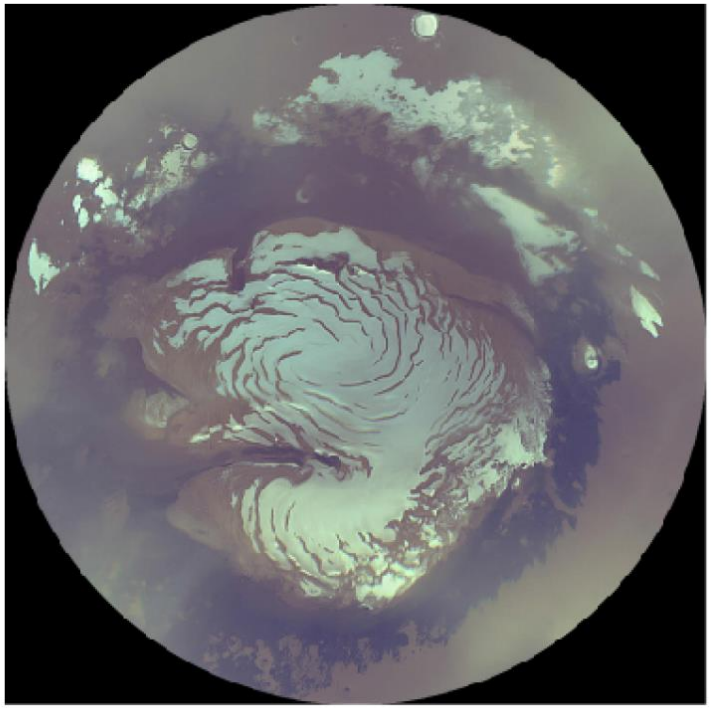


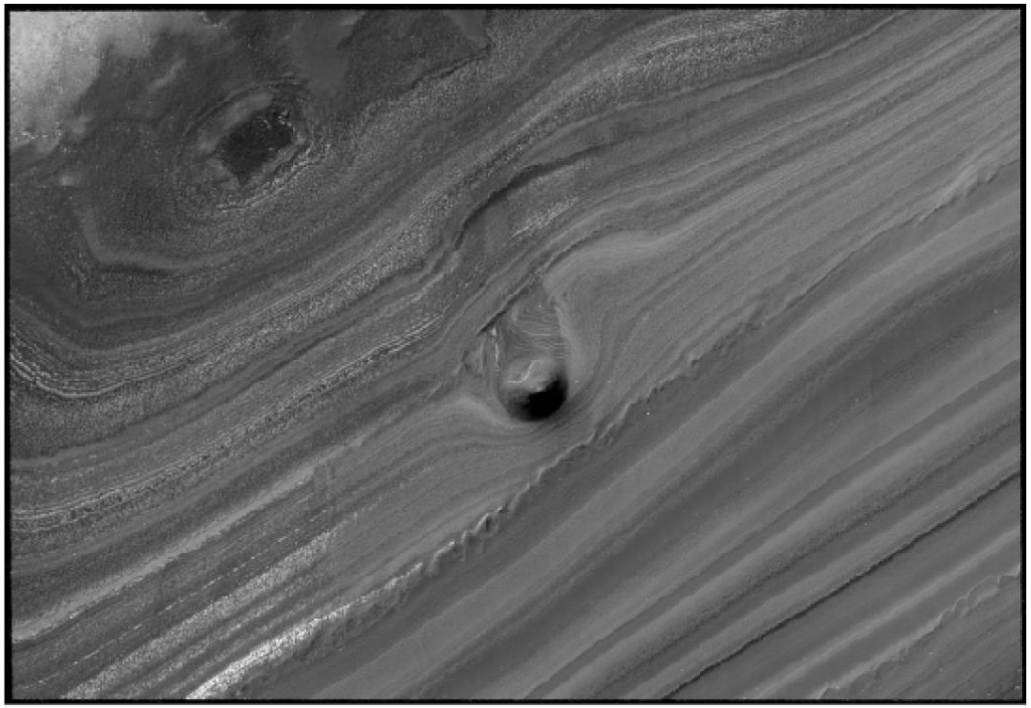


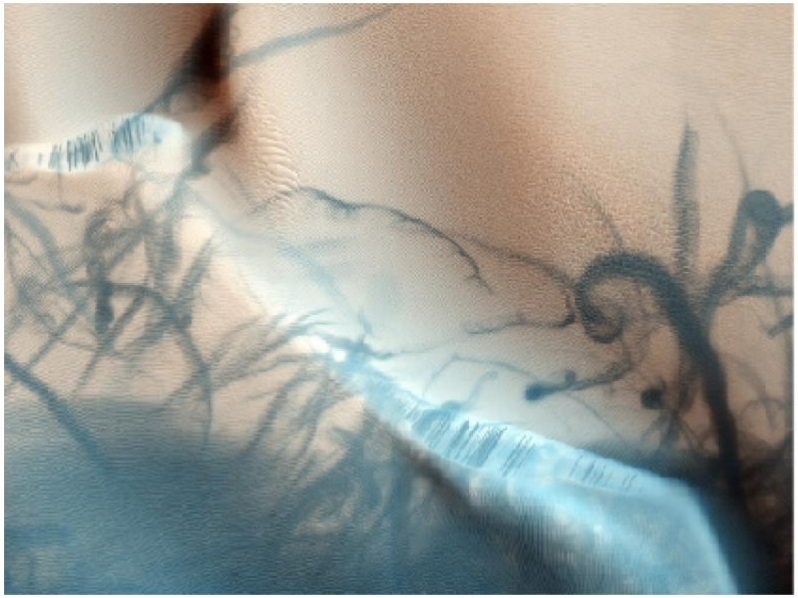

Viking 2
Viking 1
Pathfinder

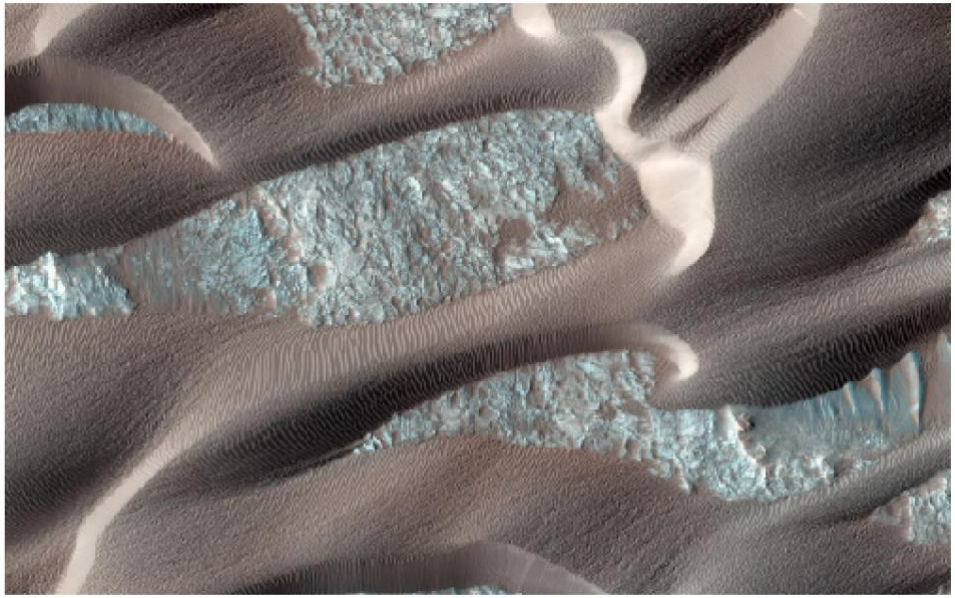
Water?

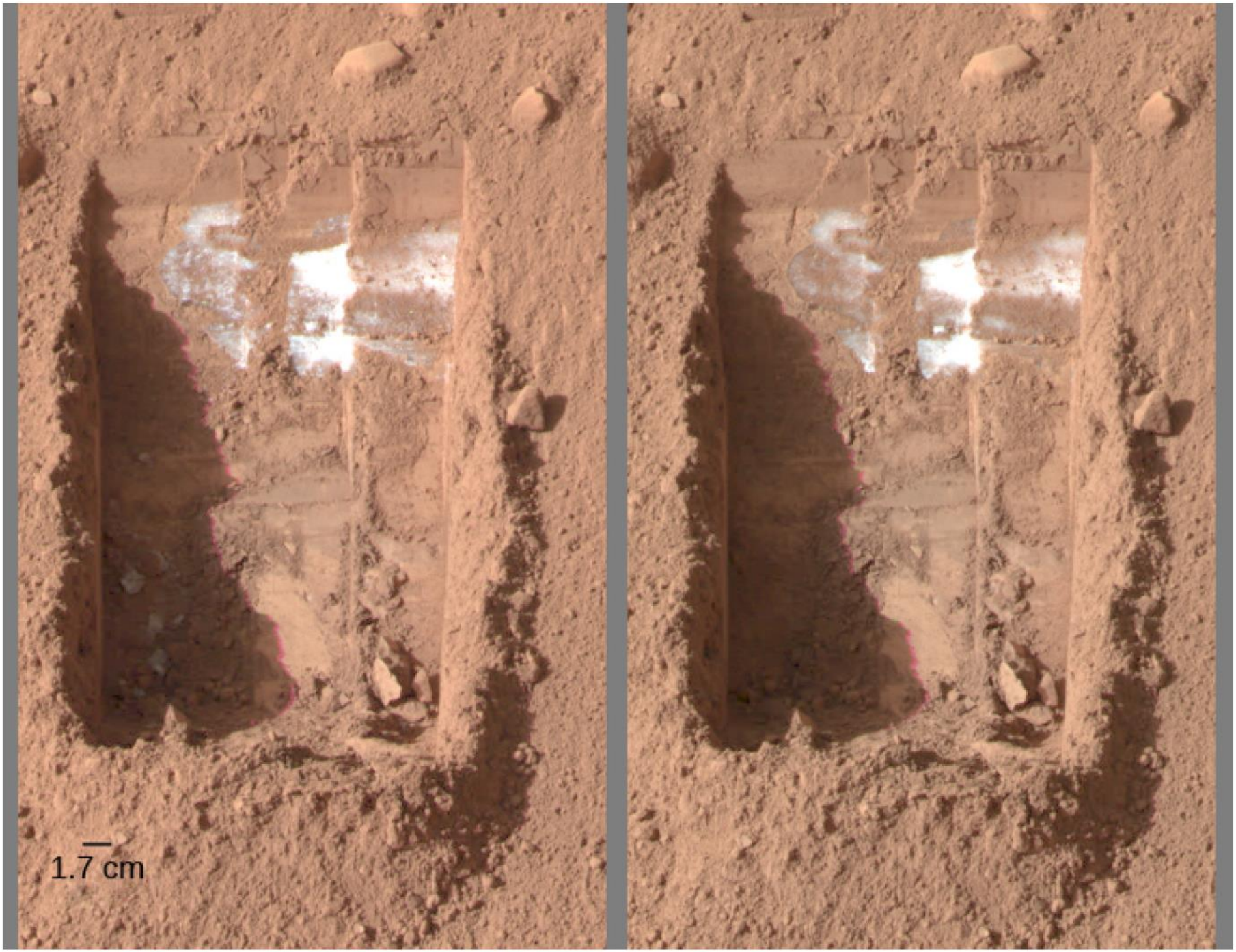


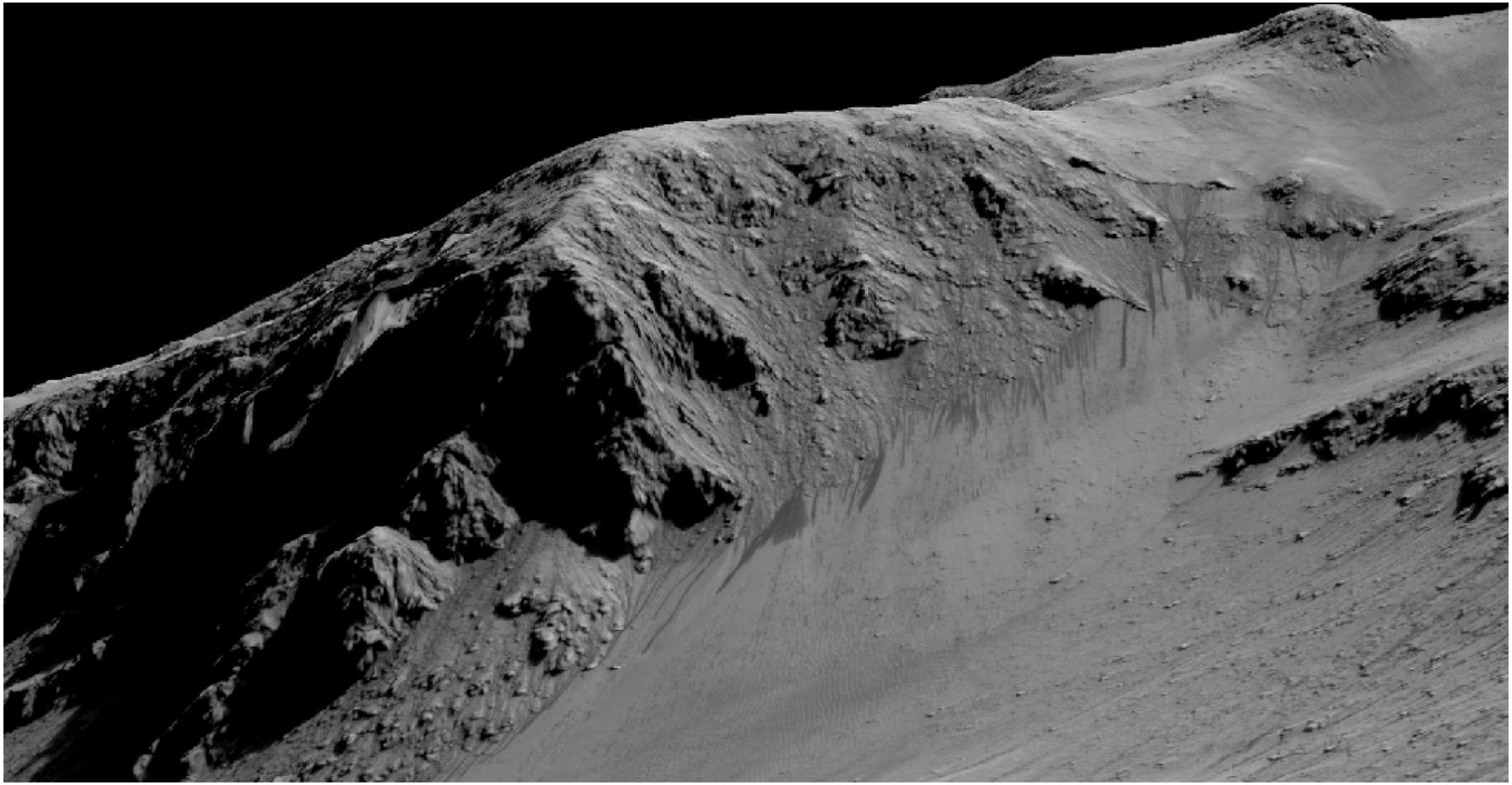






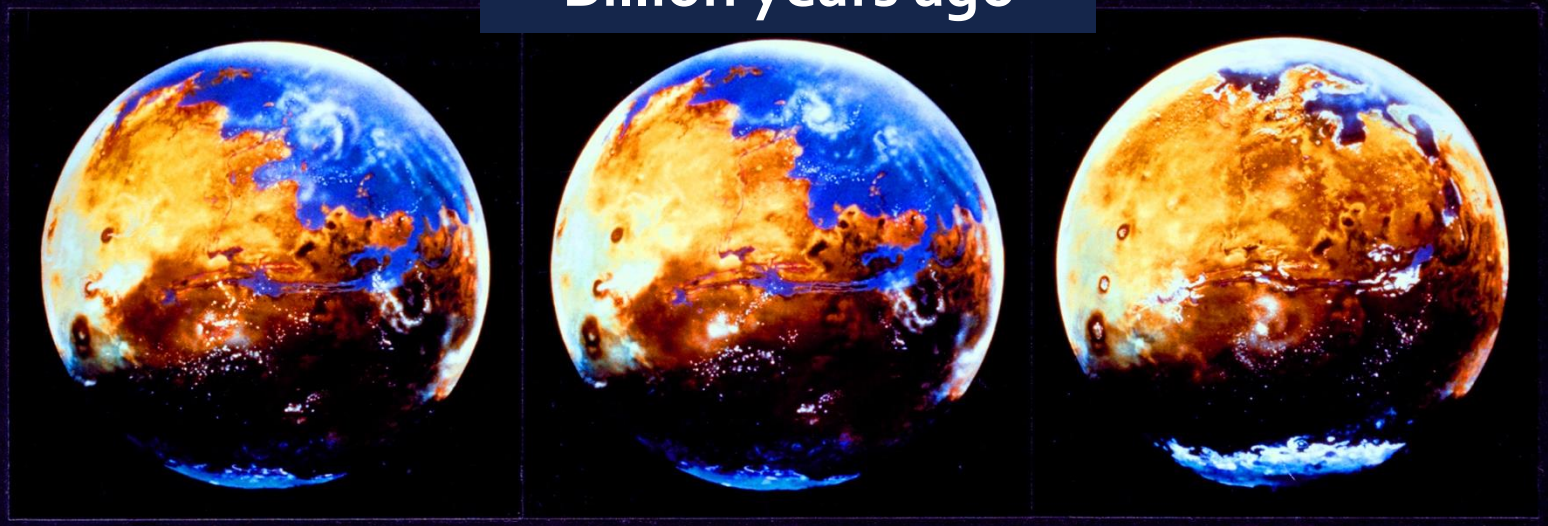


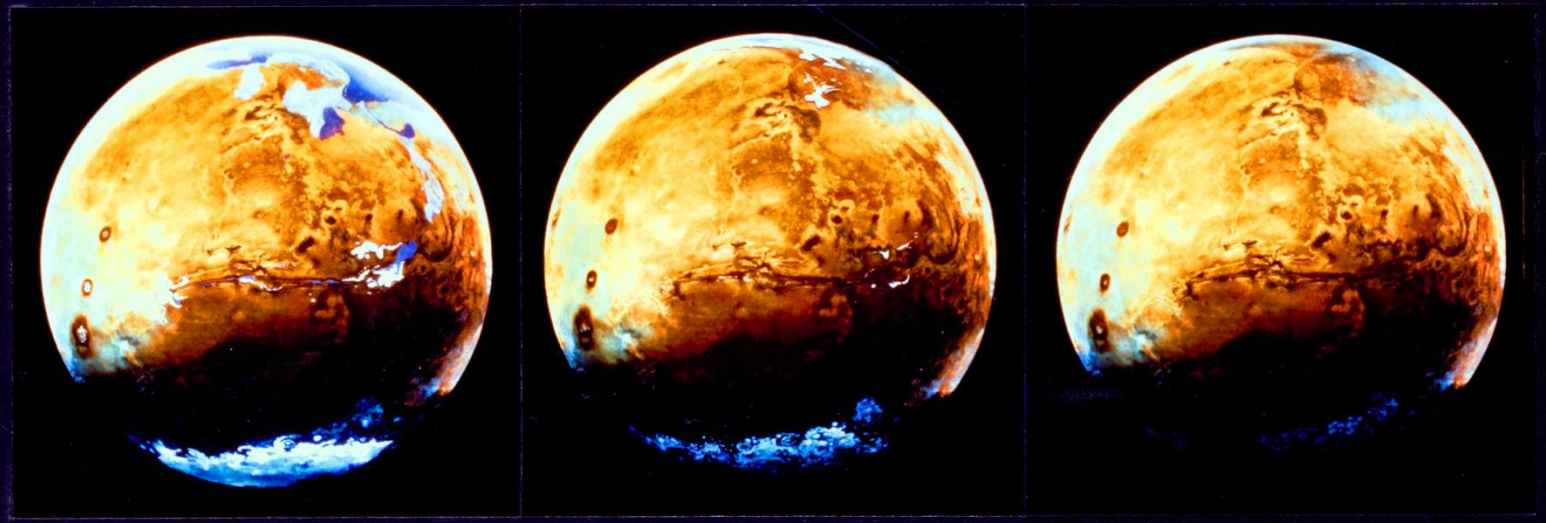

1.7 cm



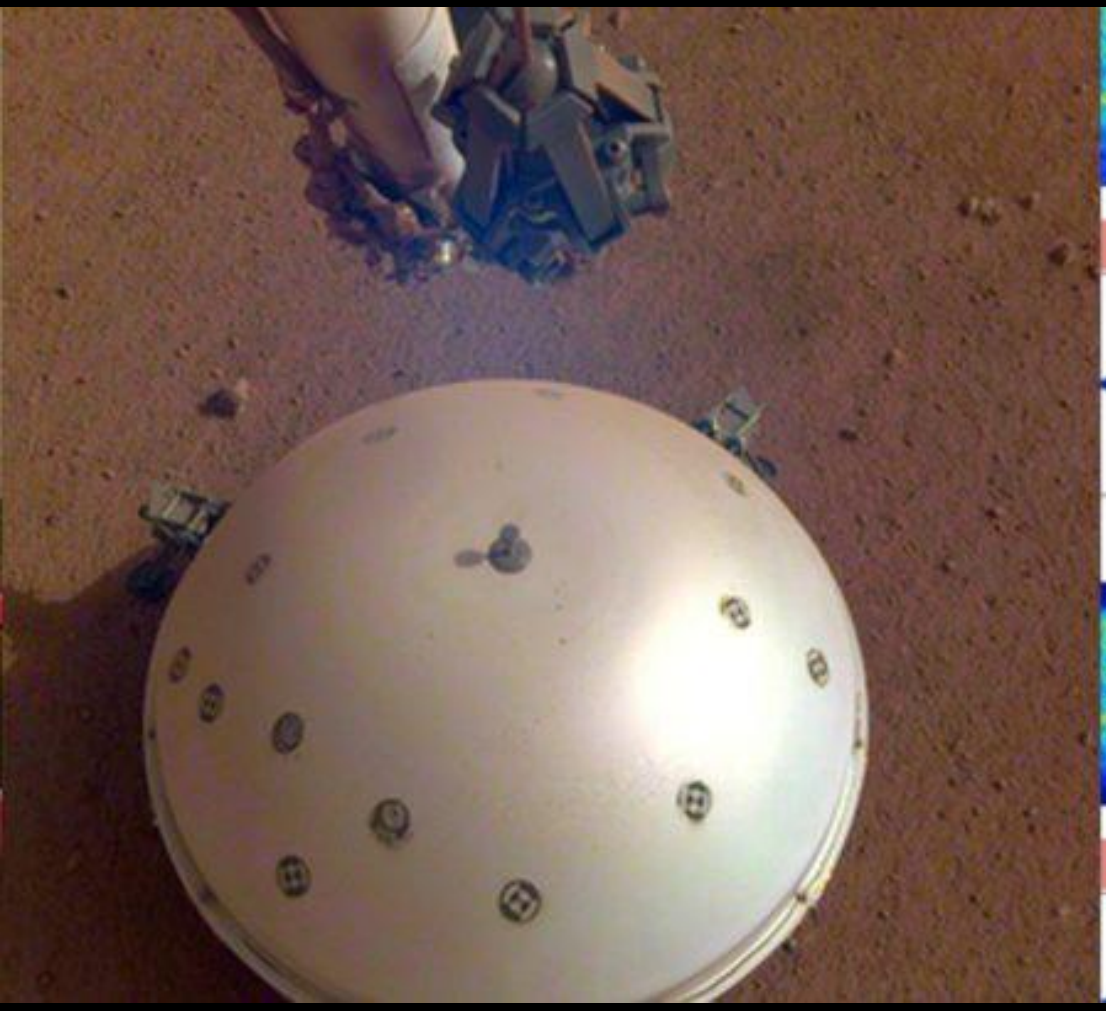
HISTORY OF WATER ON MARS

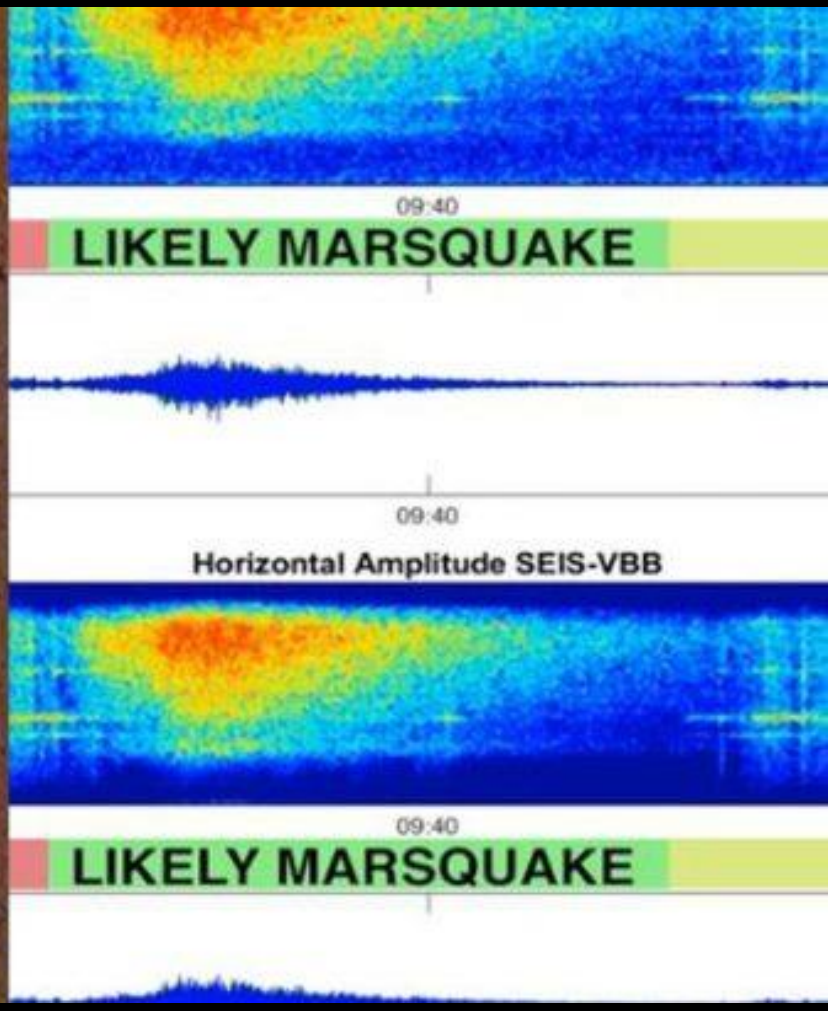
Billion years ago

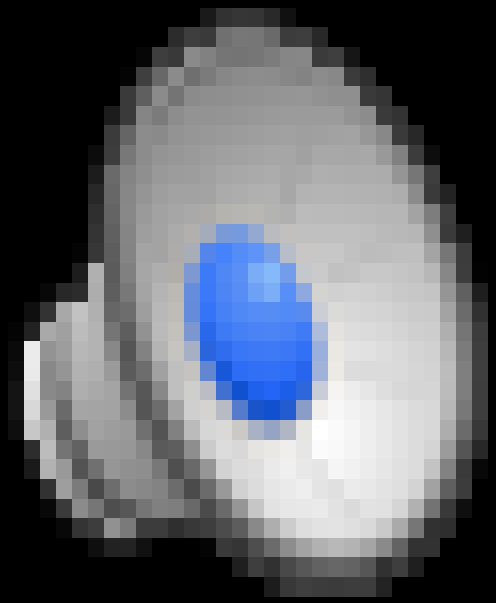


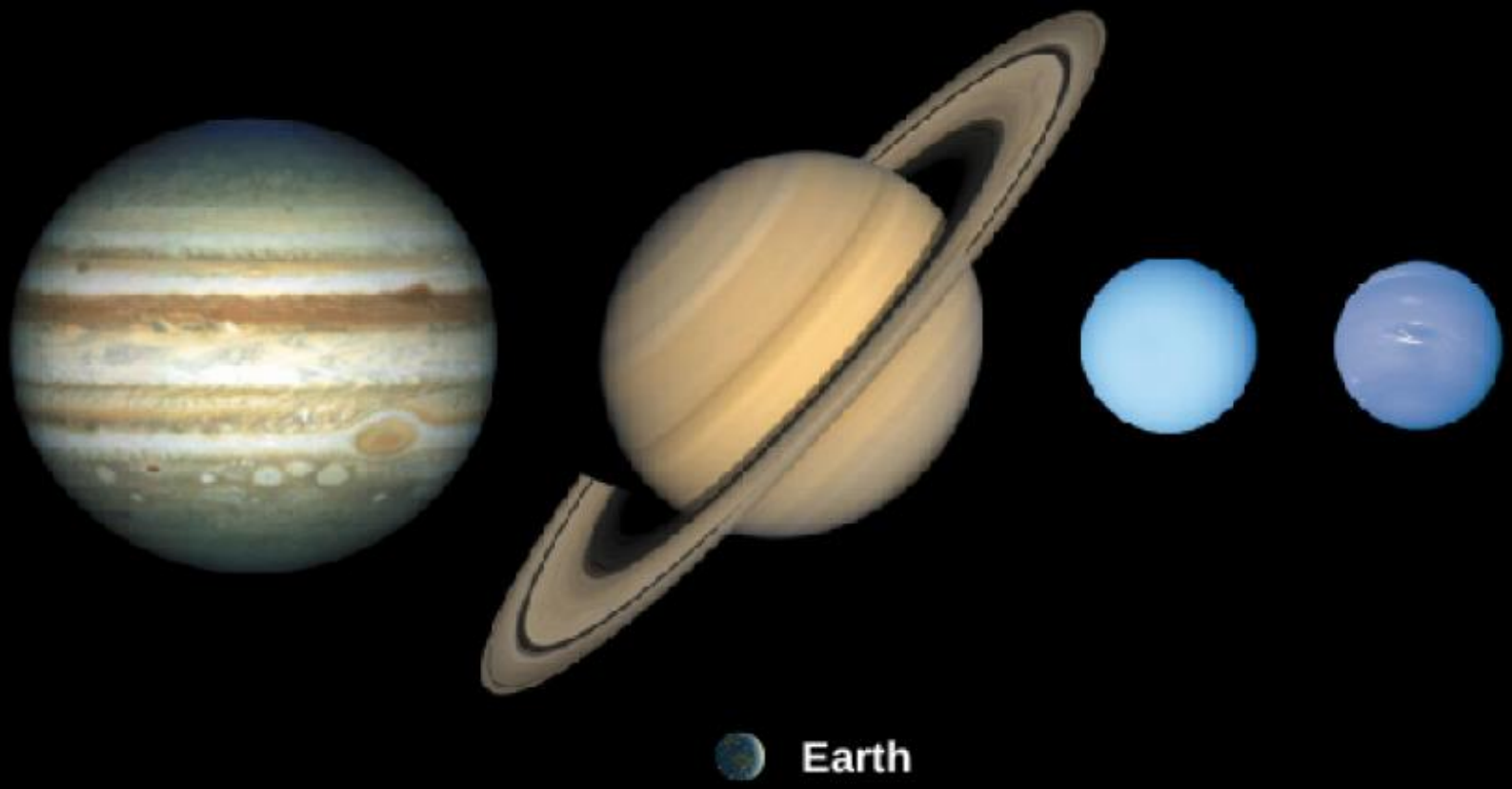


Marsquakes!




09:40
LIKELY MARSQUAKE
09:40
Horizontal Amplitude SEIS-VBB
09:40
LIKELY MARSQUAKE

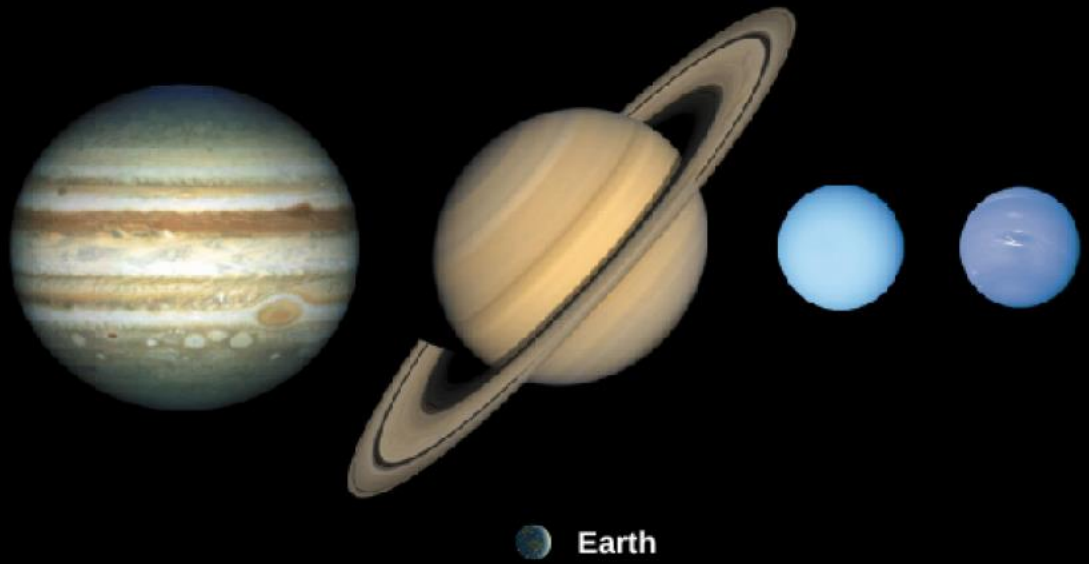



Earth

Basic Properties of the Jovian Planets

Planet	Distance (AU)	Period (years)	Diameter (km)	Mass (Earth = 1)	Density (g/cm^3)	Rotation (hours)
Jupiter	5.2	11.9	142,800	318	1.3	9.9
Saturn	9.5	29.5	120,540	95	0.7	10.7
Uranus	19.2	84.1	51,200	14	1.3	17.2
Neptune	30.0	164.8	49,500	17	1.6	16.1

Ice giants are much smaller: started with similar sized core, but could not accrete enough material

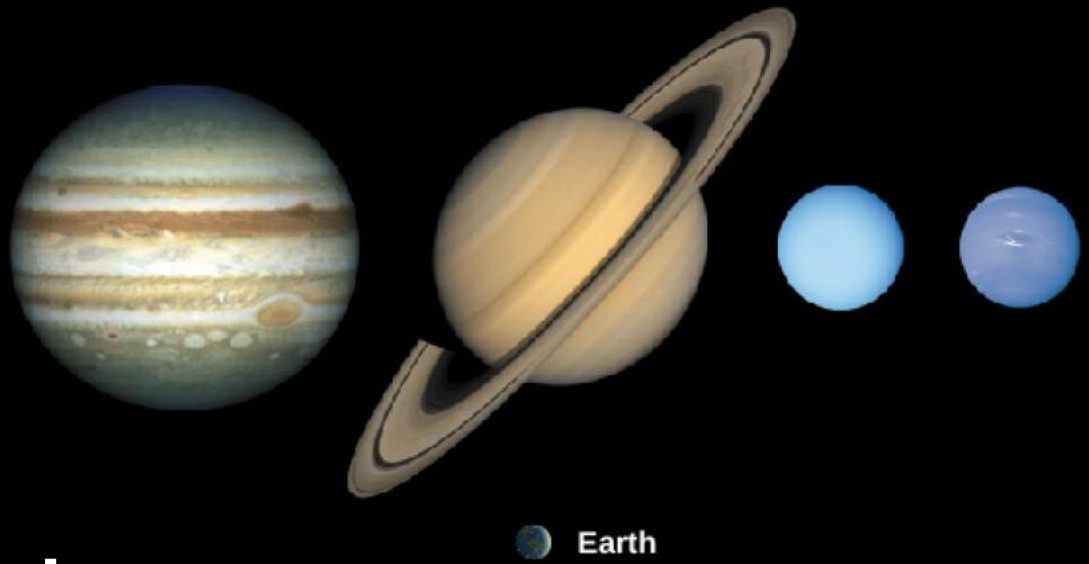


Gas giants

- Jupiter, Saturn
- Much more massive
- Abundances similar to sun

Ice Giants

- Uranus, Neptune
- Much less massive
- Similar cores as gas giants



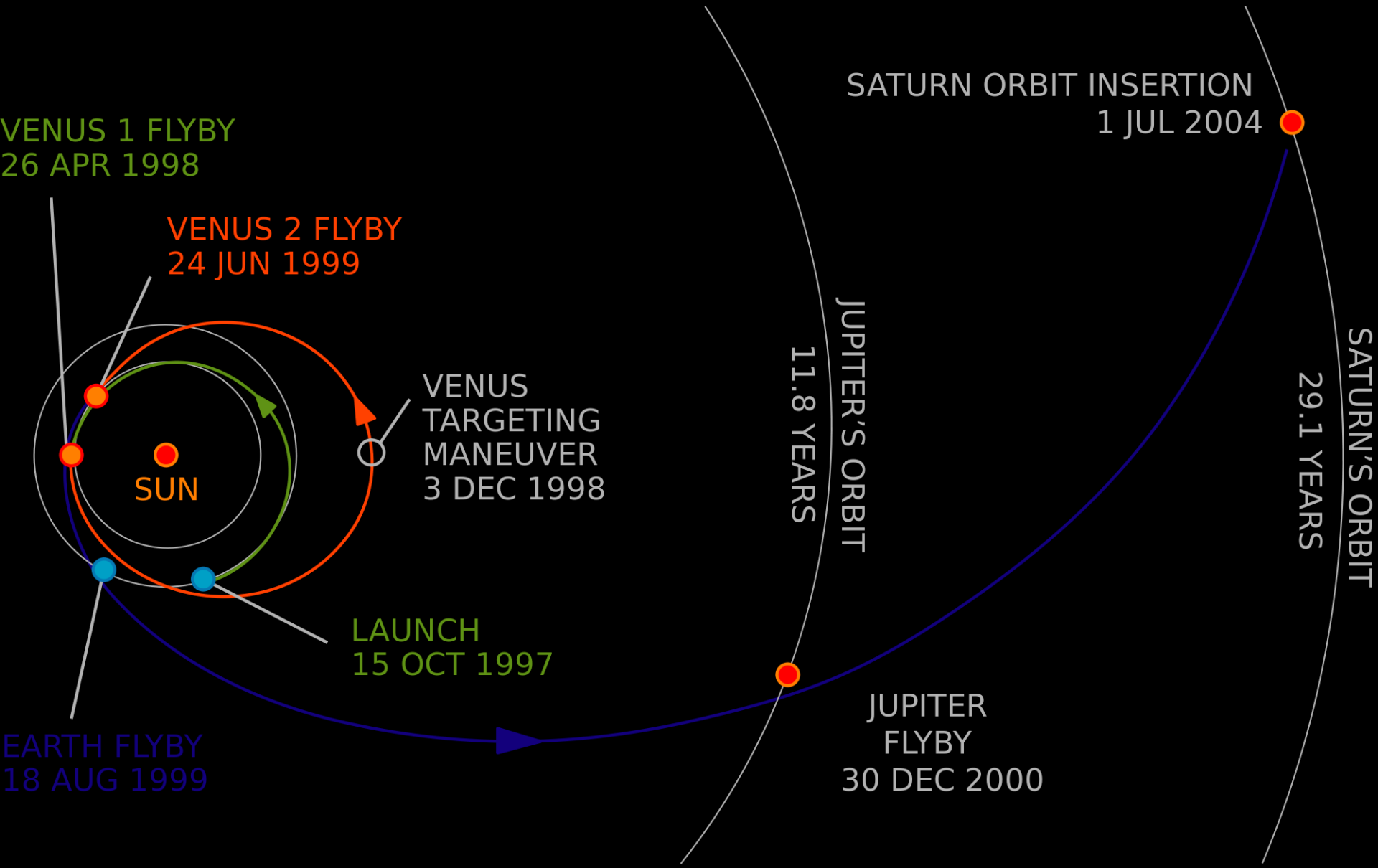
Gas giants

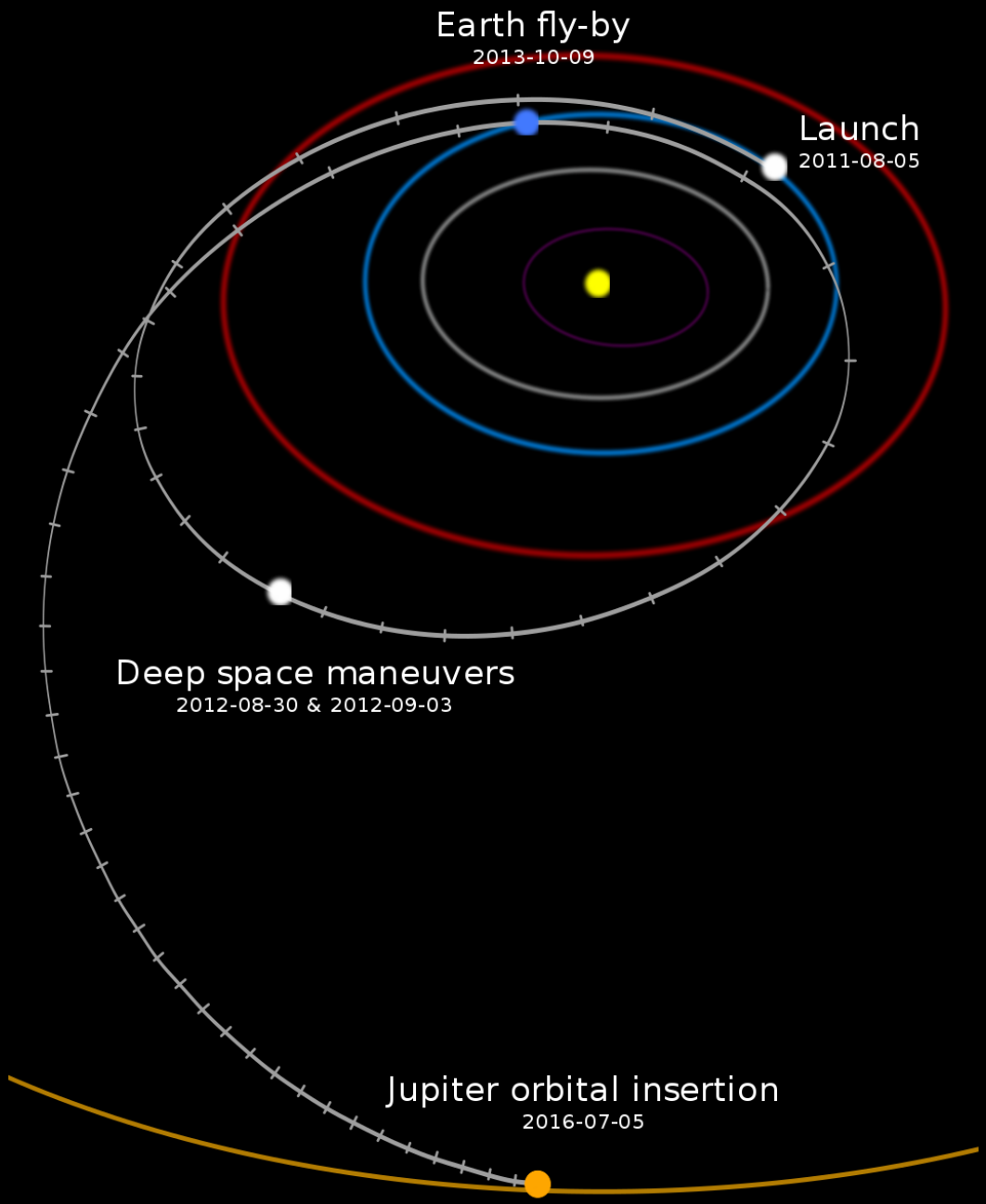
Jupiter: energy from contraction (2 cm/yr)

Saturn: energy from differentiation (heavier elements sink)

Ice Giants

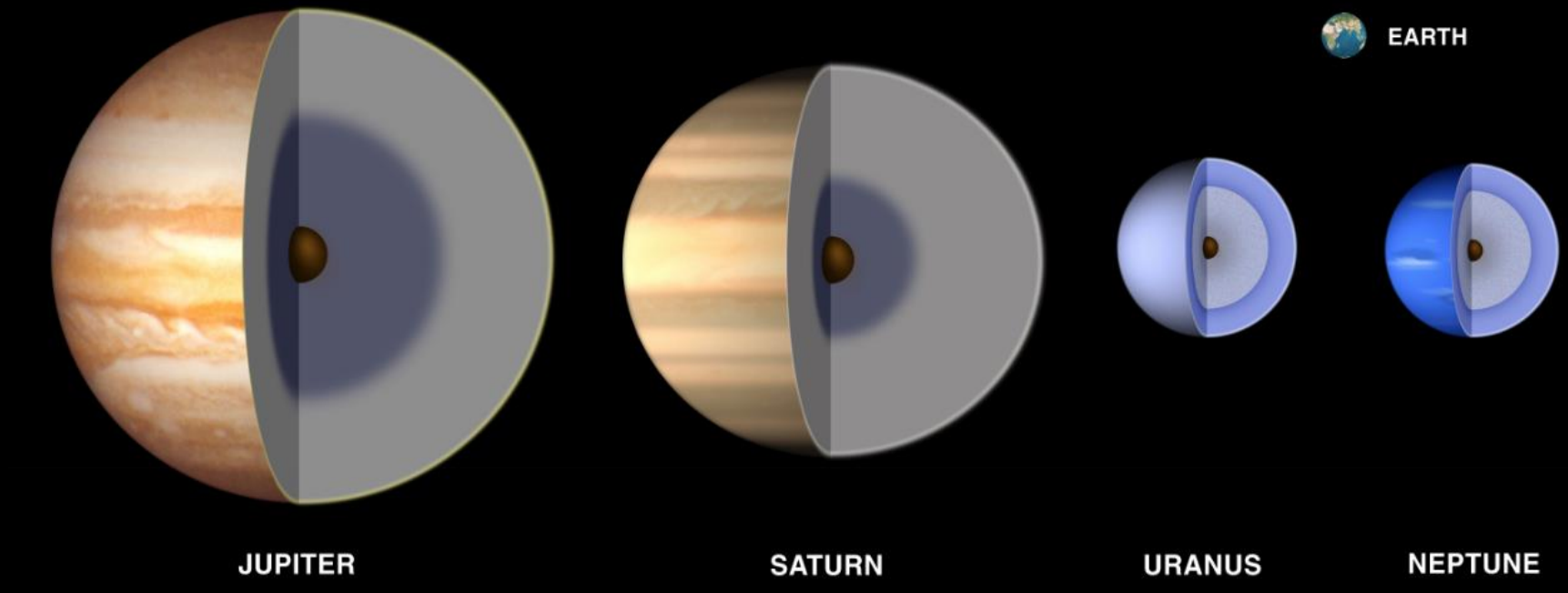
Cold

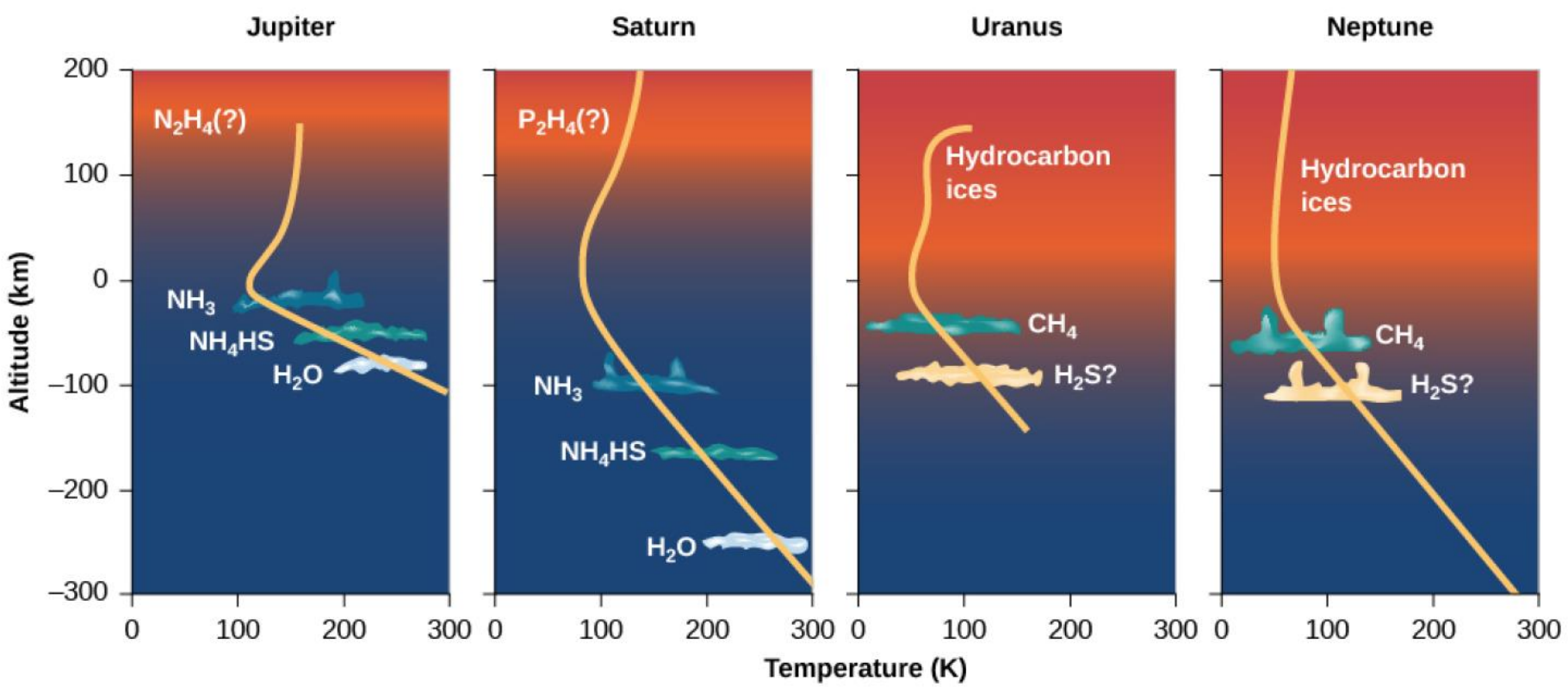

VENUS 1 FLYBY
26 APR 1998
VENUS 2 FLYBY
24 JUN 1999
VENUS
TARGETING
MANEUVER
3 DEC 1998
SUN
LAUNCH
15 OCT 1997
EARTH FLYBY
18 AUG 1999
JUPITER'S ORBIT
11.8 YEARS
JUPITER
FLYBY
30 DEC 2000
SATURN ORBIT INSERTION
1 JUL 2004
SATURN'S ORBIT
29.1 YEARS

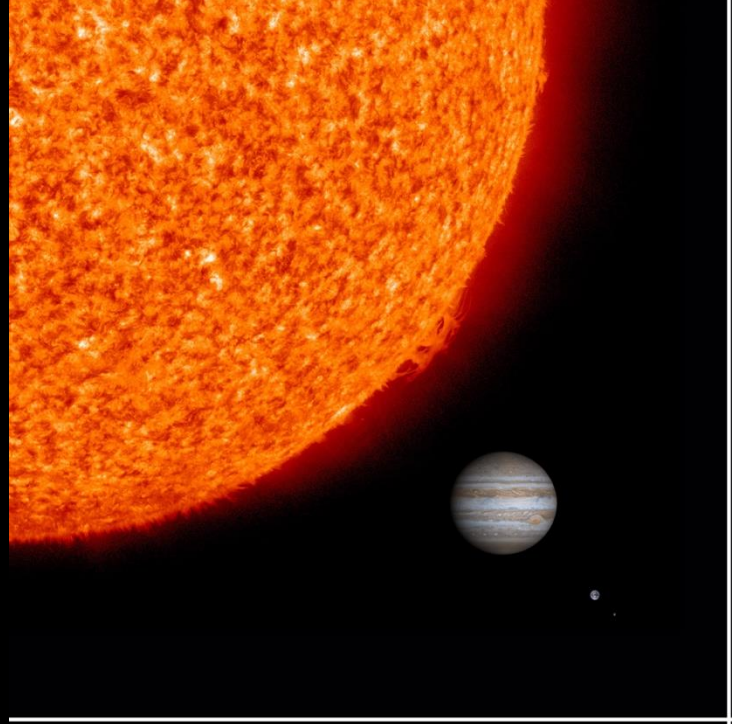

Earth fly-by
2013-10-09
Launch
2011-08-05
Deep space maneuvers
2012-08-30 & 2012-09-03
Jupiter orbital insertion
2016-07-05

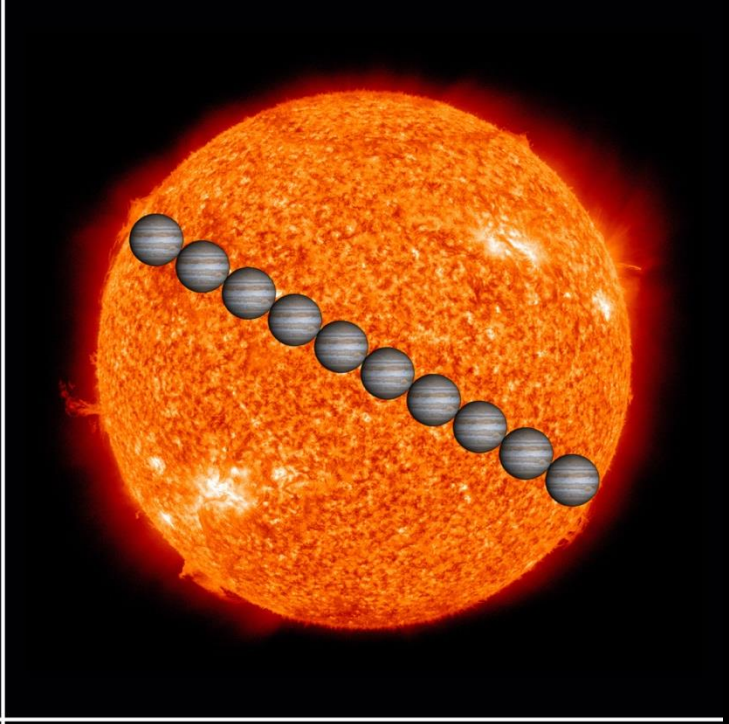
Missions to the Giant Planets

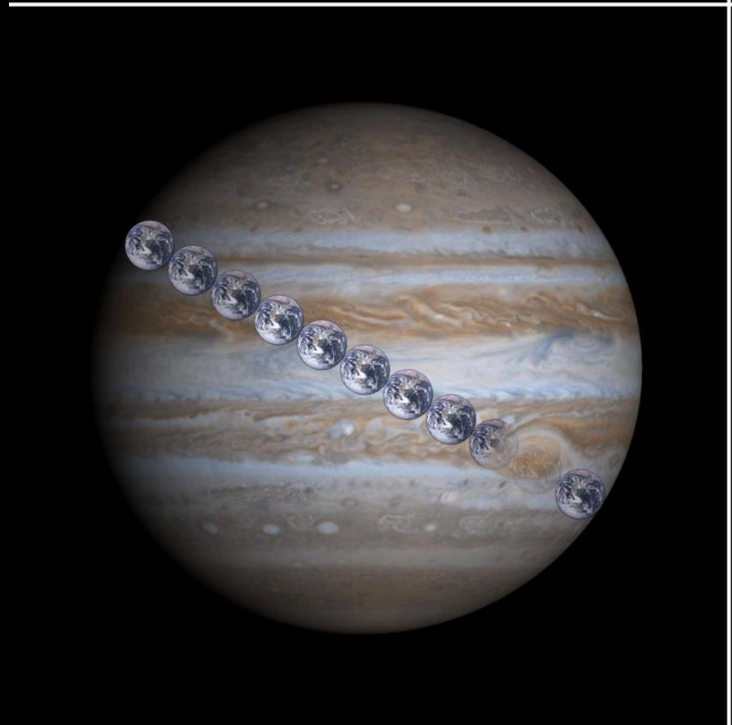
Planet	Spacecraft[1]	Encounter Date	Type
Jupiter	Pioneer 10	December 1973	Flyby
	Pioneer 11	December 1974	Flyby
	Voyager 1	March 1979	Flyby
	Voyager 2	July 1979	Flyby
	Ulysses	February 1992	Flyby during gravity assist
	Galileo	December 1995	Orbiter and probe
	Cassini	December 2002	Flyby
	New Horizons	February 2007	Flyby during gravity assist
	Juno	July 2016	Orbiter
Saturn	Pioneer 11	September 1979	Flyby
	Voyager 1	November 1980	Flyby
	Voyager 2	August 1981	Flyby
	Cassini	July 2004 (Saturn orbit injection 2000)	Orbiter

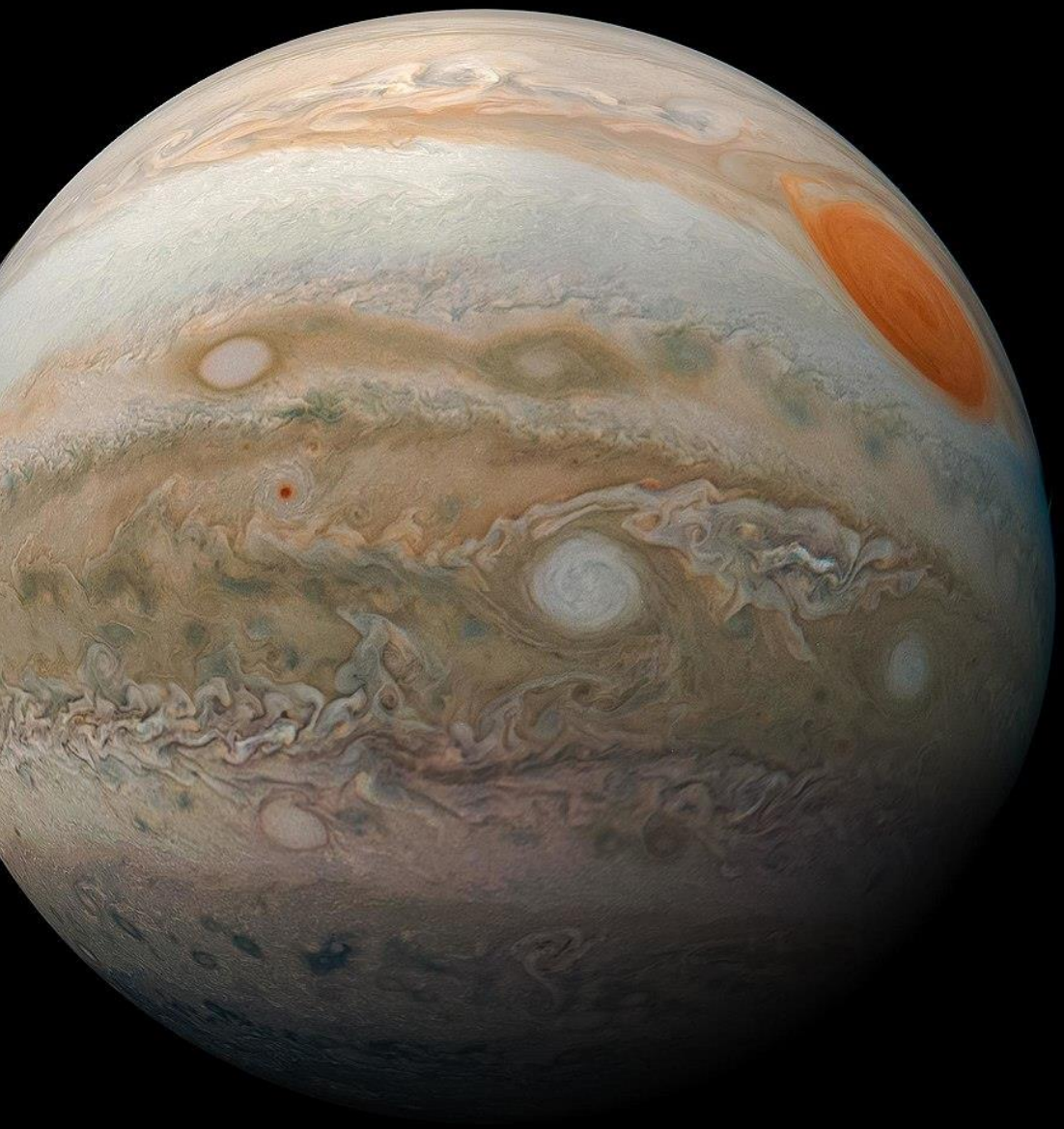

EARTH
JUPITER
SATURN
URANUS
NEPTUNE
Molecular hydrogen
Metallic hydrogen
Hydrogen, helium, methane gas
Mantle (water, ammonia, methane ices)
Core (rock, ice)


Jupiter
Saturn
Uranus
Neptune
Altitude (km)
200
100
0
–100
–200
–300
N_2H_4(?)
NH_3
NH_4HS
H_2O
P_2H_4(?)
NH_3
NH_4HS
H_2O
Hydrocarbon ices
CH_4
H_2S?
Hydrocarbon ices
CH_4
H_2S?
0
100
200
300
Temperature (K)



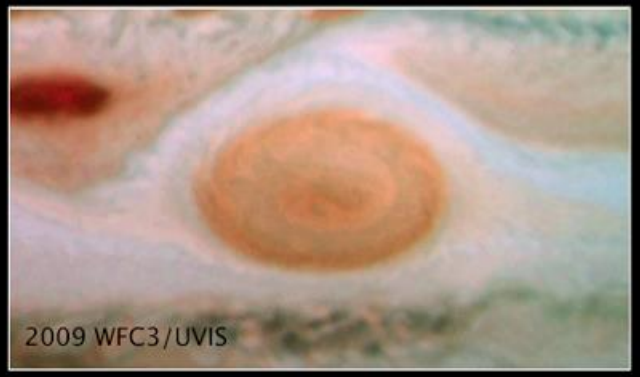


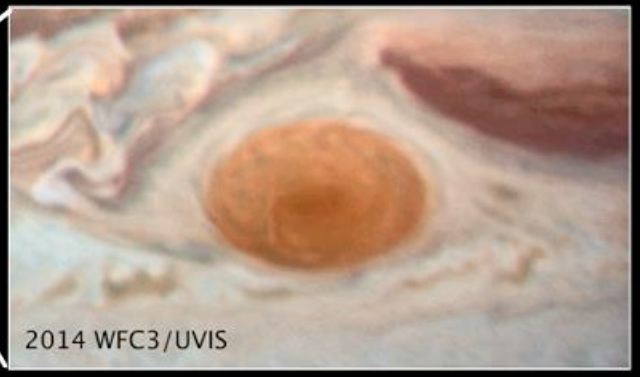




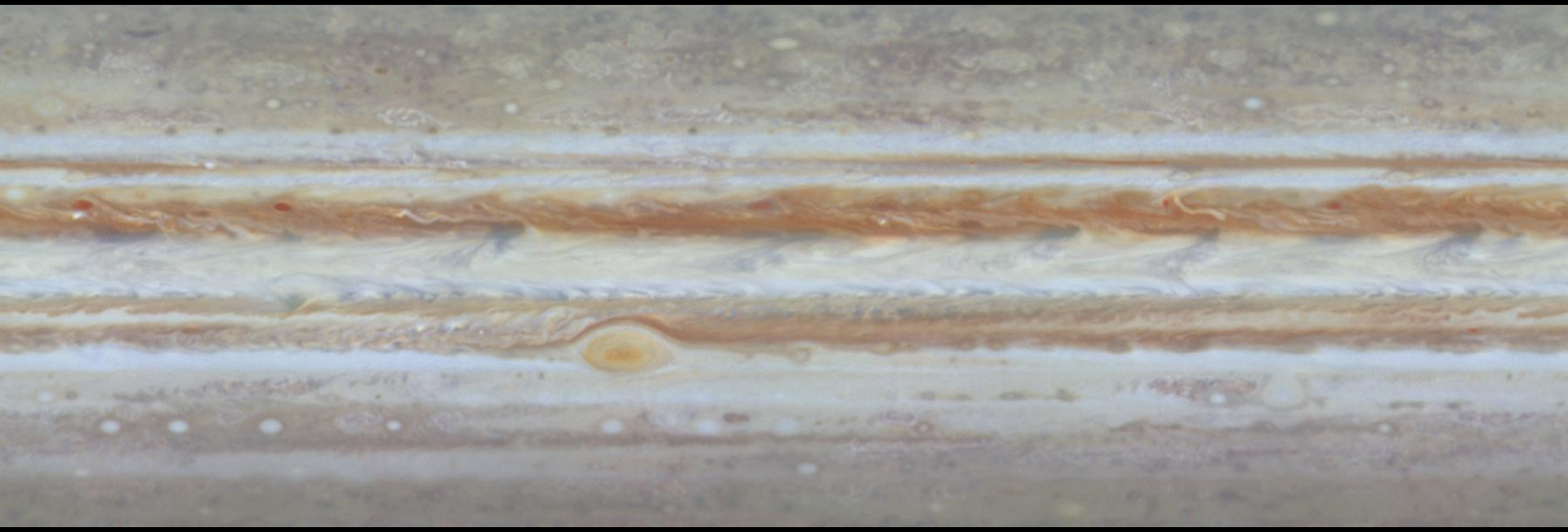
Bands of clouds

Great Red Spot: high-pressure storm





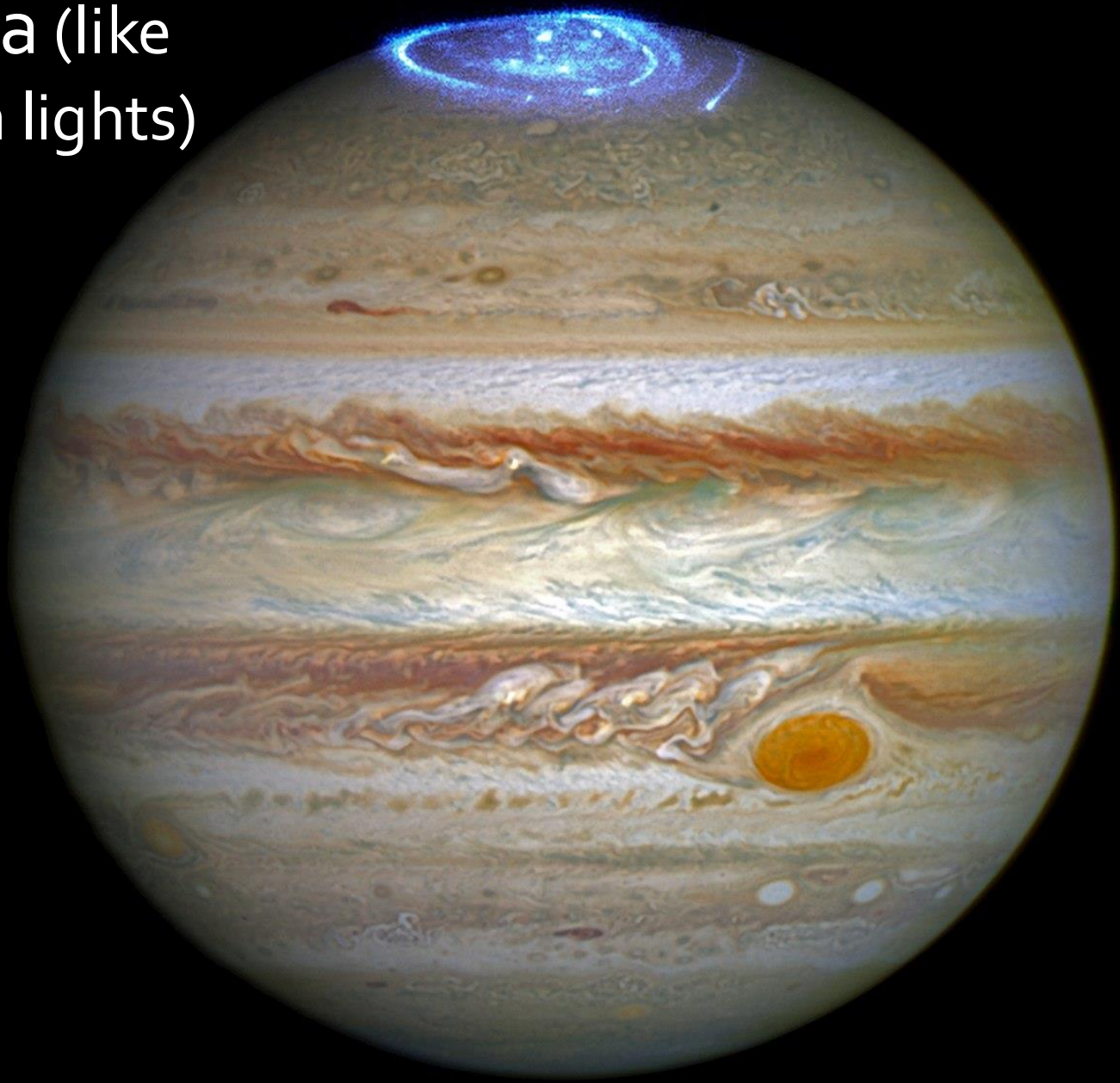
Red spot is shrinking!

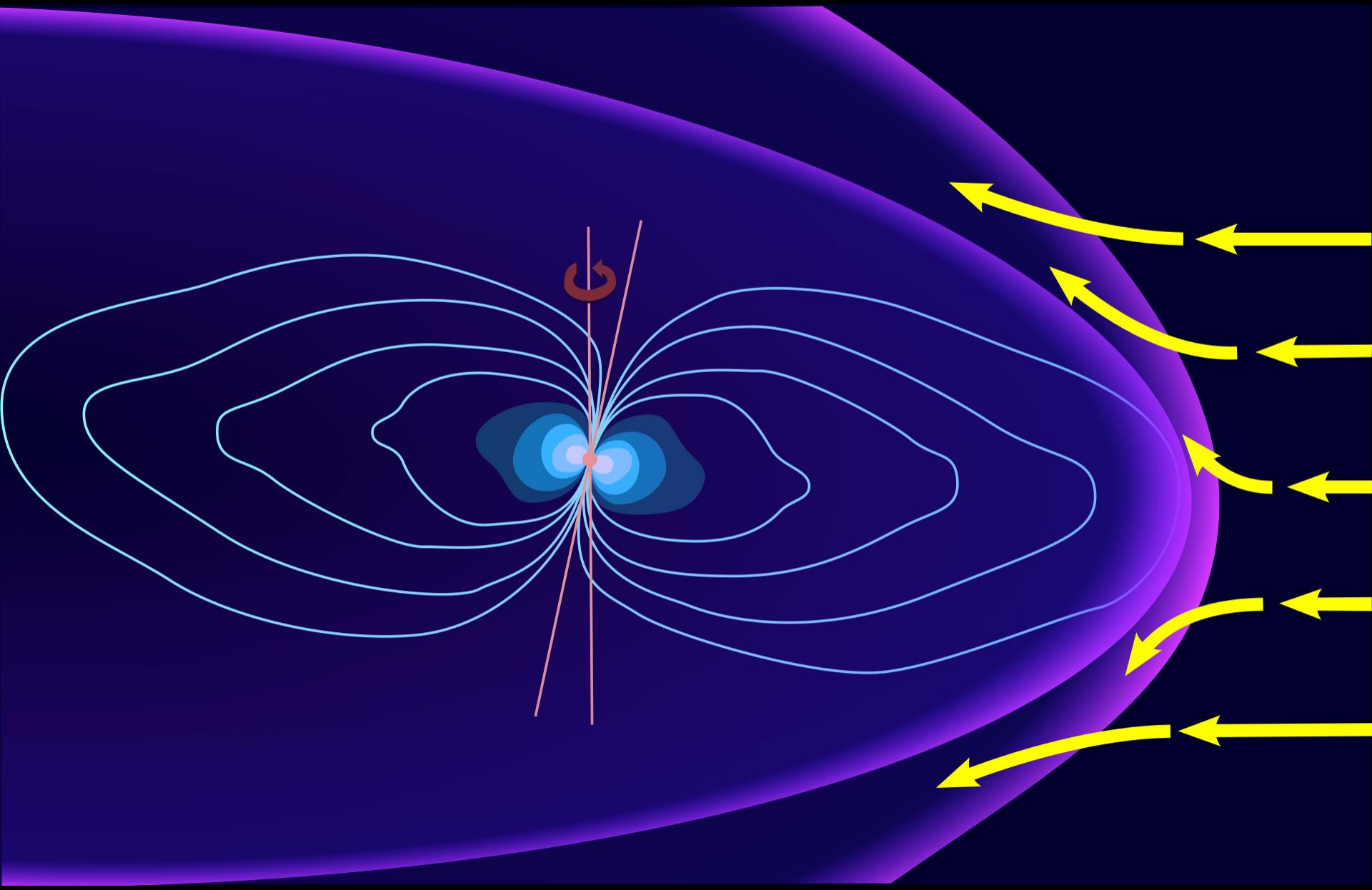


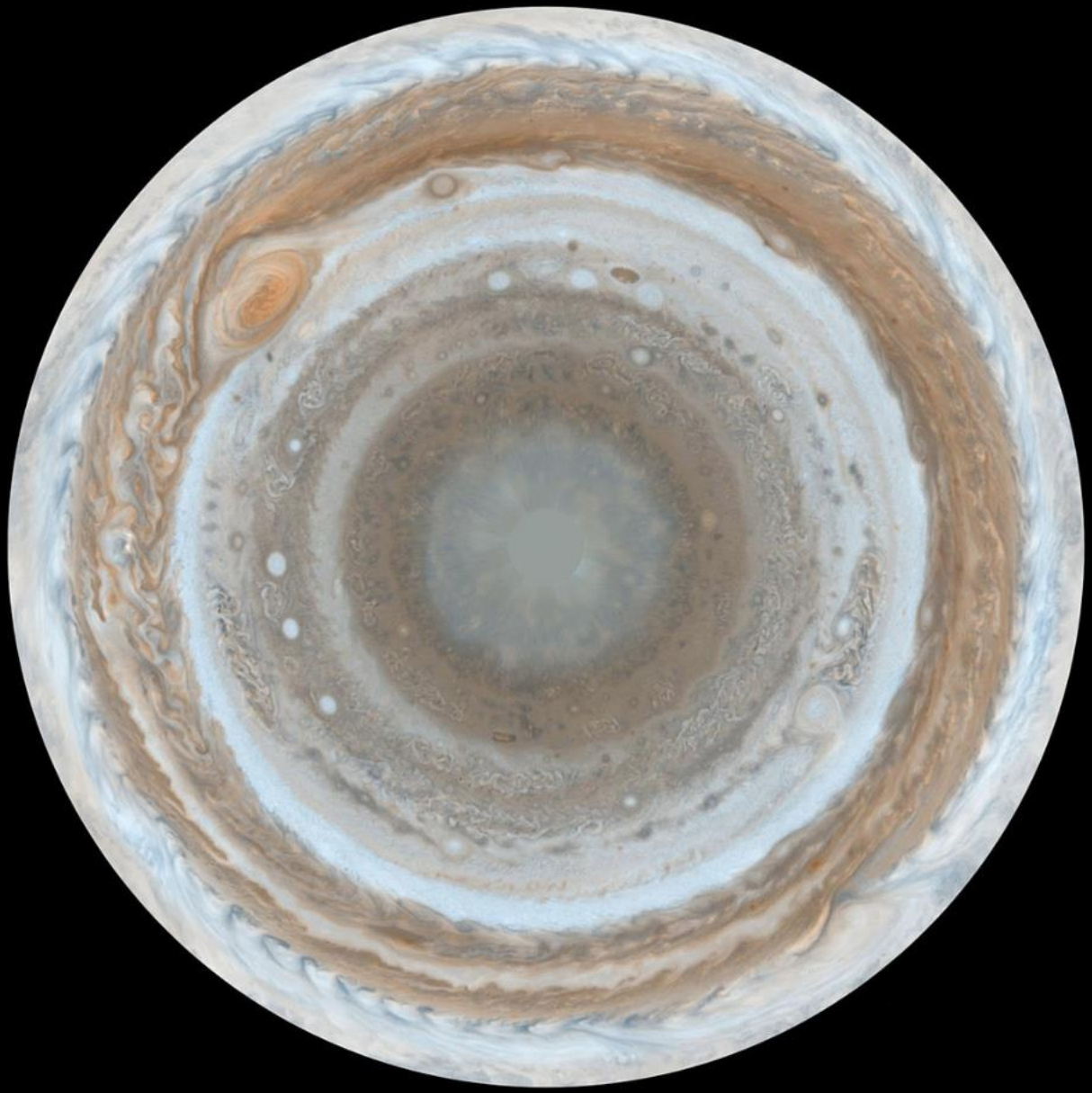
Bands rotate at different speeds

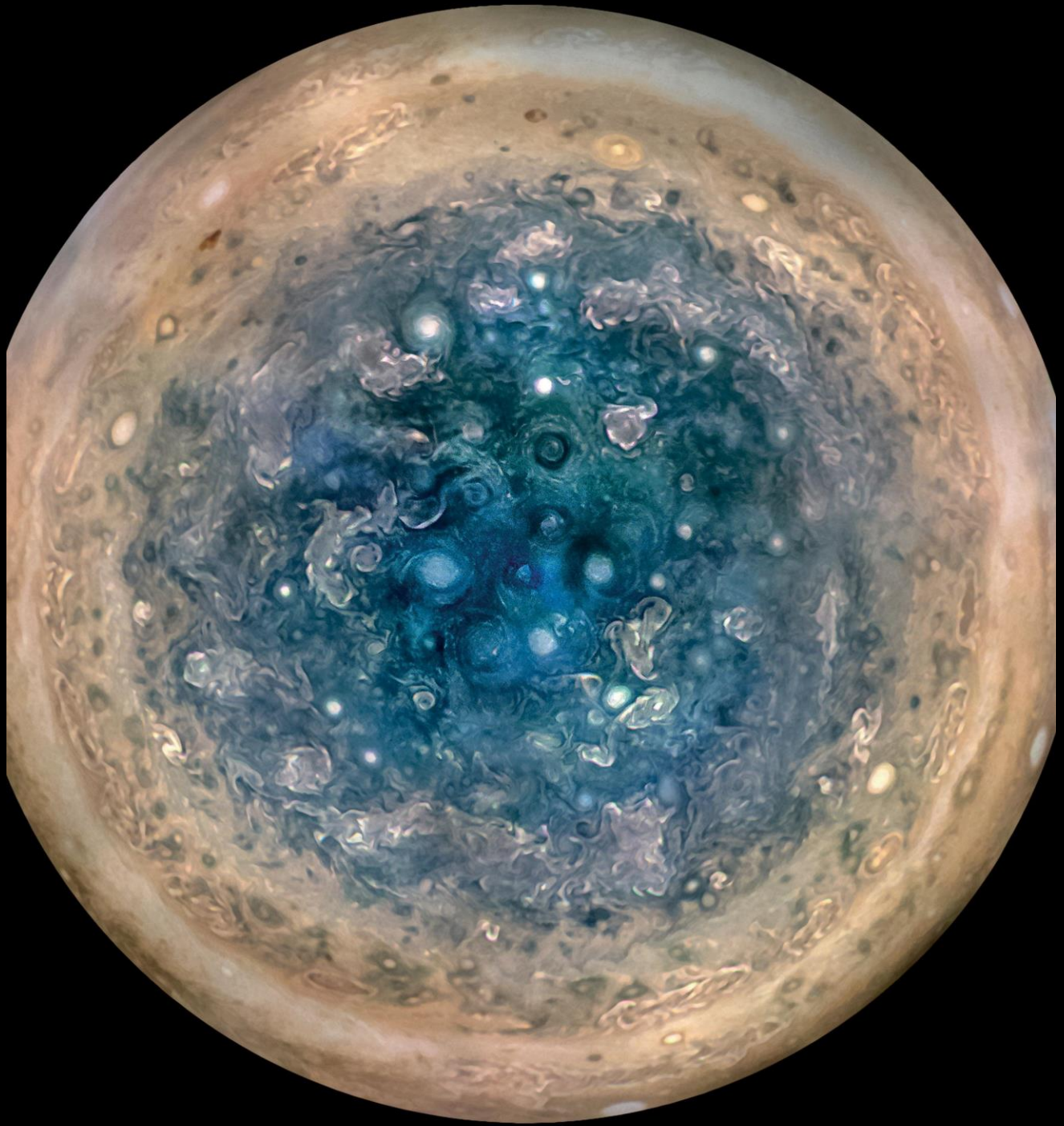
(like weather on earth)

Jovian aurora (like Earth: Northern lights)

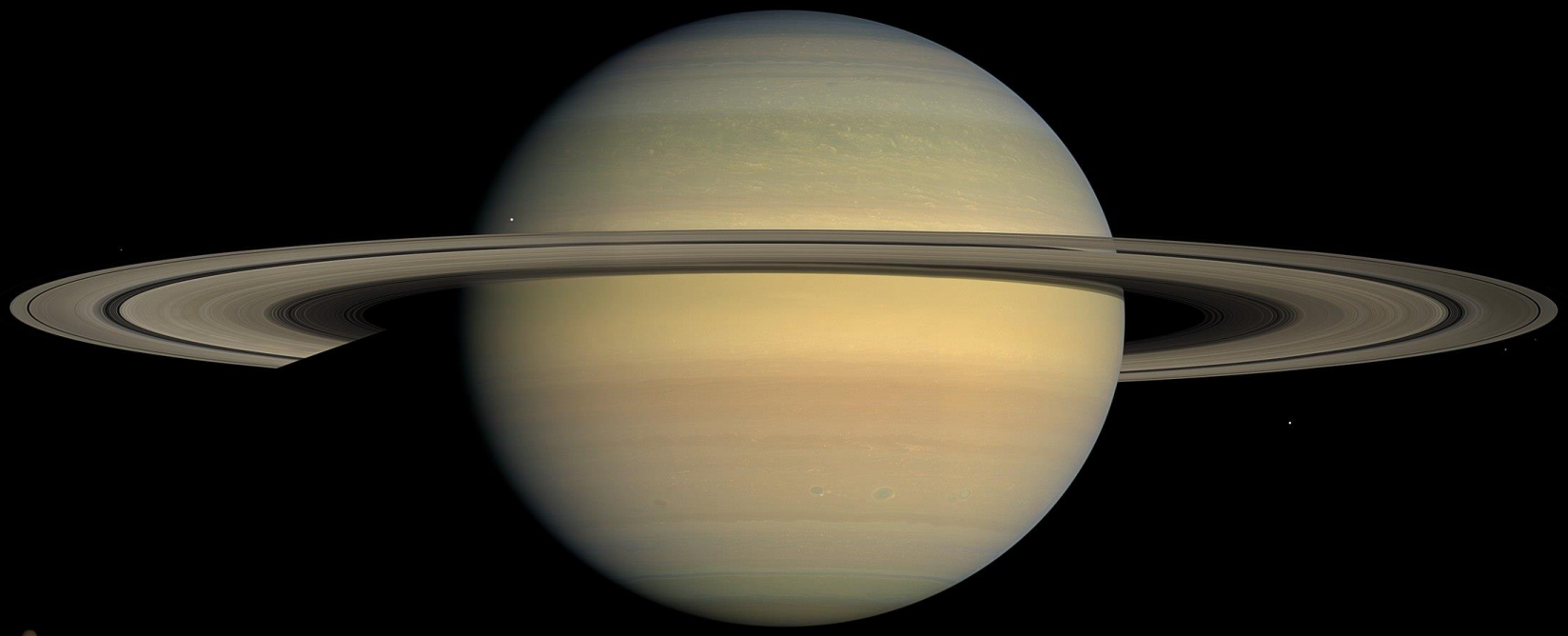


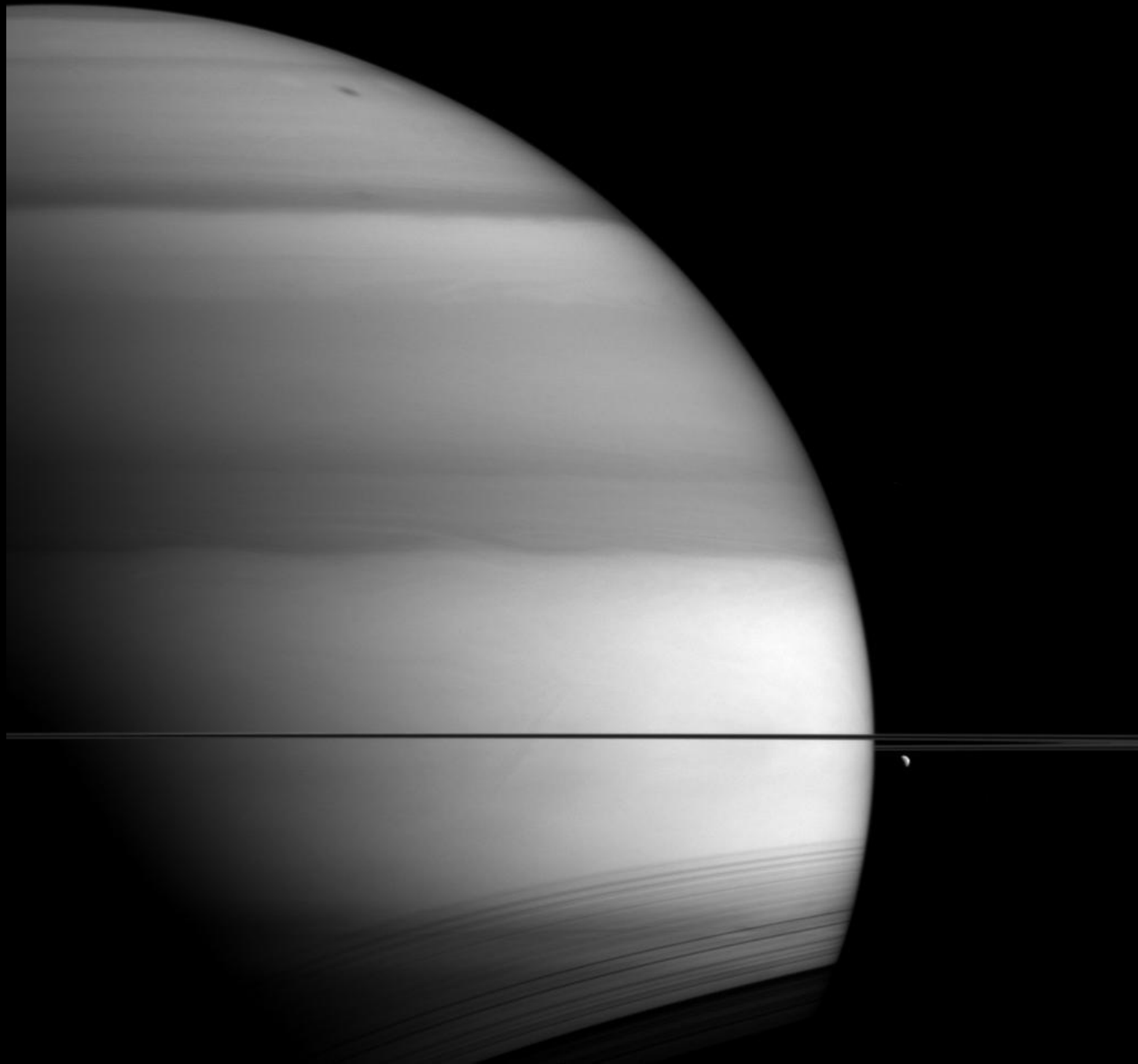


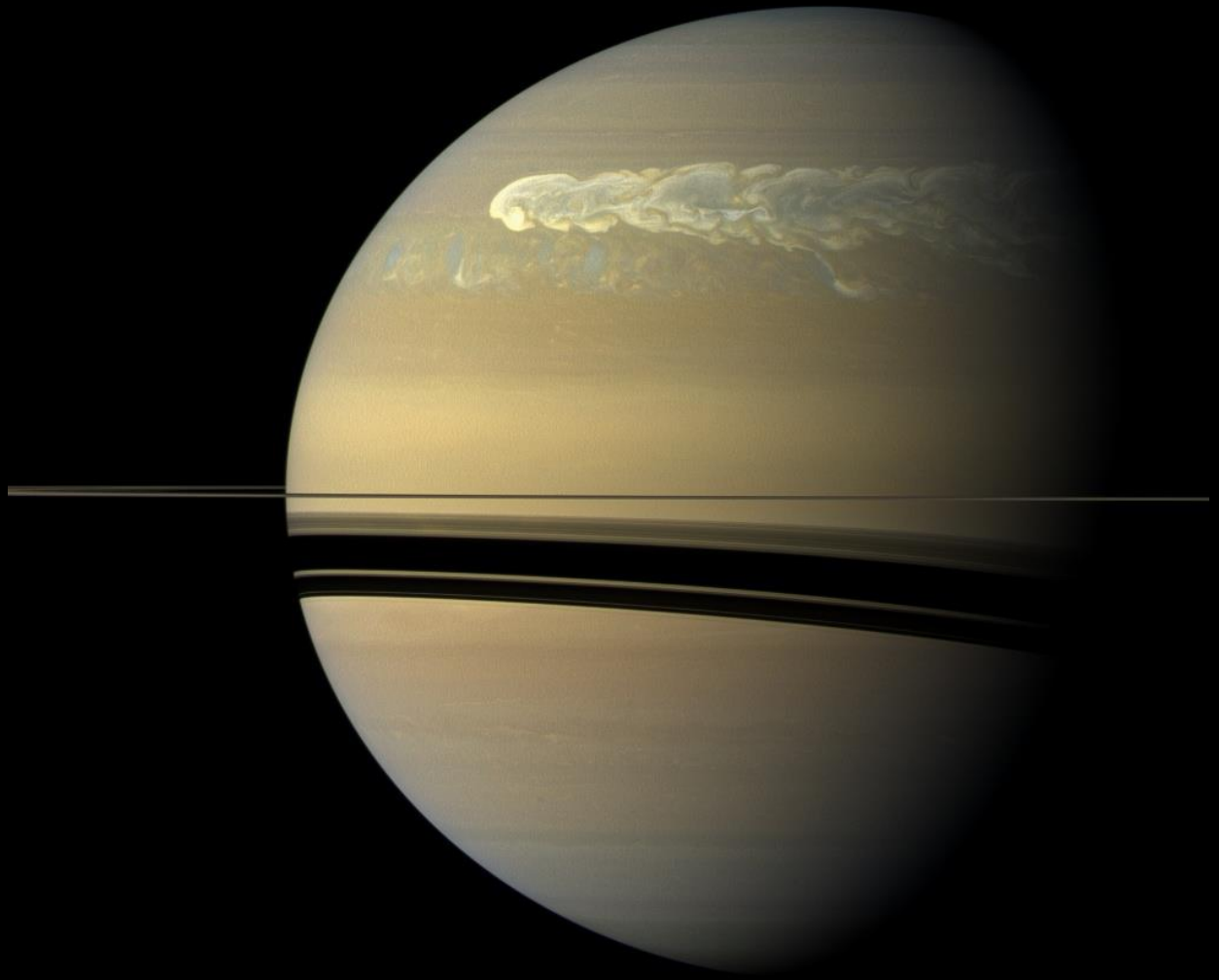


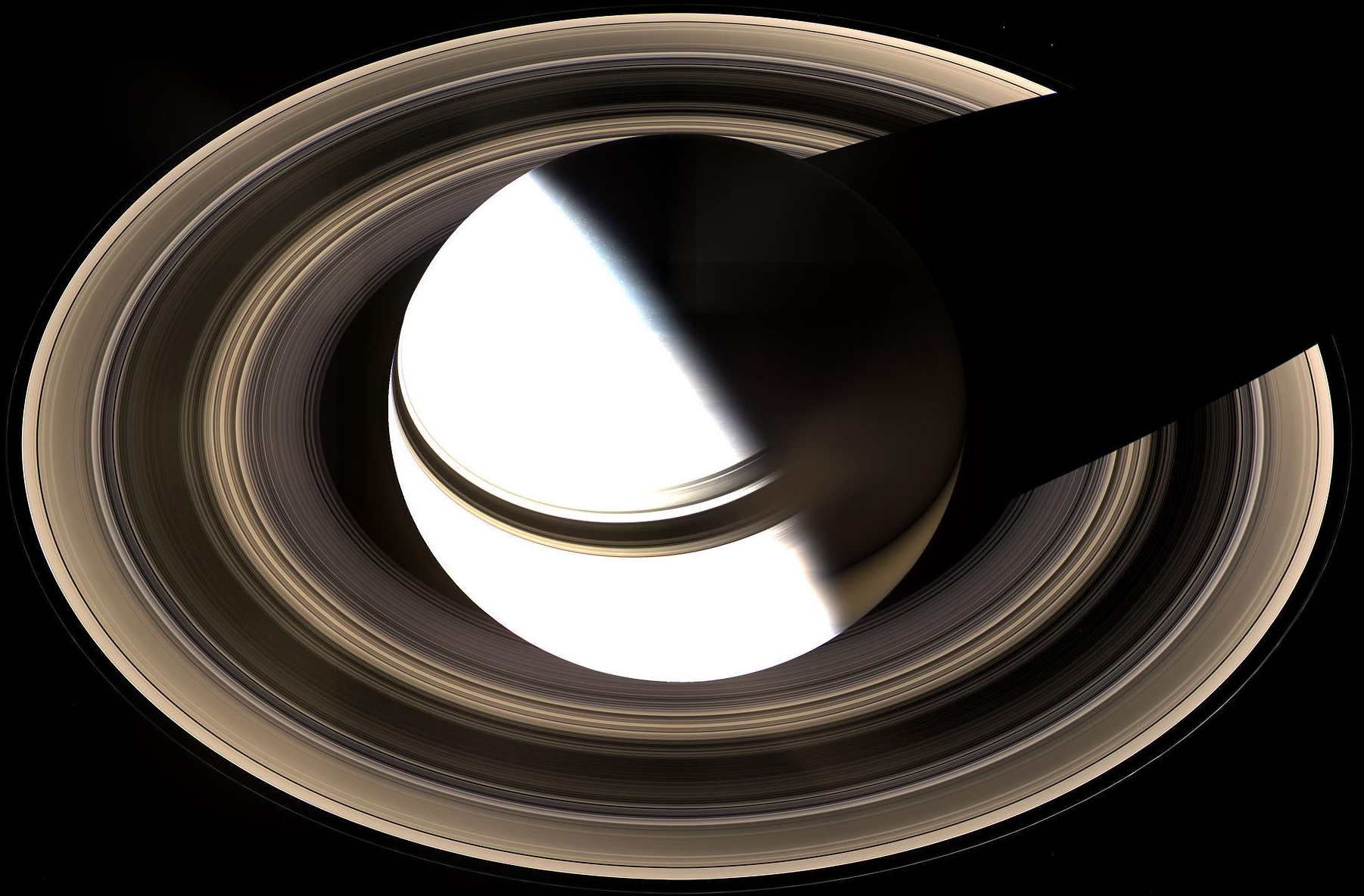


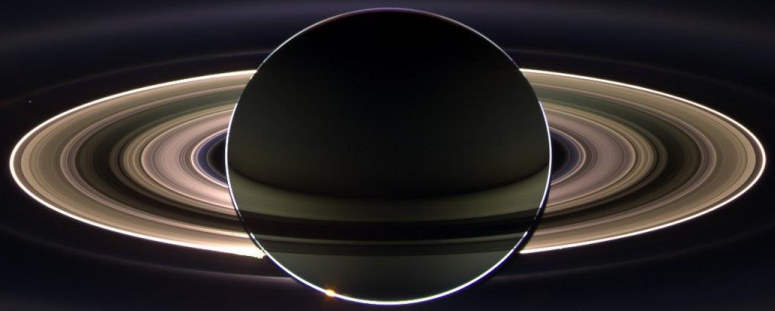
Saturn (and its rings)

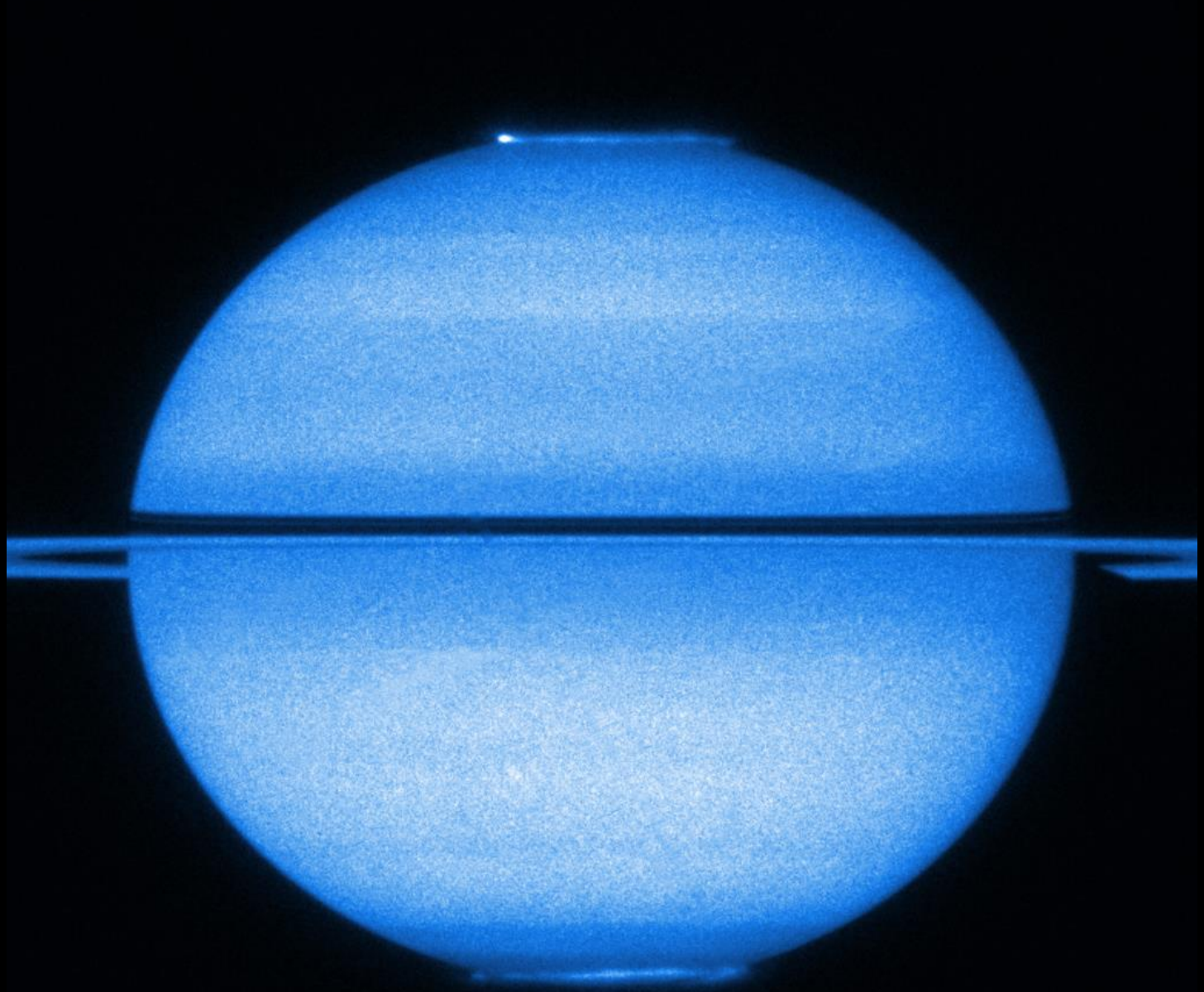




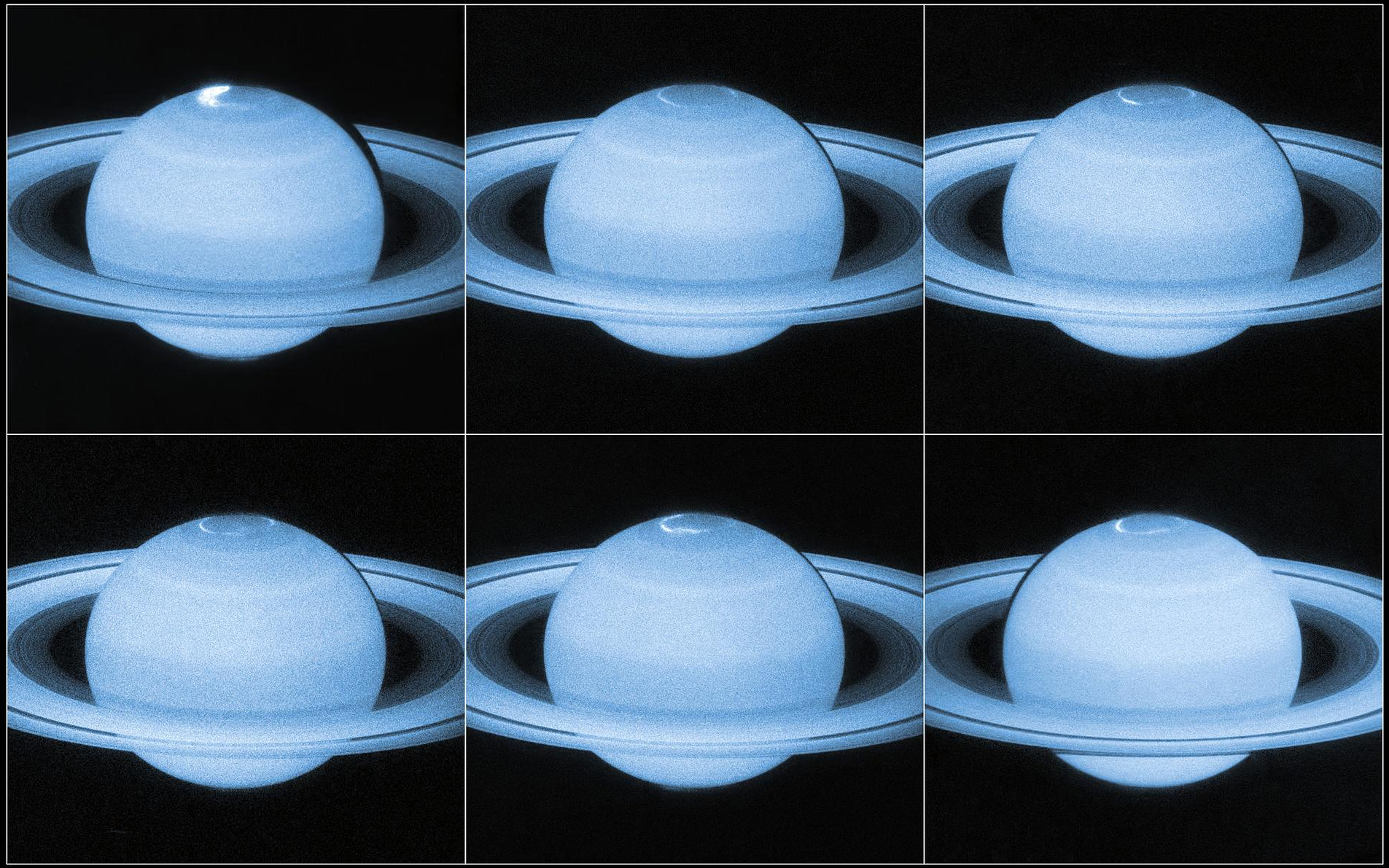


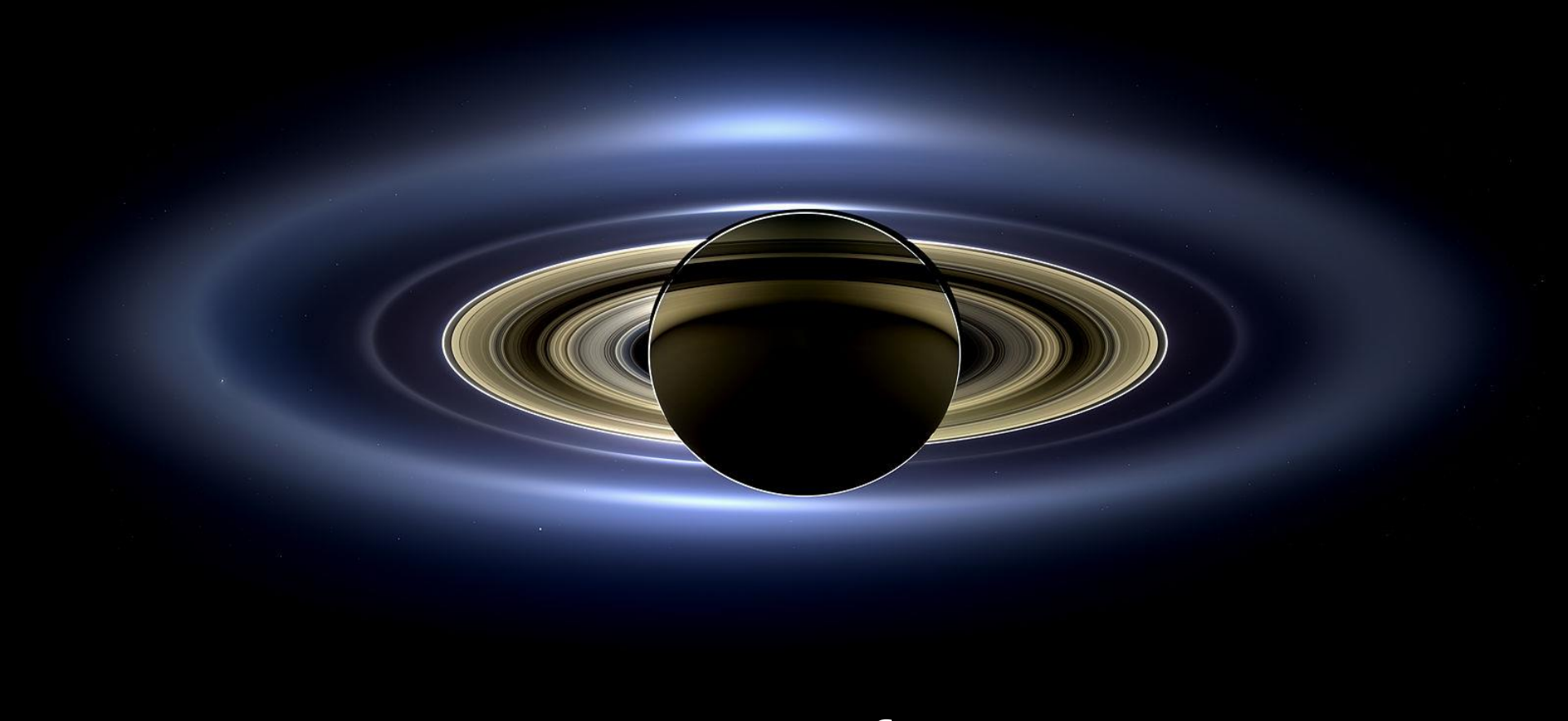




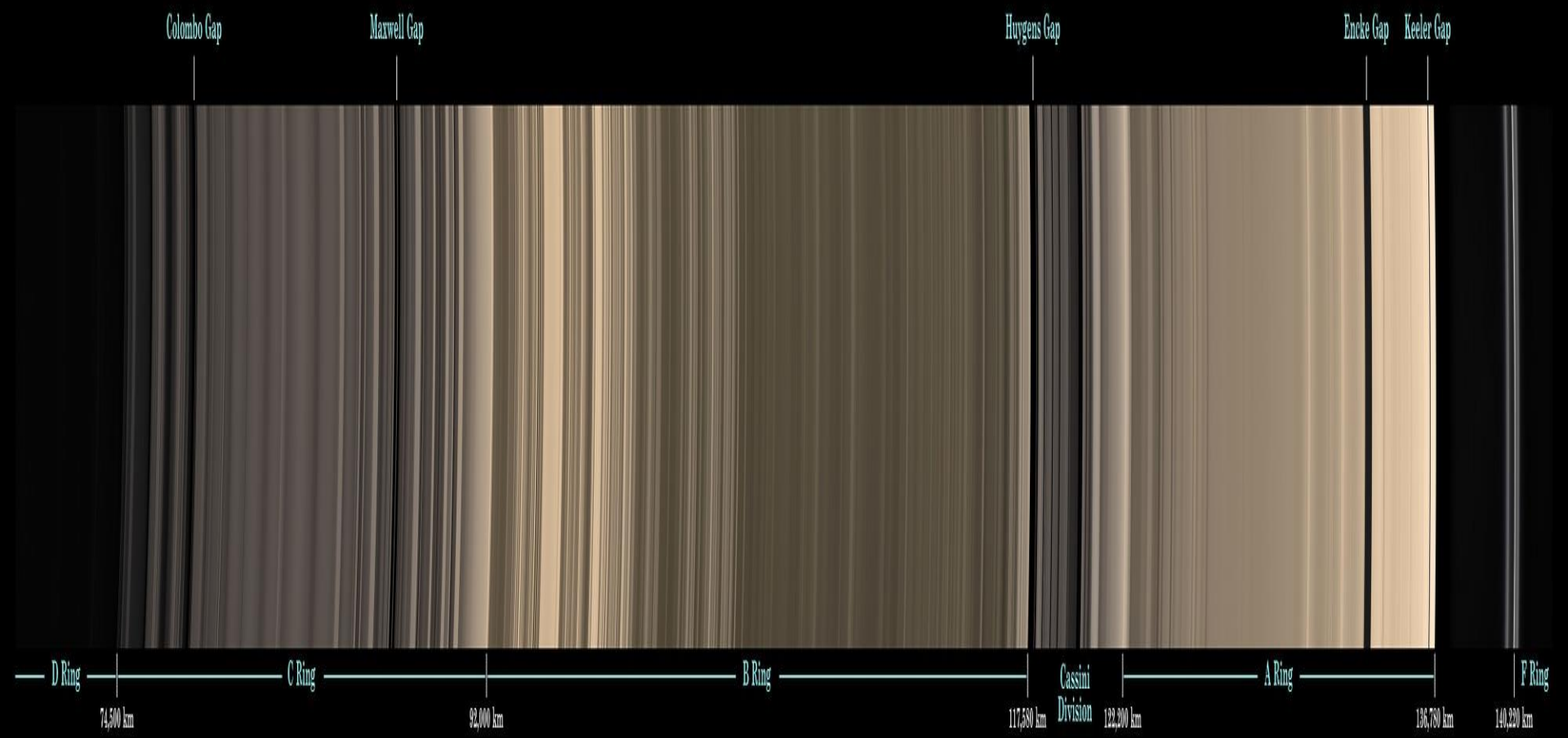


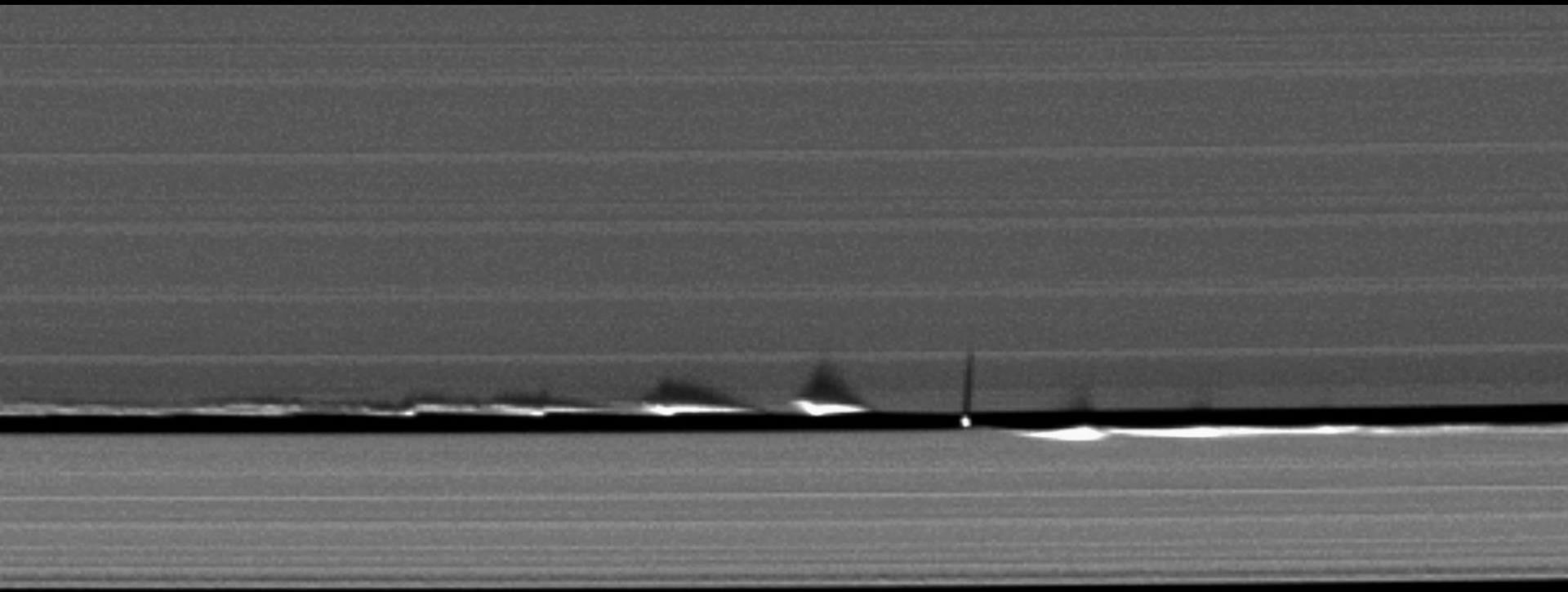
Saturn’s aurora

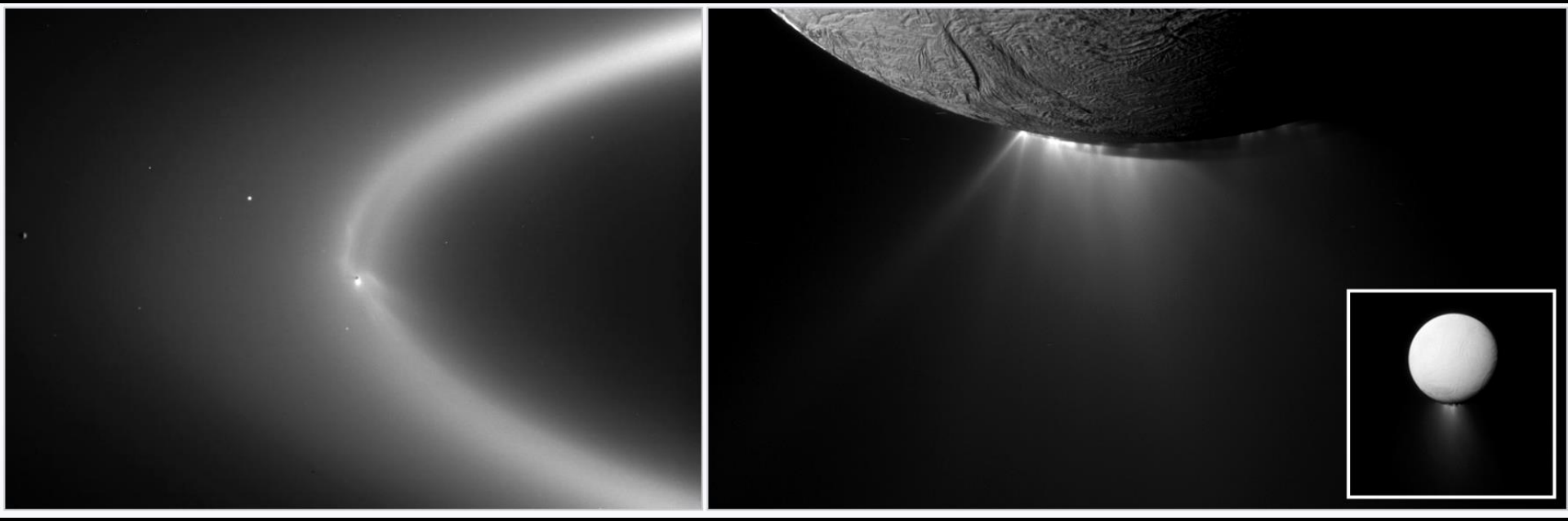




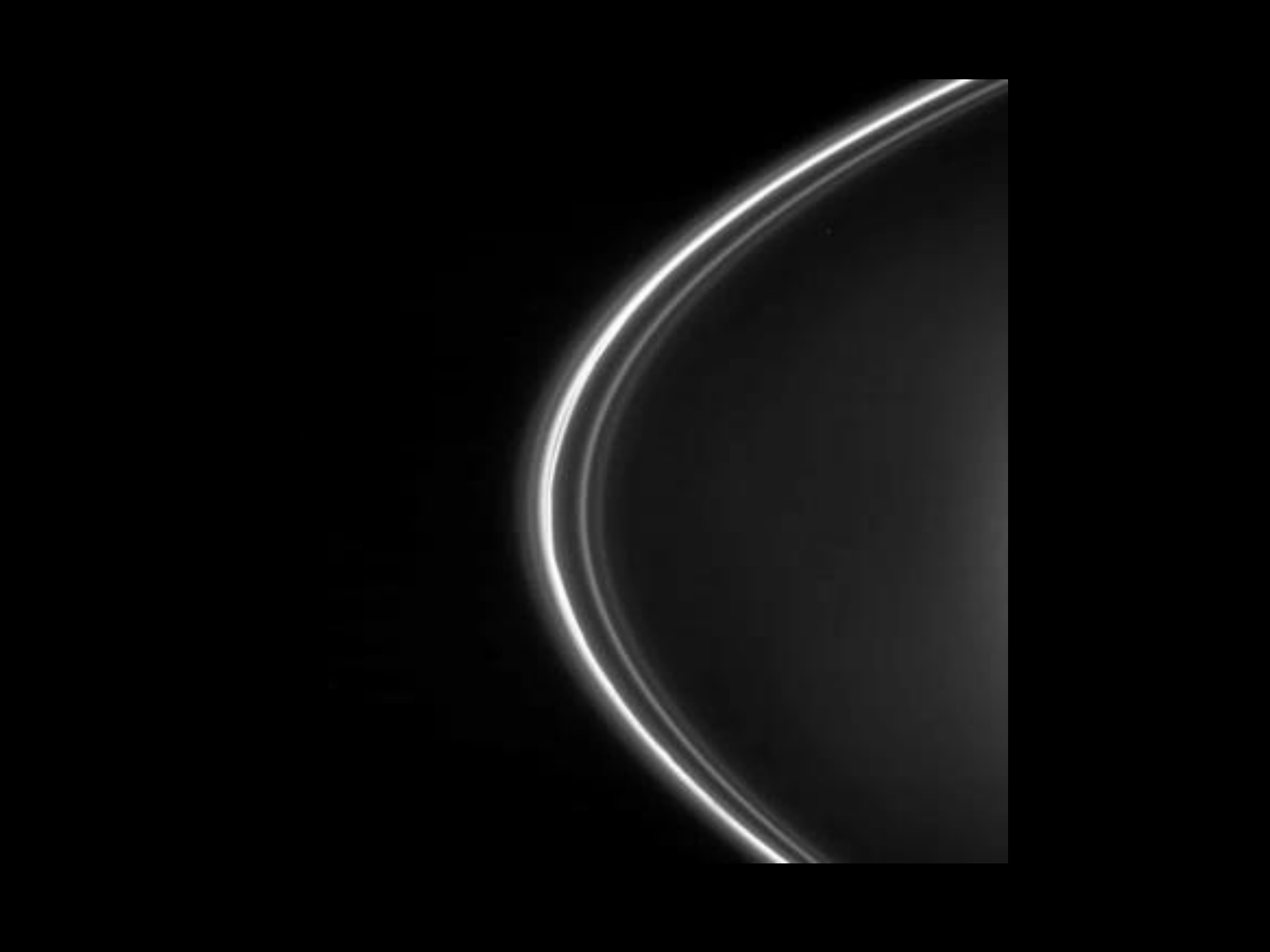
Rings: water ice a few m across
remnants of a moon
Thousands of km across; ~10 m thick!
<100 million years old

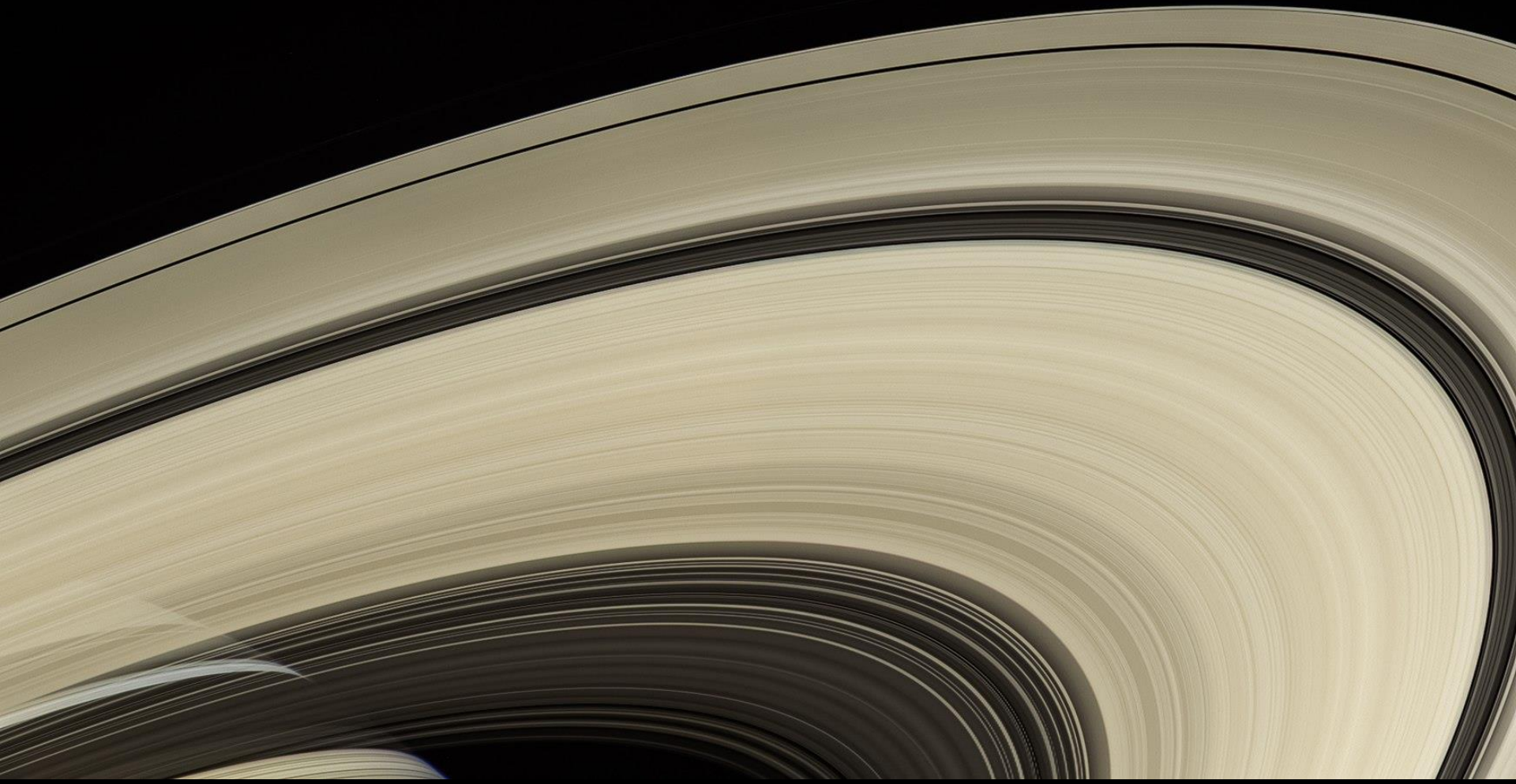

Colombo Gap
Maxwell Gap
Huygens Gap
Encke Gap
Keeler Gap
D Ring
C Ring
B Ring
Cassini Division
A Ring
F Ring
74,500 km
92,000 km
117,580 km
122,200 km
136,780 km
140,220 km

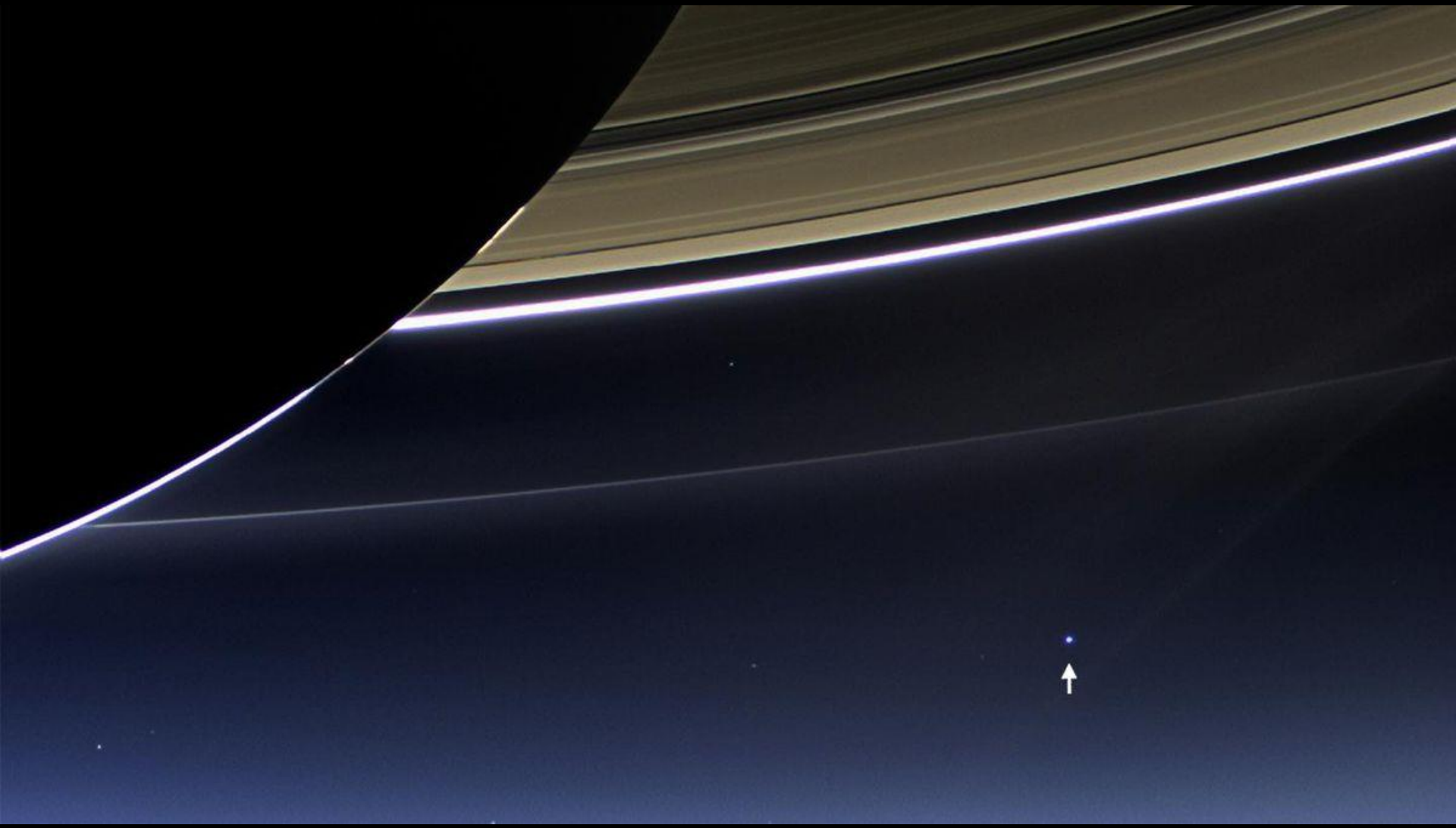




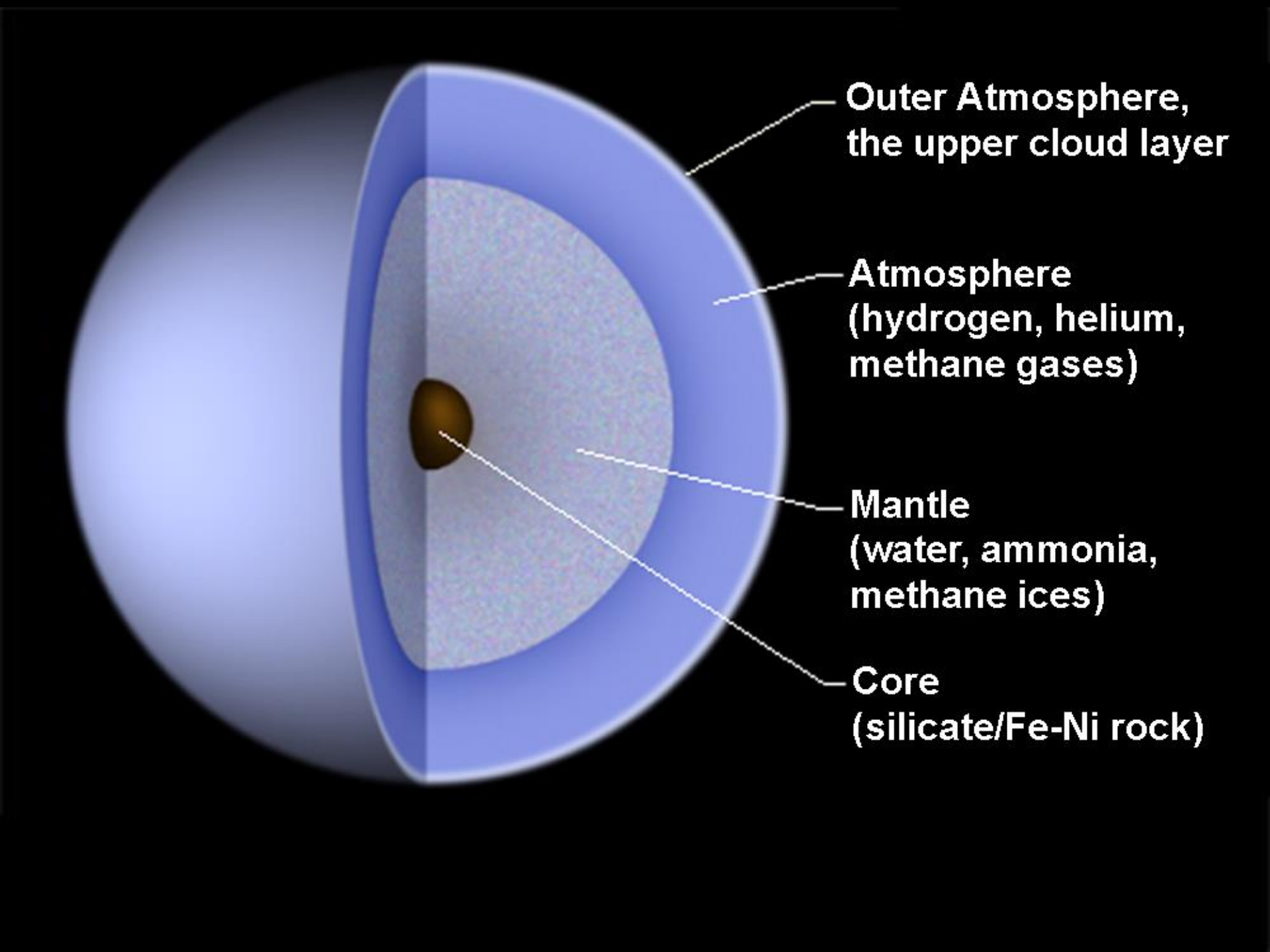
E ring: thousands of m thick
Water from geysers on the moon Enceladus



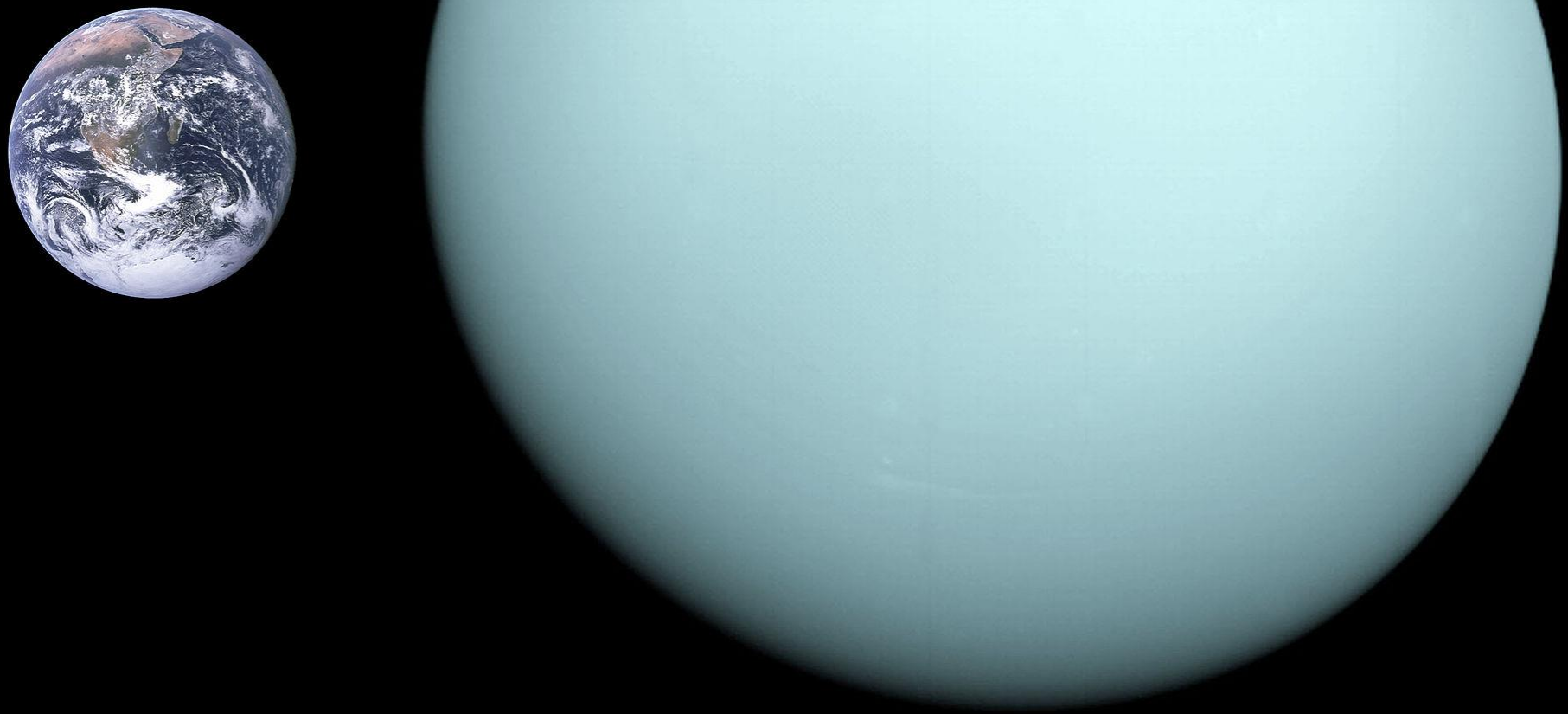


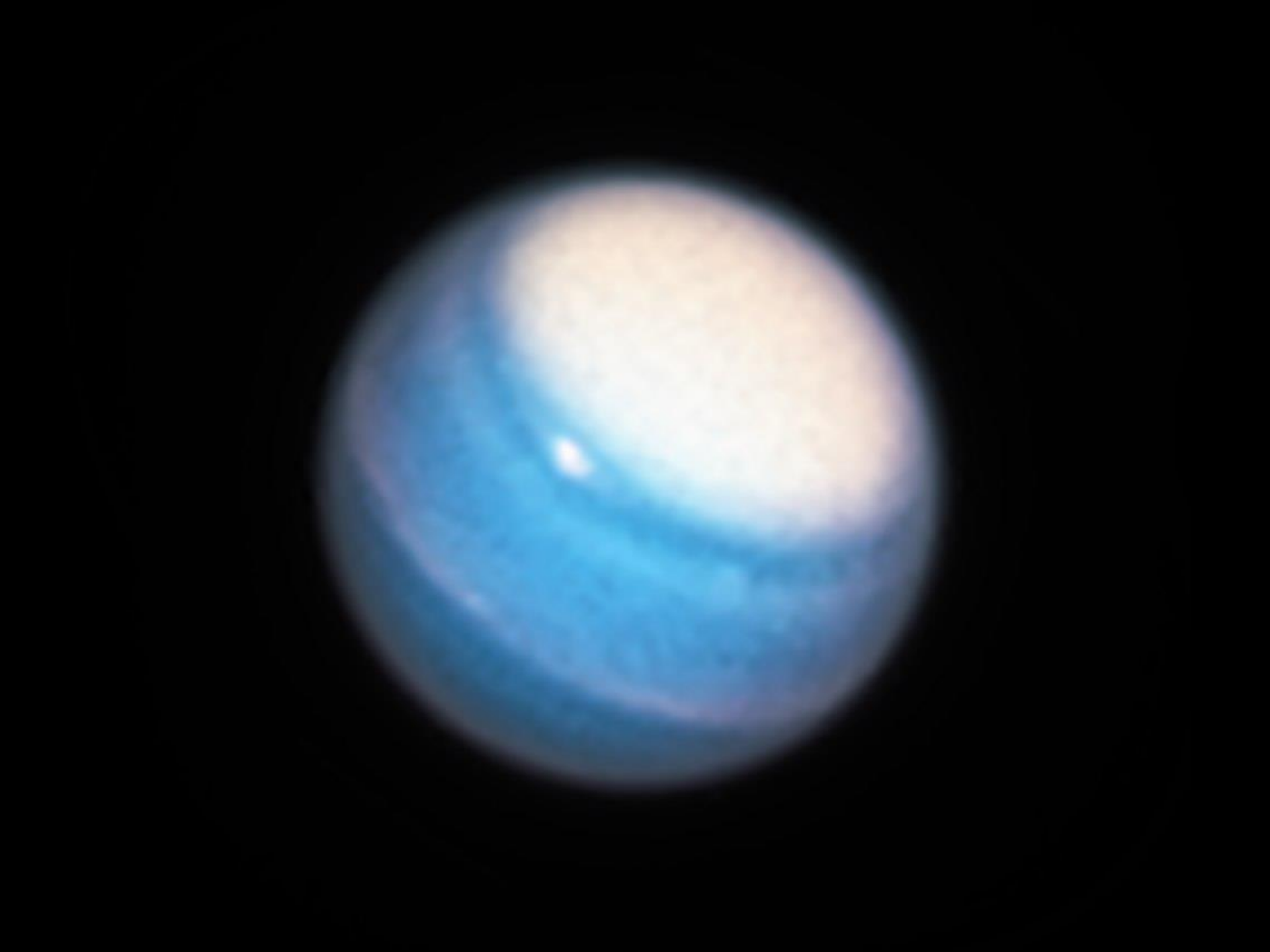


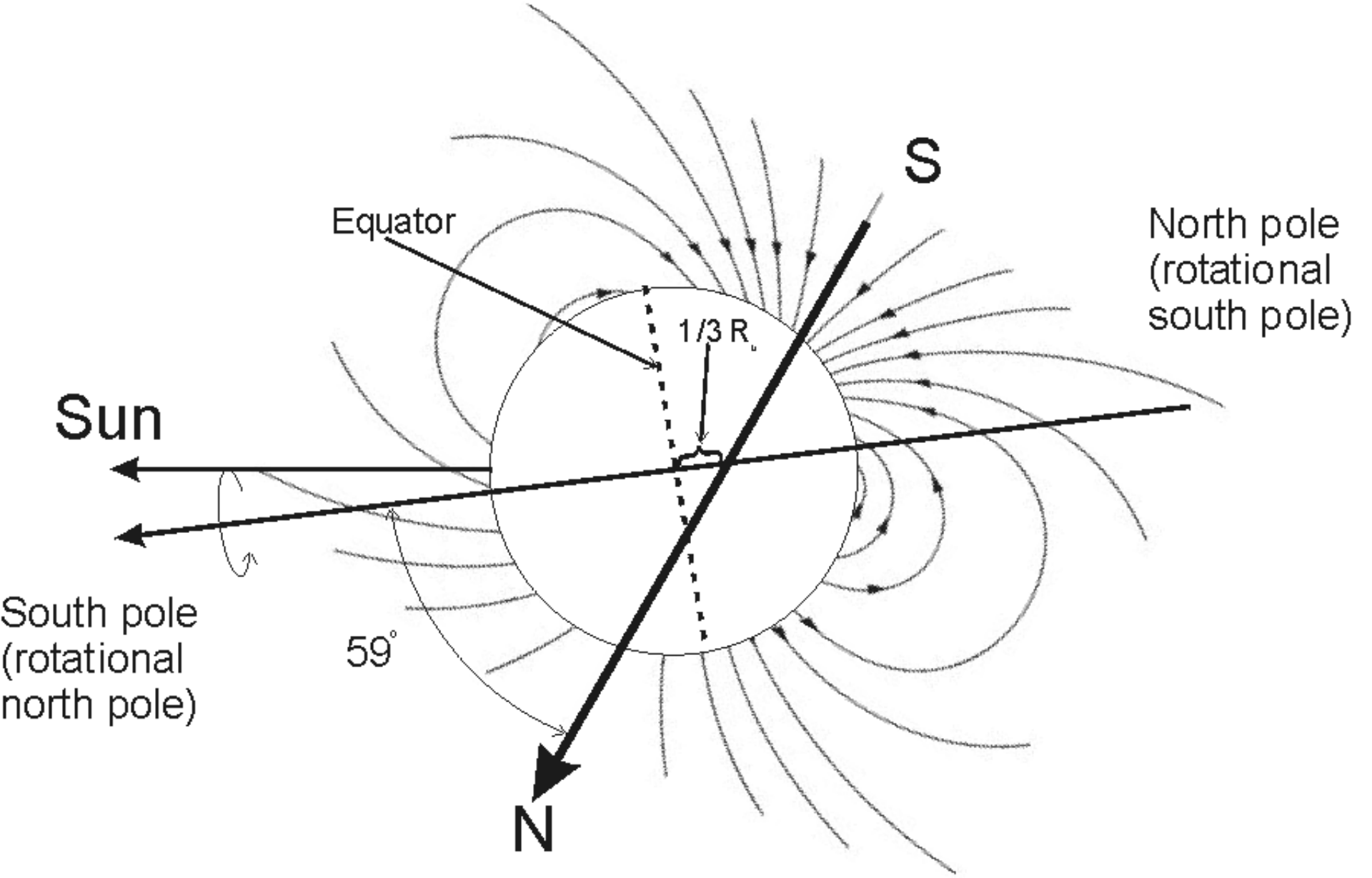
Uranus


Outer Atmosphere,
the upper cloud layer
Atmosphere
(hydrogen, helium,
methane gases)
Mantle
(water, ammonia,
methane ices)
Core
(silicate/Fe-Ni rock)

Tilted by 90 degrees!
-past collision

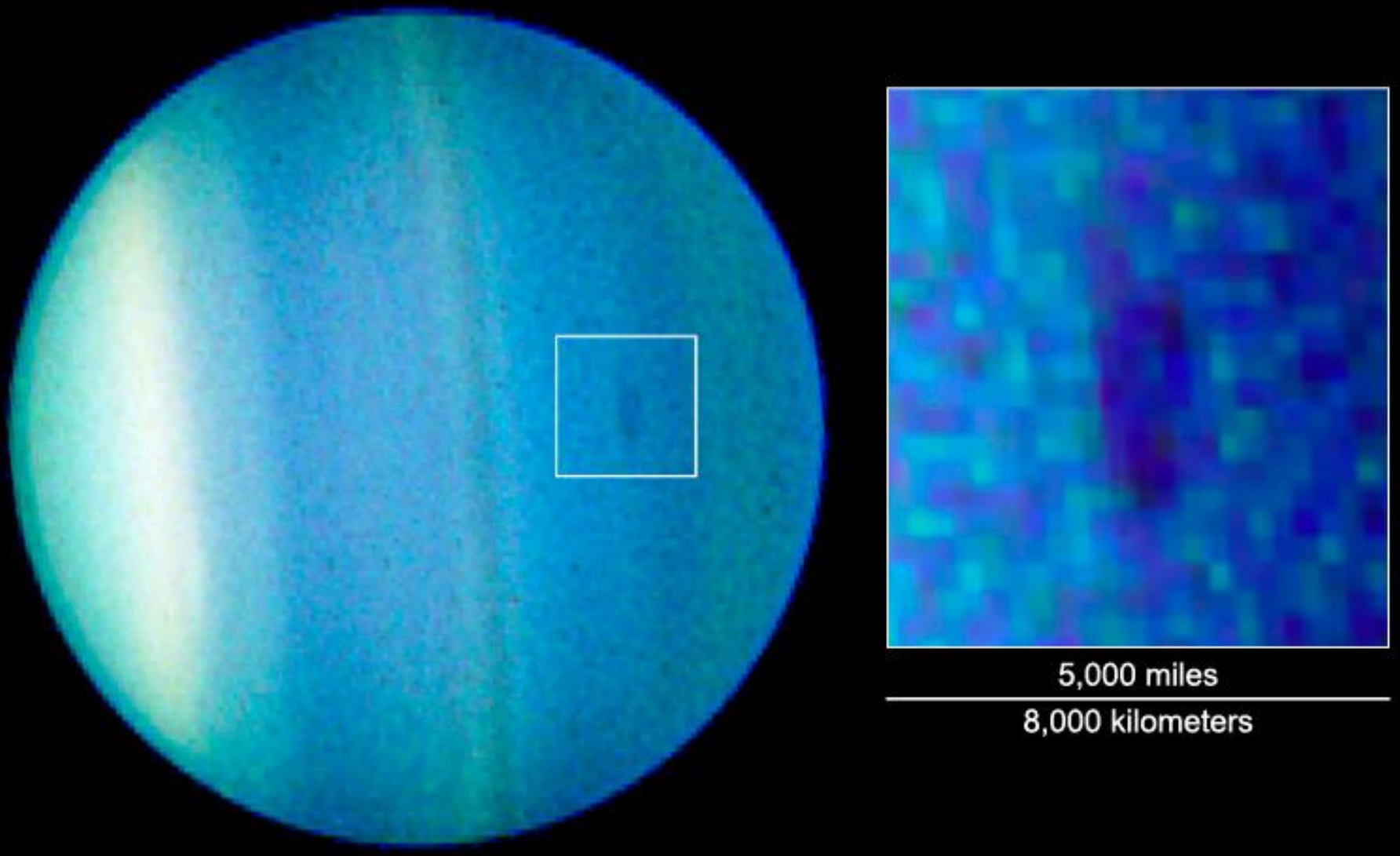





S
Equator
North pole
(rotational
south pole)
1/3 R
Sun
South pole
(rotational
north pole)
59°
N

Uranus Dark Spot

Hubble Space Telescope ▪ ACS

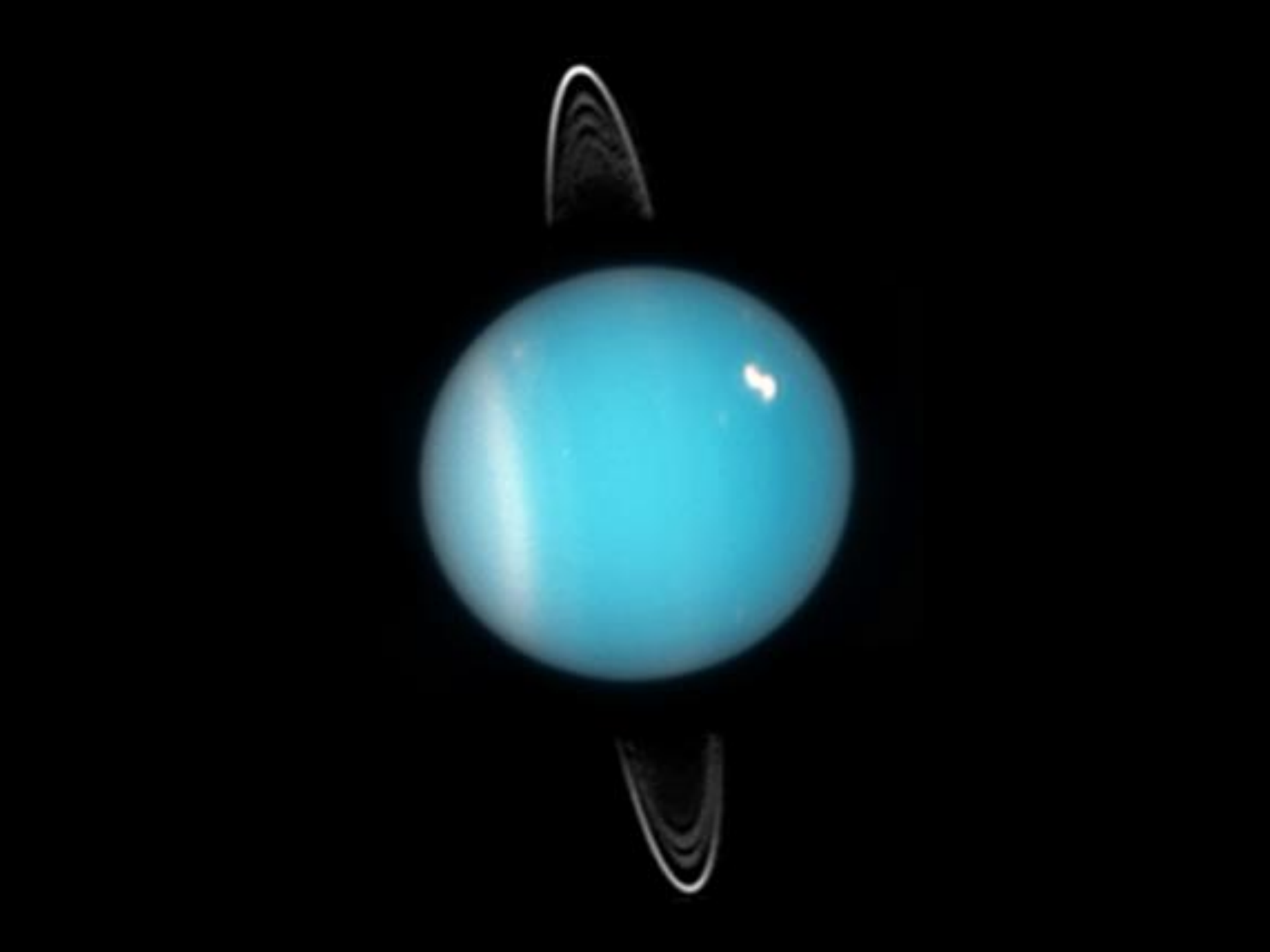


5,000 miles

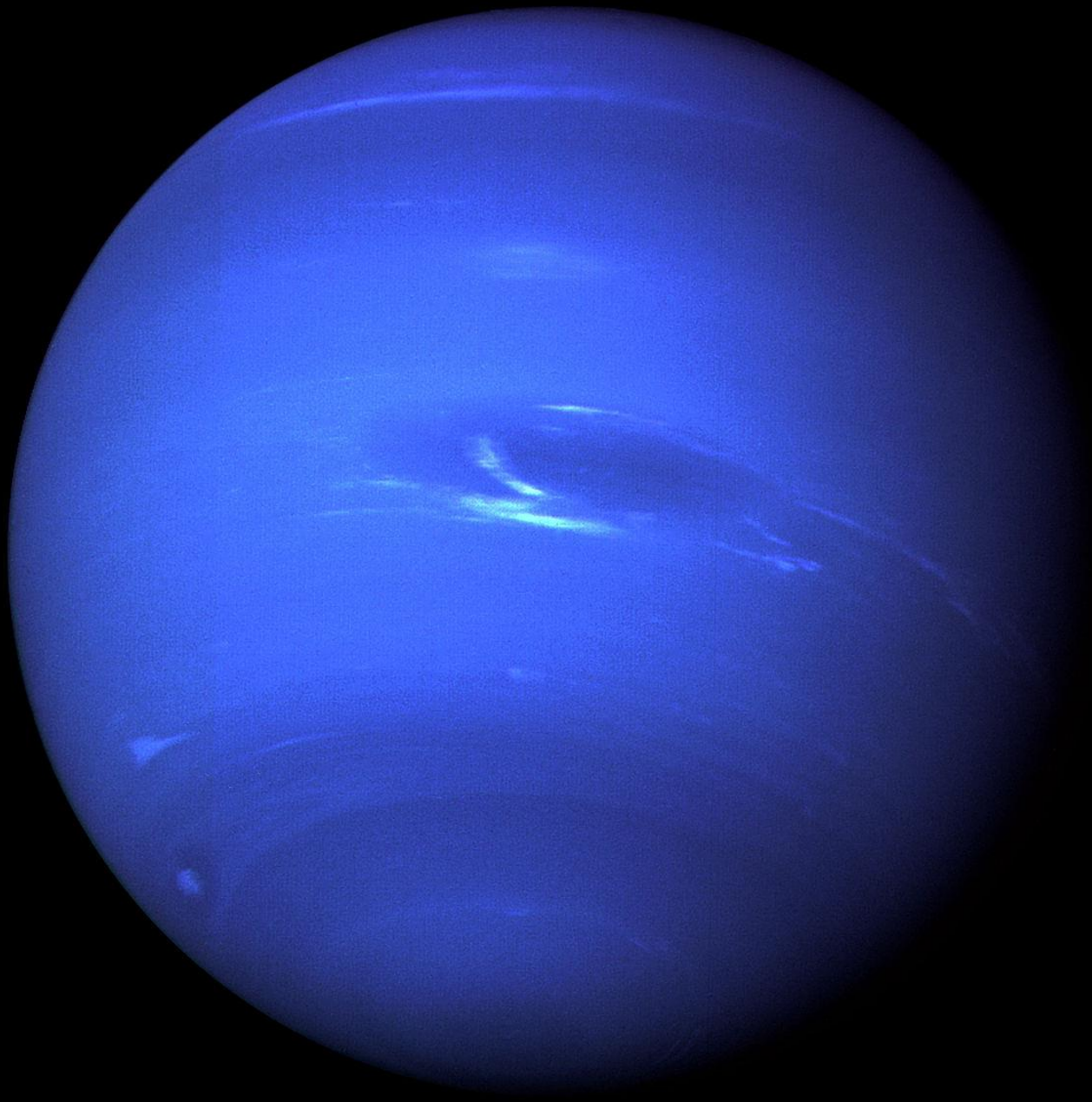
8,000 kilometers

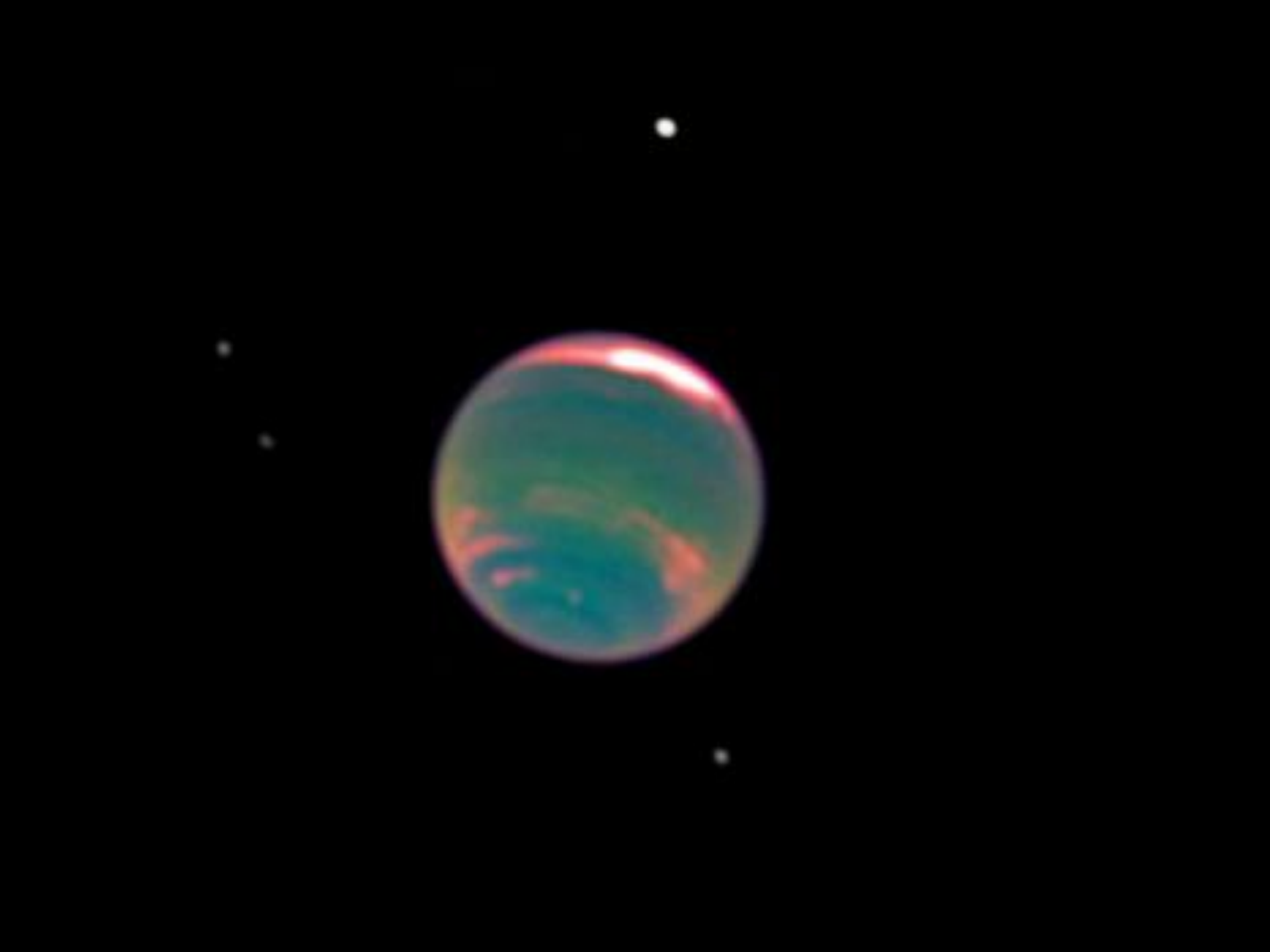
NASA, ESA, and L. Sromovsky (University of Wisconsin)

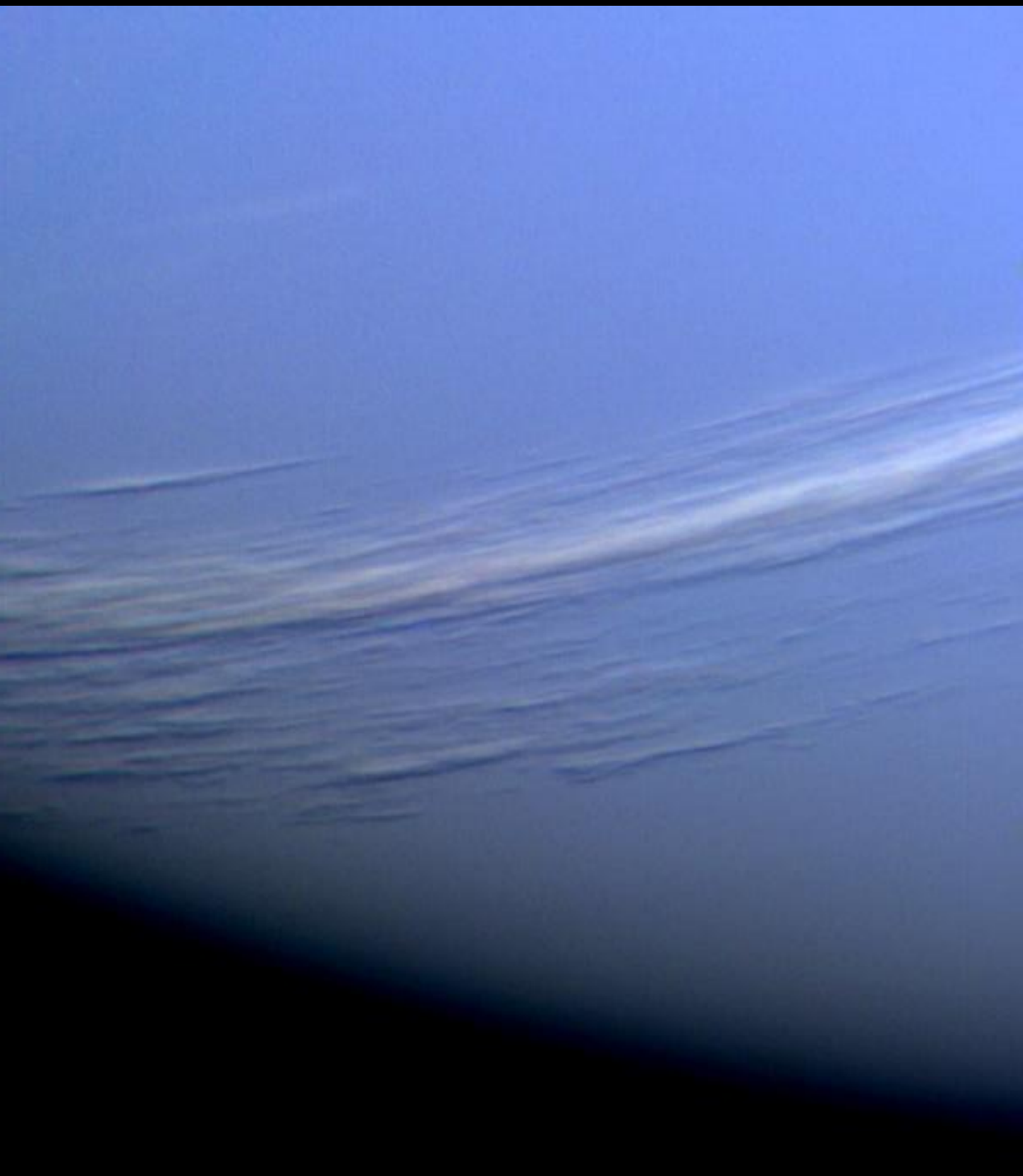
STScI-PRC06-47

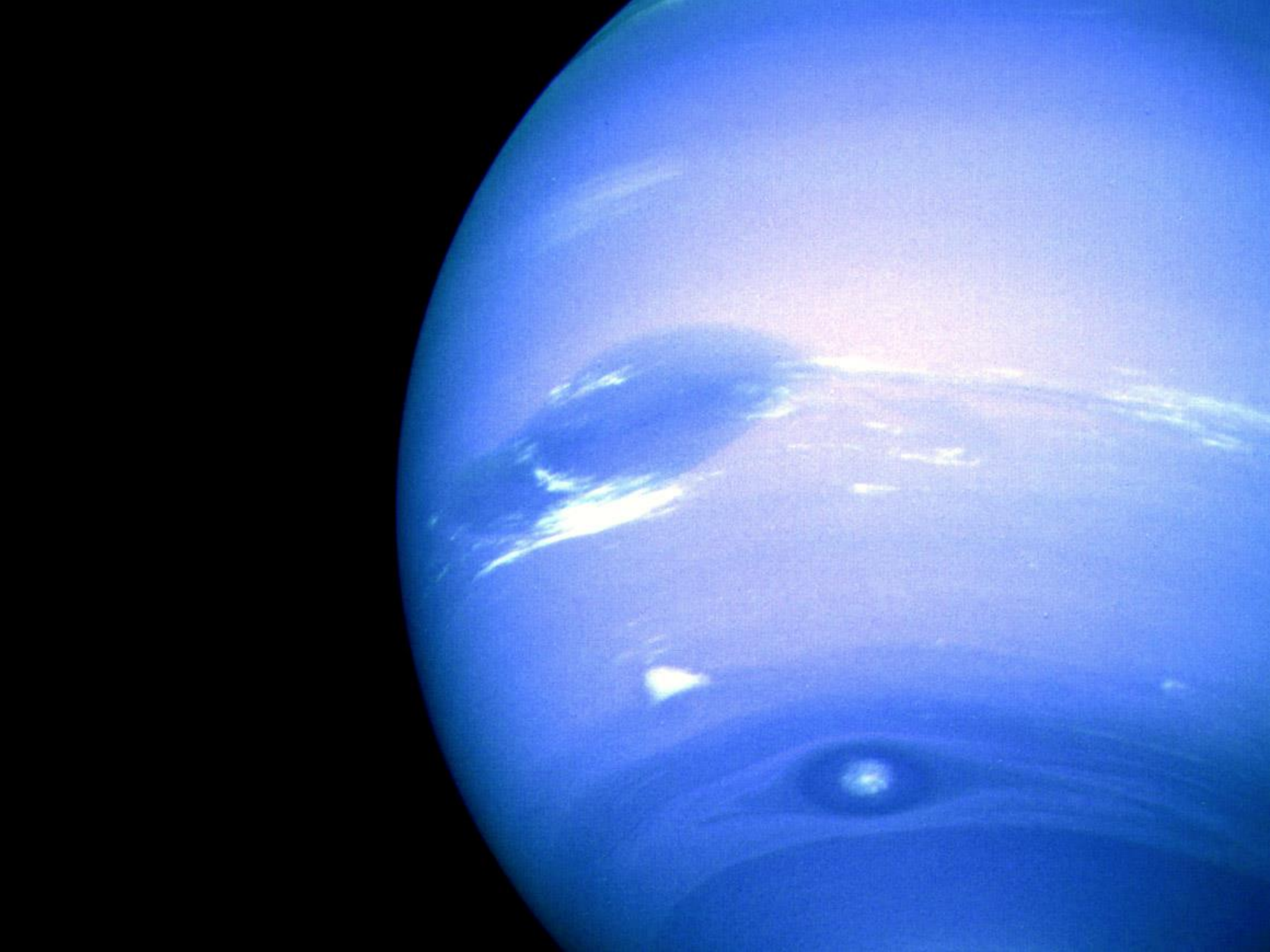


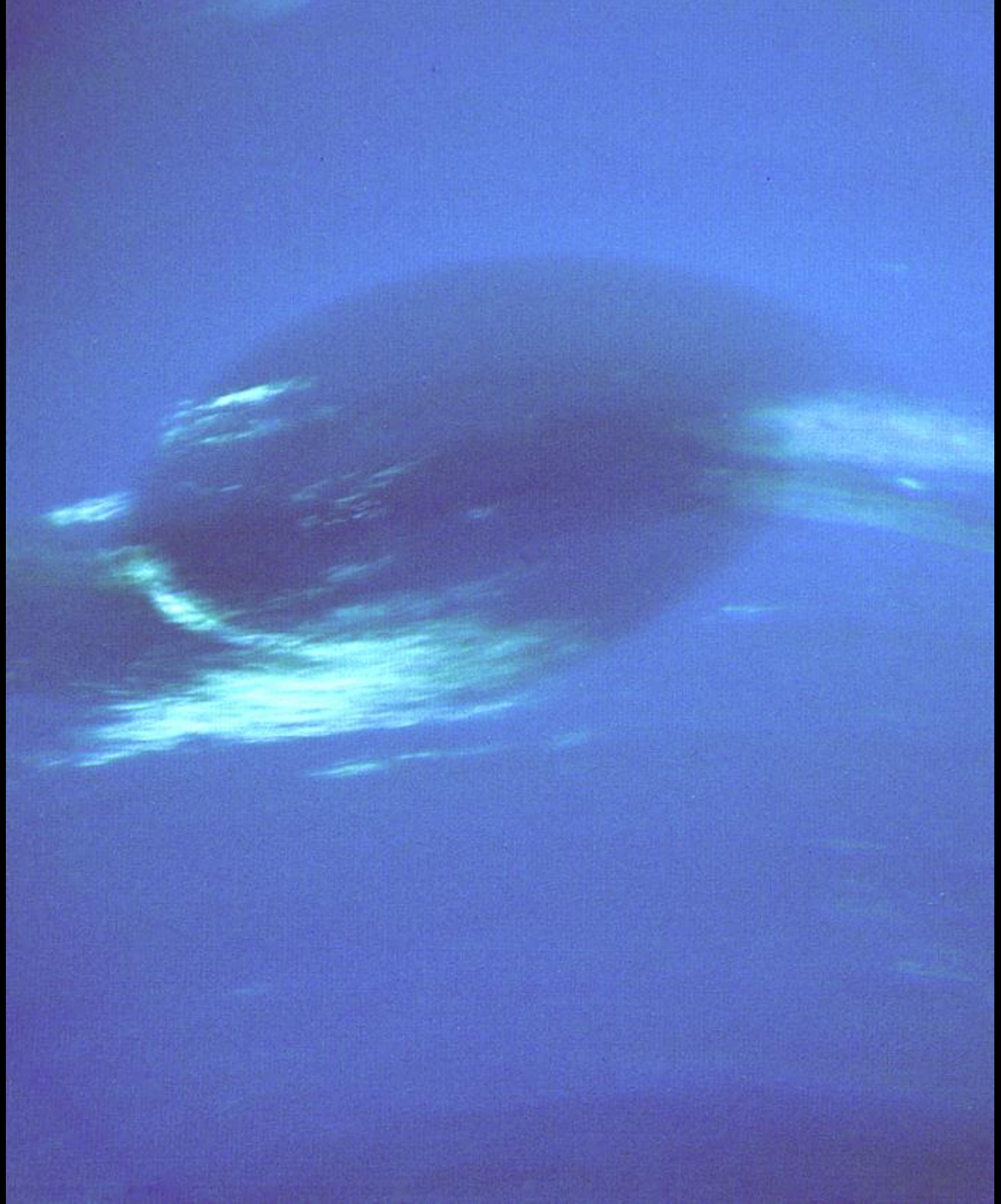
Neptune

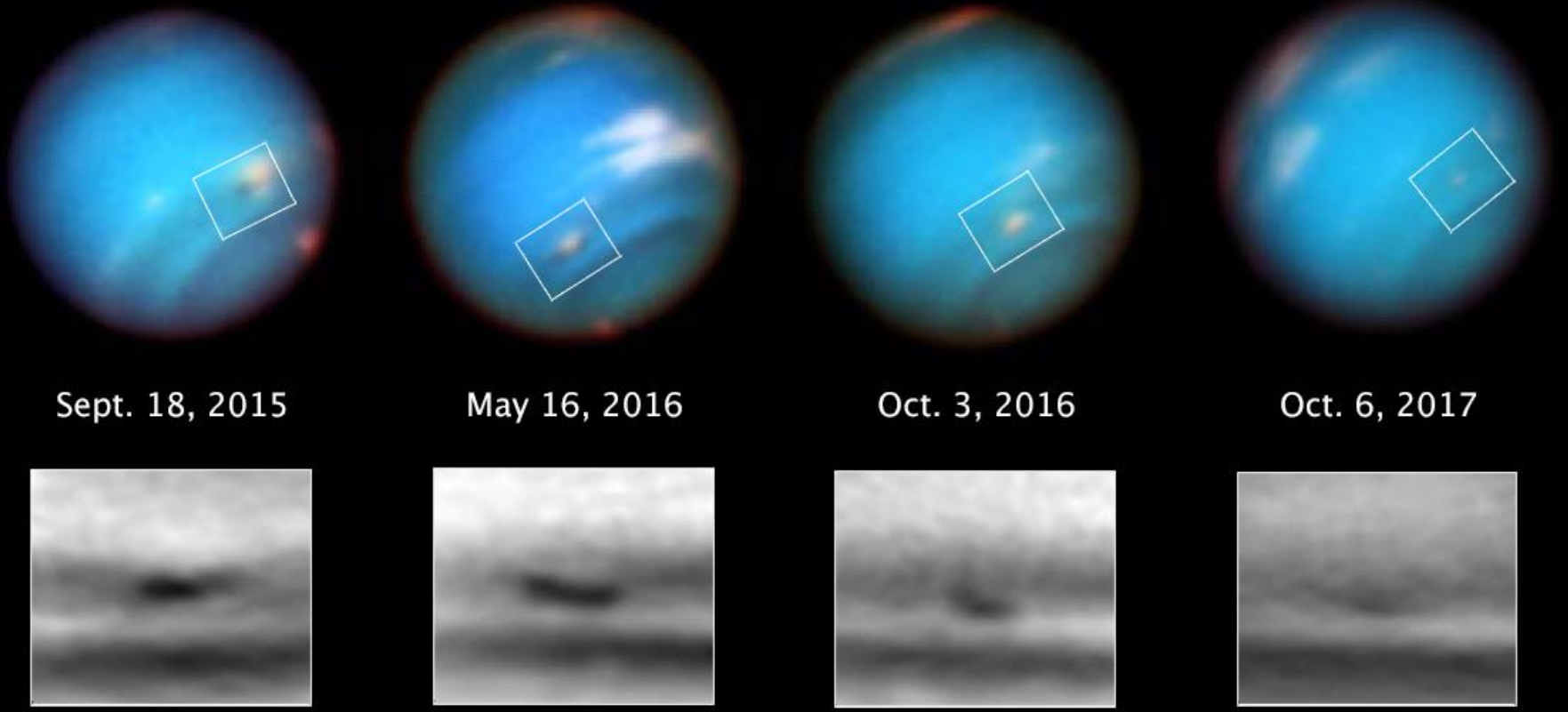


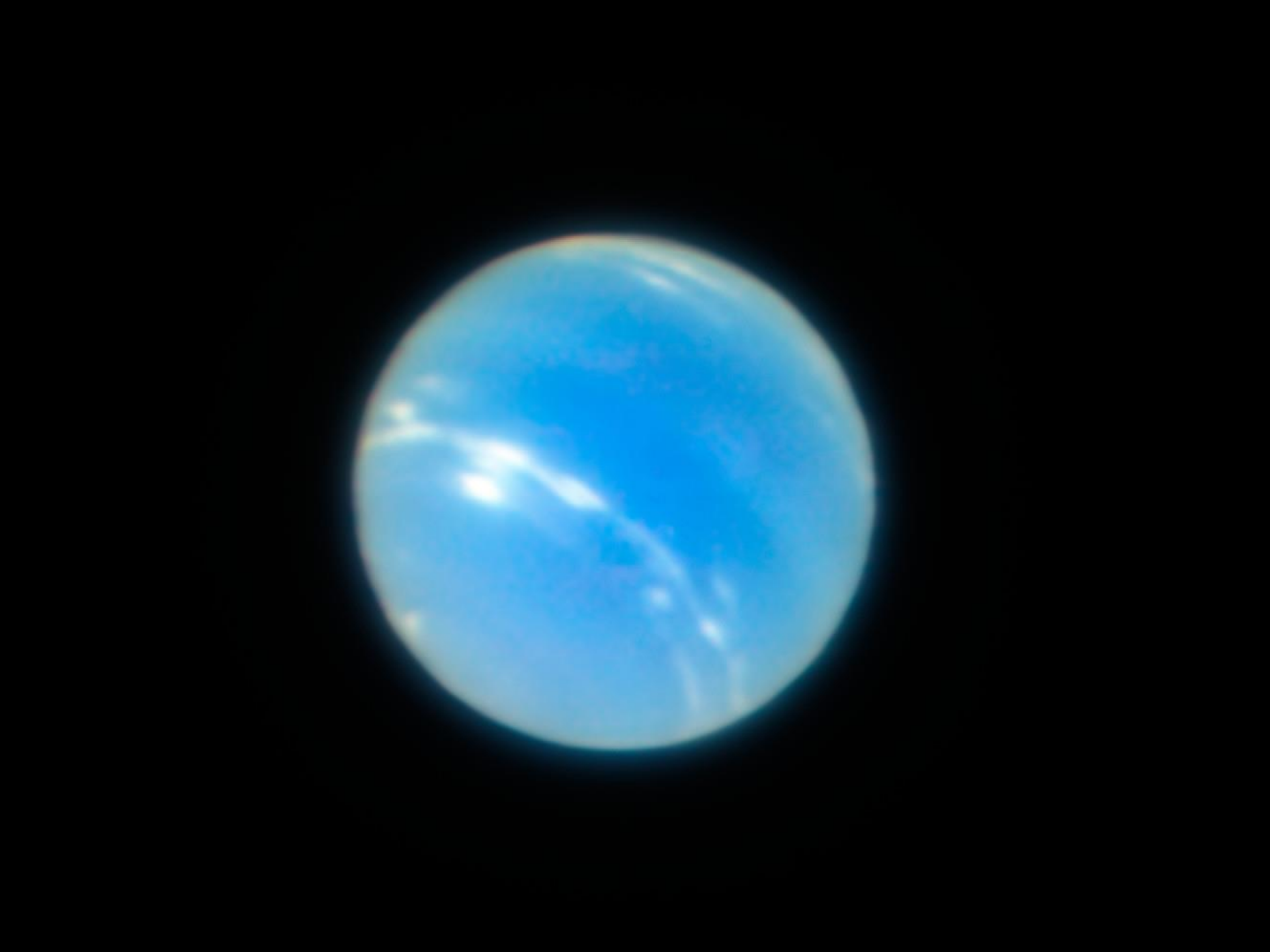


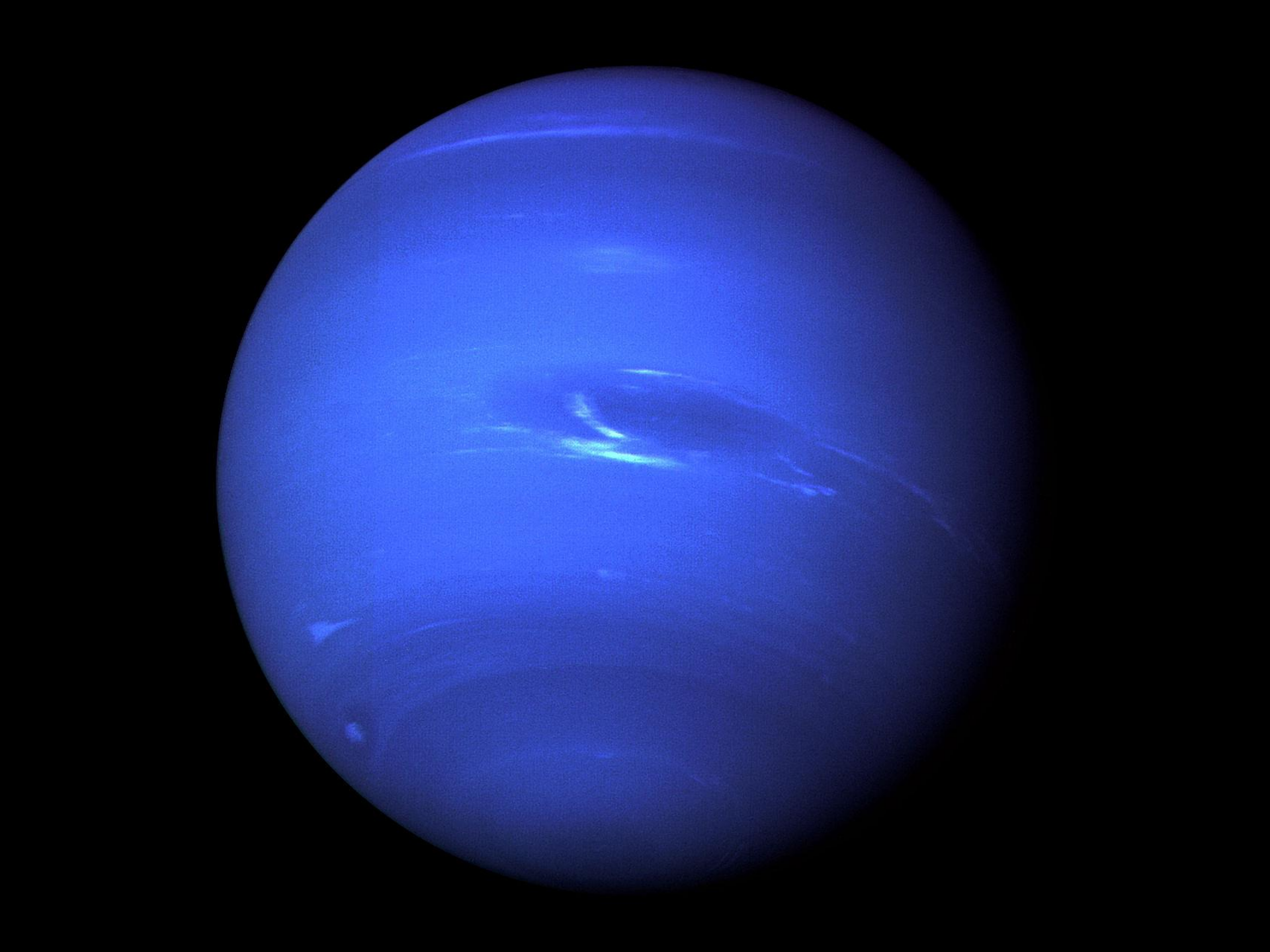


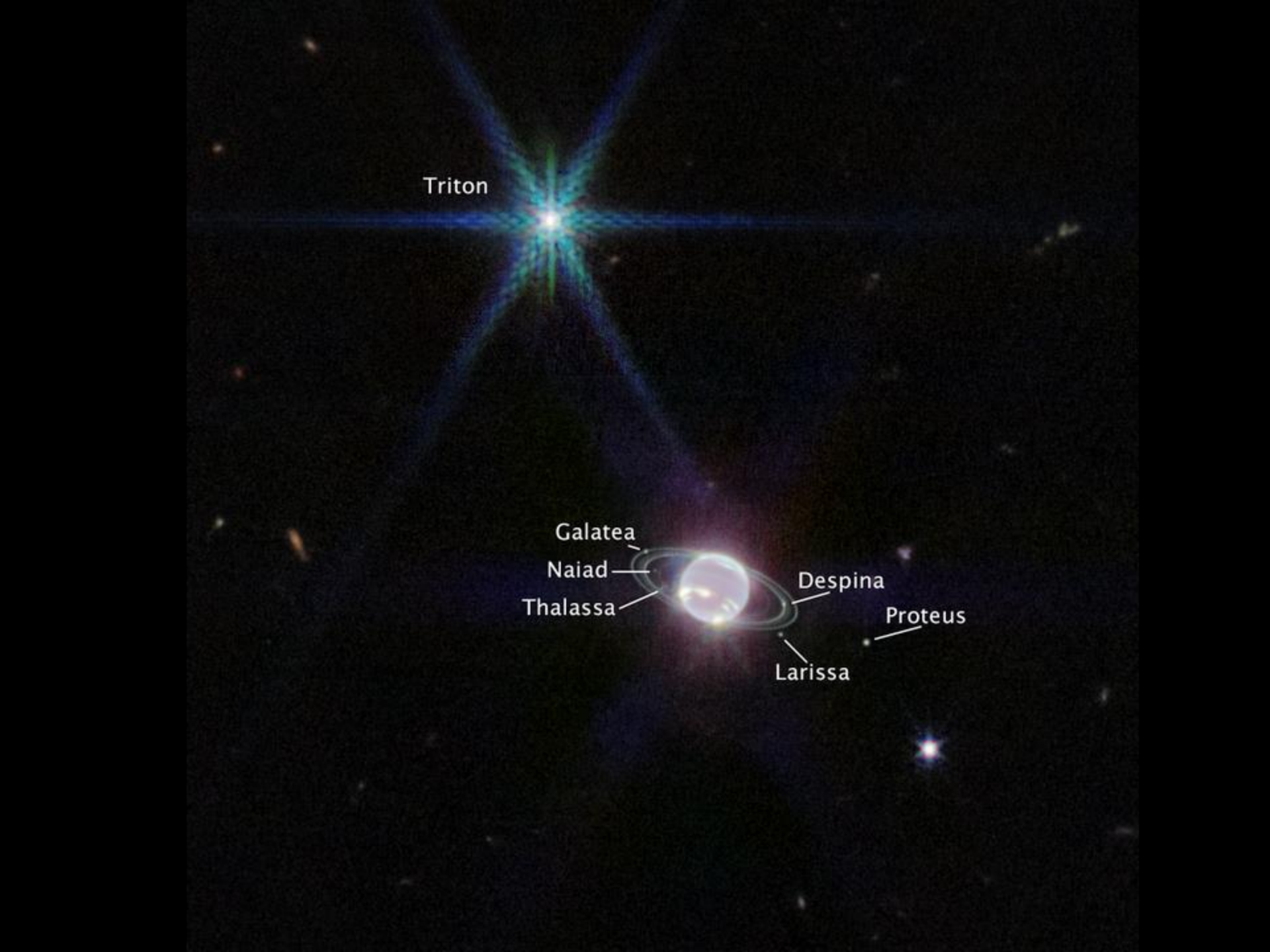




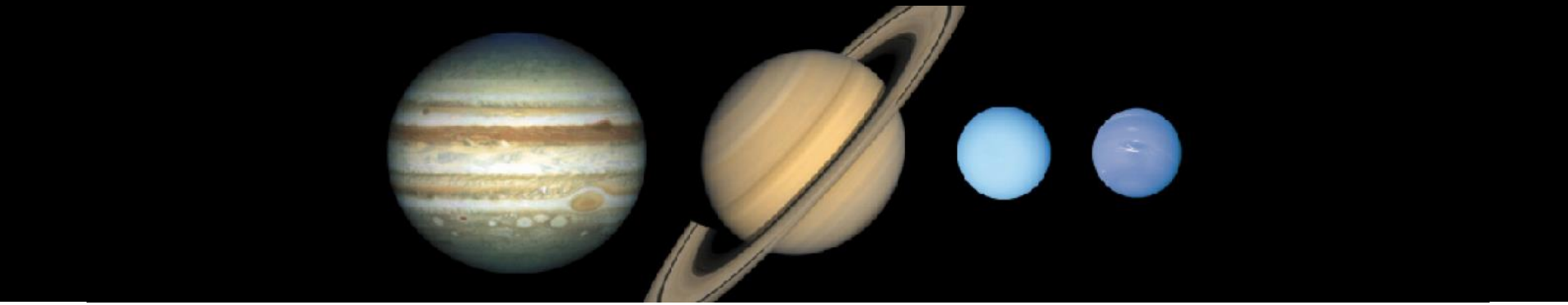

Sept. 18, 2015
May 16, 2016
Oct. 3, 2016
Oct. 6, 2017

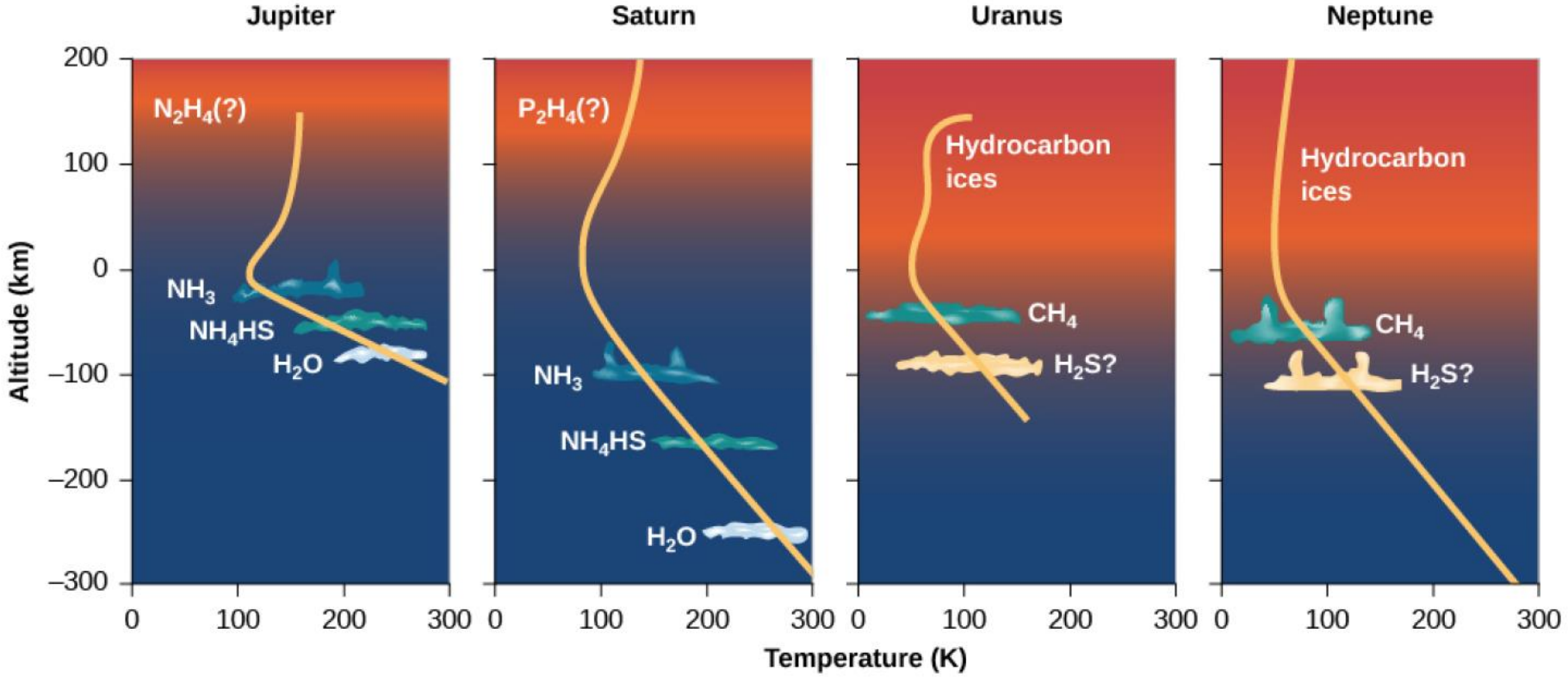





Triton
Galatea
Naiad
Thalassa
Despina
Proteus
Larissa

Clouds: scattering prevents detections of structure

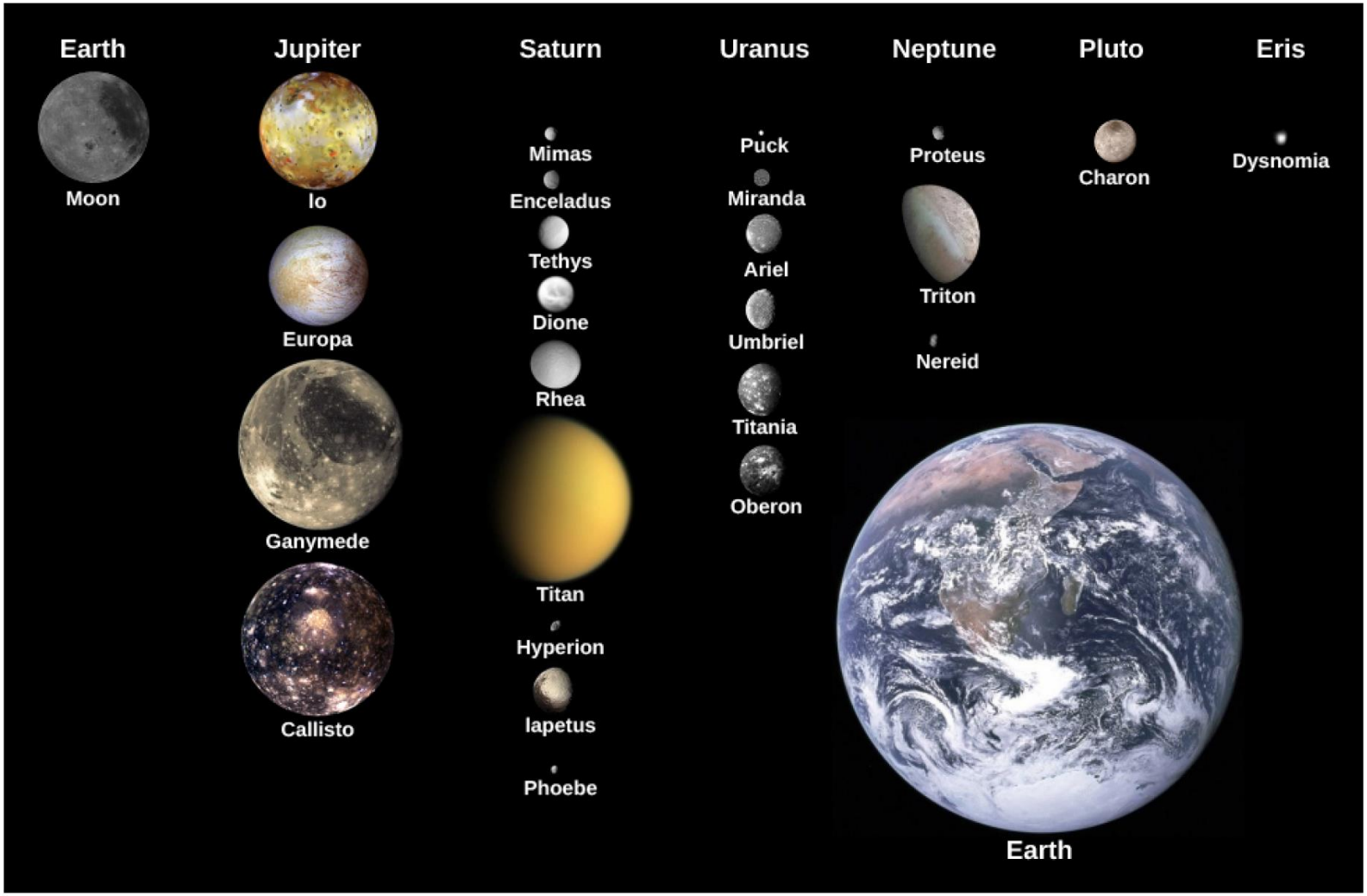


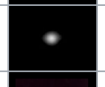
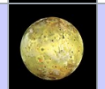
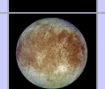
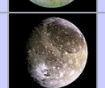
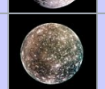
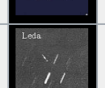
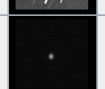


Summary – number of moons

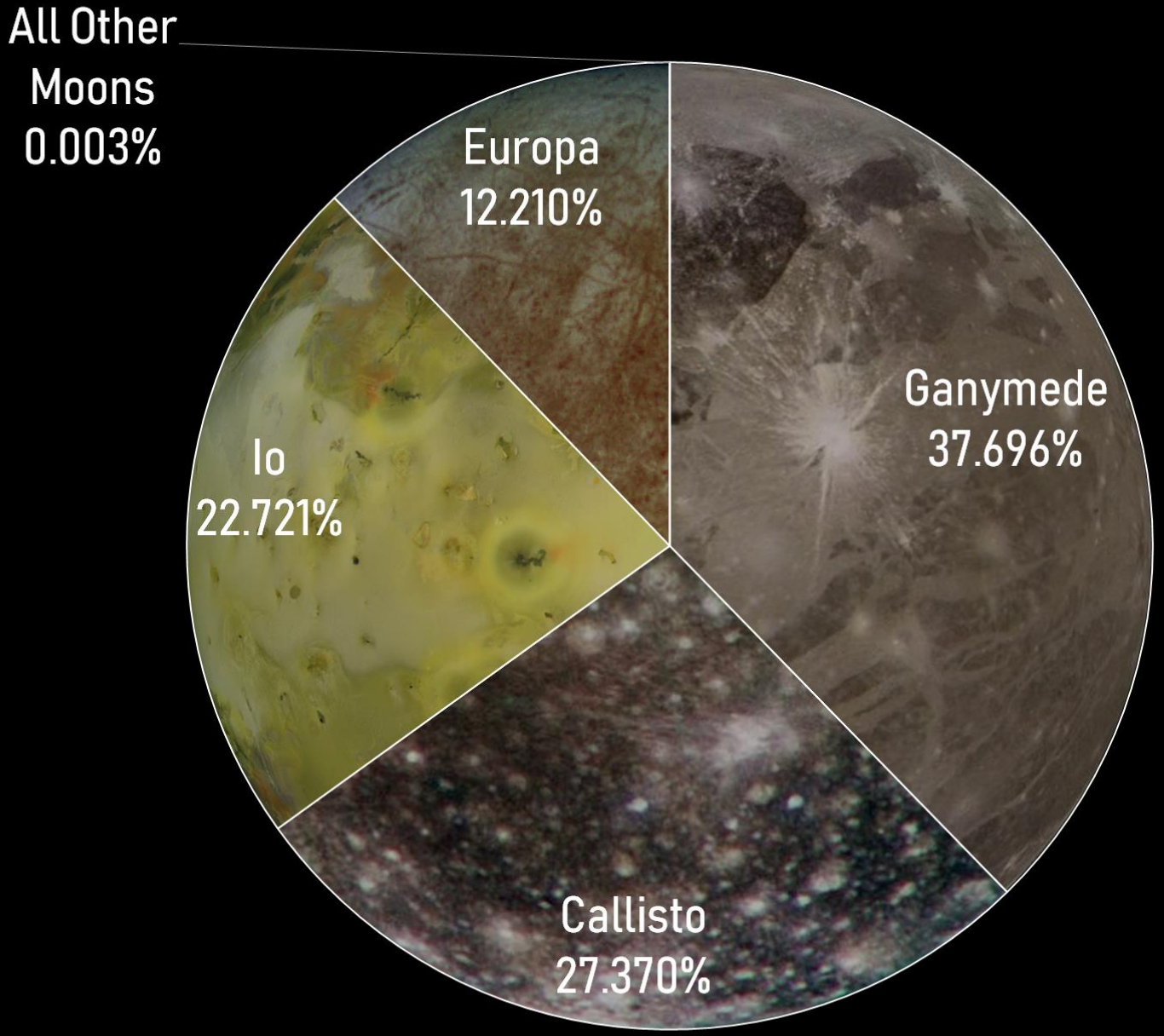
Planet	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Number of moons	0	0	1	2	79	62	27	14

Dwarf planet	Ceres	Pluto	Haumea	Makemake	Eris
Number of moons	0	5	2	1	1



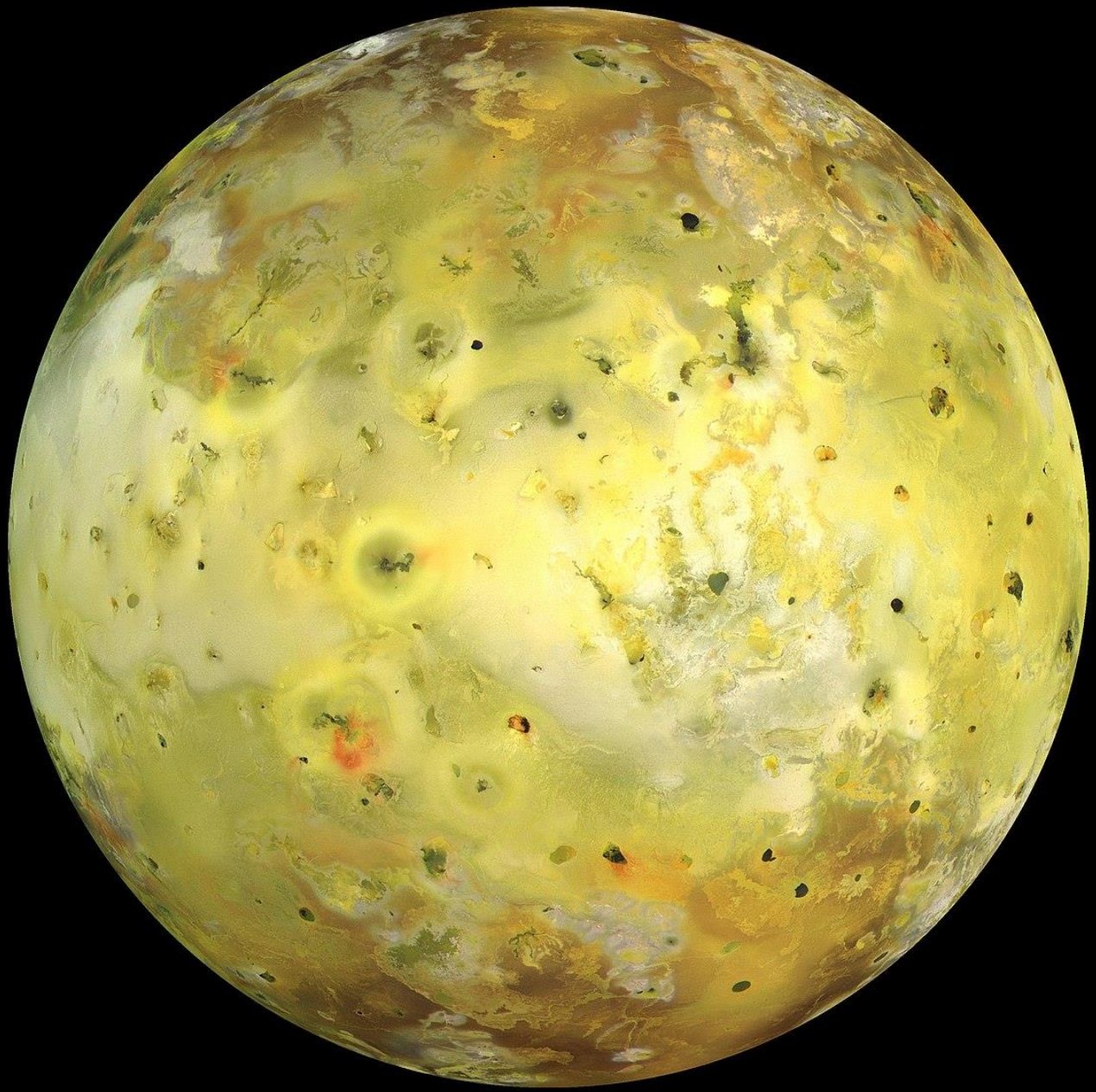
Order [note 3]	Label [note 4]	Name	Pronunciation	Image	Abs. magn.	Diameter (km)[note 5]	Mass (×10^16 kg)	Semi-major axis (km)[46]	Orbital period (d)[46][note 6]	Inclination (°)[46]	Eccentr. [41]	Discovery year[23]	Discoverer[23]	Group [note 7]
1	XVI	Metis	/ˈmiːtɪs/		10.5	60×40×34	≈3.6	128 852	+7h 10m 16s	2.226	0.0077	1979	Synnott (Voyager 1)	Inner
2	XV	Adrastea	/əˈdræstiə/		12.0	20×16×14	≈0.2	129 000	+7h 15m 21s	2.217	0.0063	1979	Jewitt (Voyager 2)	Inner
3	V	Amalthea	/əˈmælθiə/[47]		7.1	250×146×128 (167 ±4.0)	208	181 366	+12h 01m 46s	2.565	0.0075	1892	Barnard	Inner
4	XIV	Thebe	/ˈθiːbi/		9.0	116×98×84	≈43	222 452	+16h 16m 02s	2.909	0.0180	1979	Synnott (Voyager 1)	Inner
5	I	**Io**♠	/ˈaɪoʊ/		−1.7	3 660.0 ×3 637.4 ×3 630.6	8 931 900	421 700	+1.7691	0.050[48]	0.0041	1610	Galilei	Galilean
6	II	**Europa**♠	/jʊəˈroʊpə/[49]		−1.4	3 121.6	4 800 000	671 034	+3.5512	0.471[48]	0.0094	1610	Galilei	Galilean
7	III	**Ganymede**♠	/ˈgænɪmiːd/[50][51]		−2.1	5 262.4	14 819 000	1 070 412	+7.1546	0.204[48]	0.0011	1610	Galilei	Galilean
8	IV	**Callisto**♠	/kəˈlɪstoʊ/		−1.2	4 820.6	10 759 000	1 882 709	+16.689	0.205[48]	0.0074	1610	Galilei	Galilean
9	XVIII	Themisto†	/θɪˈmɪstoʊ/		13.5	8	0.069	7 393 216	+129.87	45.762	0.2115	1975/2000	Kowal & Roemer/ Sheppard et al.	*Themisto*
10	XIII	Leda†	/liːdə/		12.8	16	0.6	11 187 781	+240.82	27.562	0.1673	1974	Kowal	Himalia
11	VI	Himalia†	/hɑːˈmeɪliə/		8.3	170	670	11 451 971	+250.23	30.486	0.1513	1904	Perrine	Himalia
12	LXXI	S/2018 J 1†			15.9	2	0.0015	11 453 004	+250.40	30.606	0.0944	2018	Sheppard et al.	Himalia

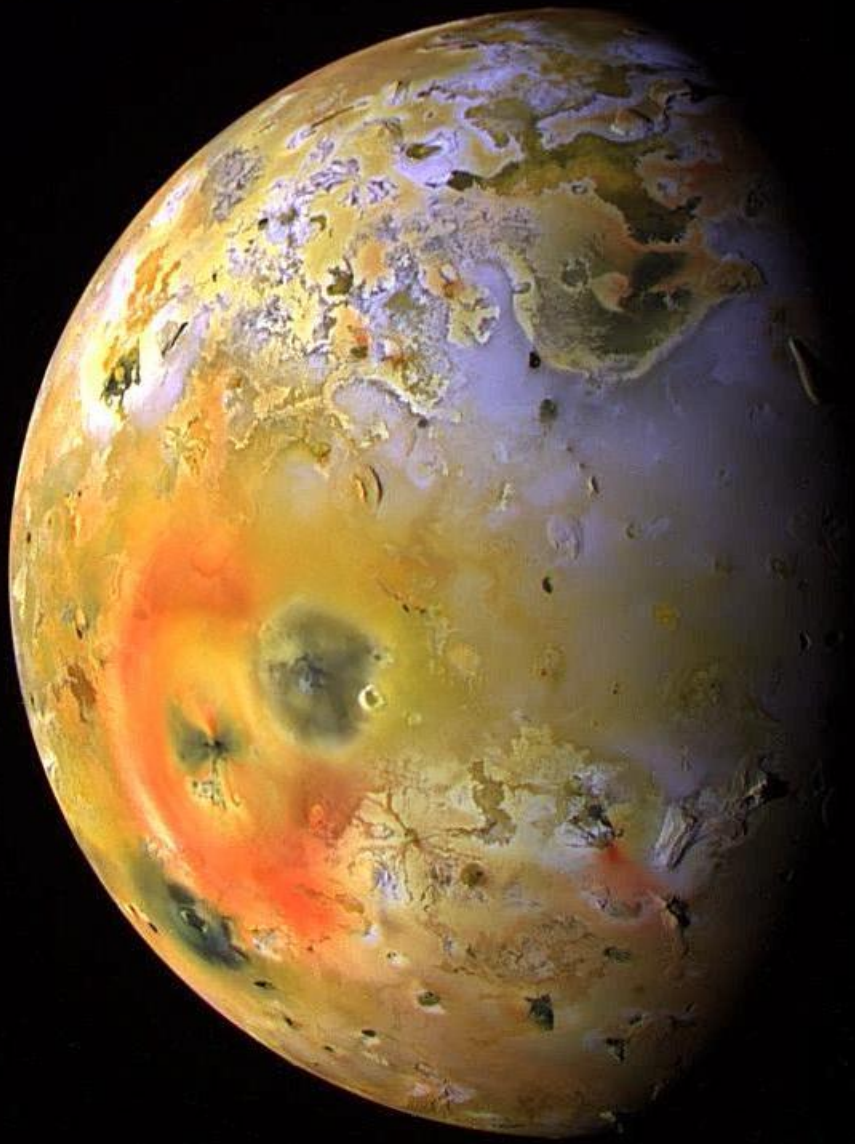
Relative Masses of Jovian Satellites



Galilean satellites of Jupiter

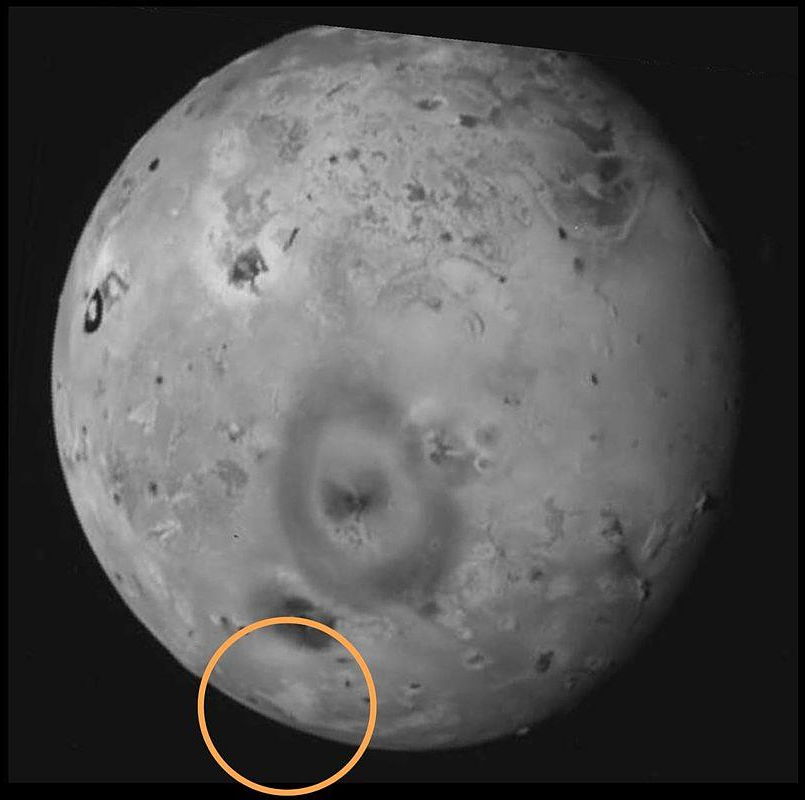
Io: a volcanic moon heated by tides





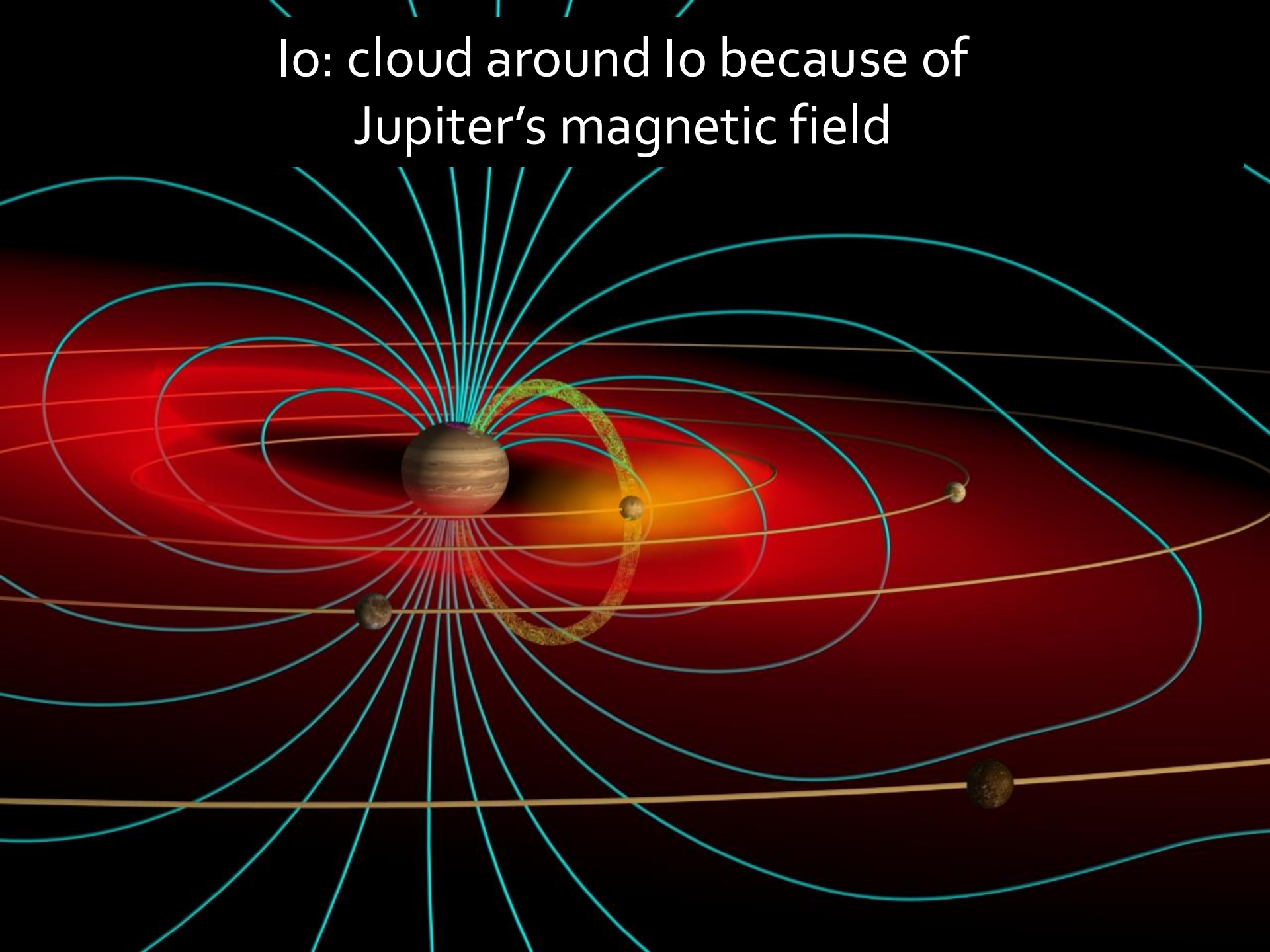
Io Surface Changes

Galileo 1999

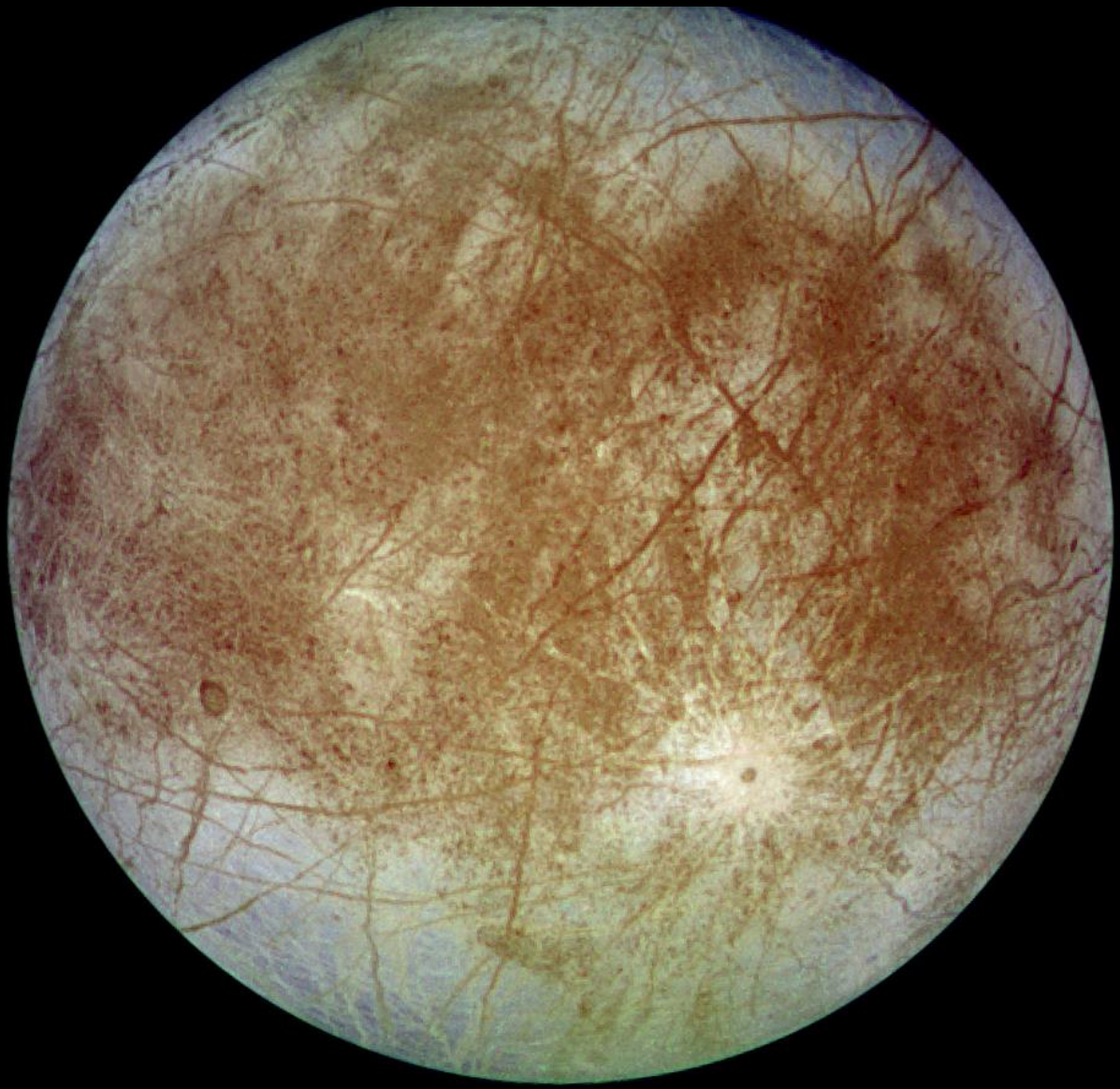


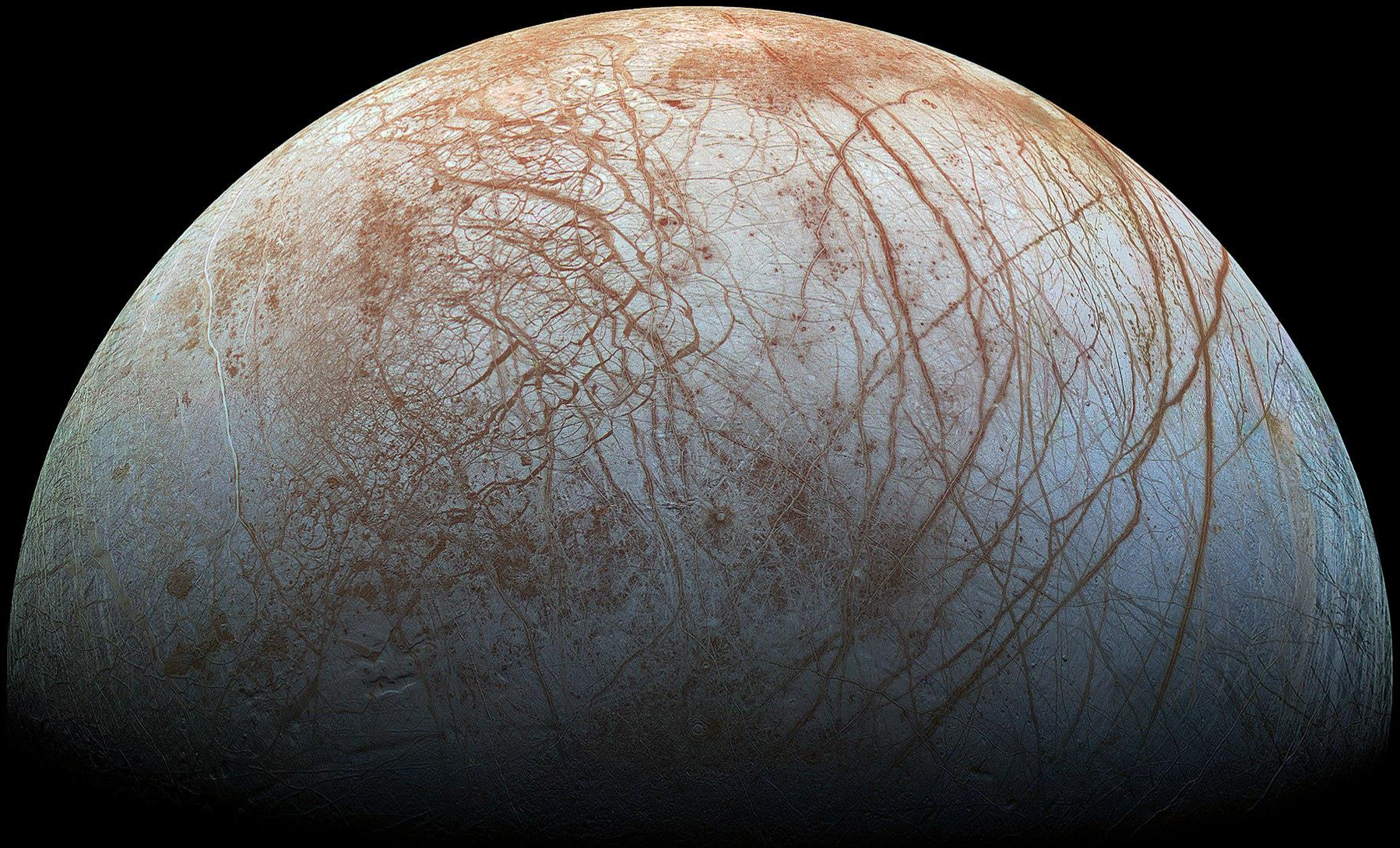
New Horizons 2007

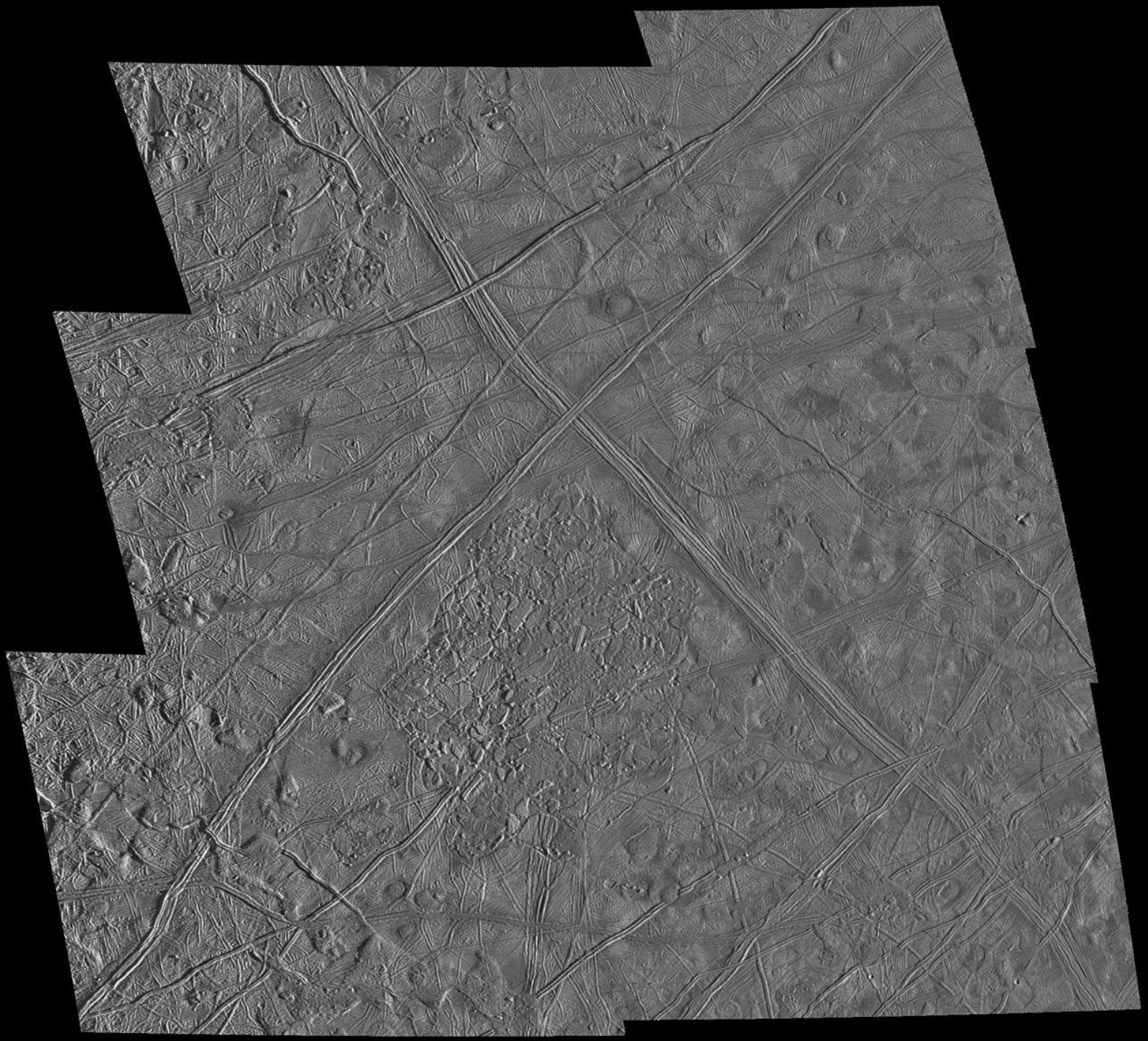
Io: cloud around Io because of Jupiter's magnetic field

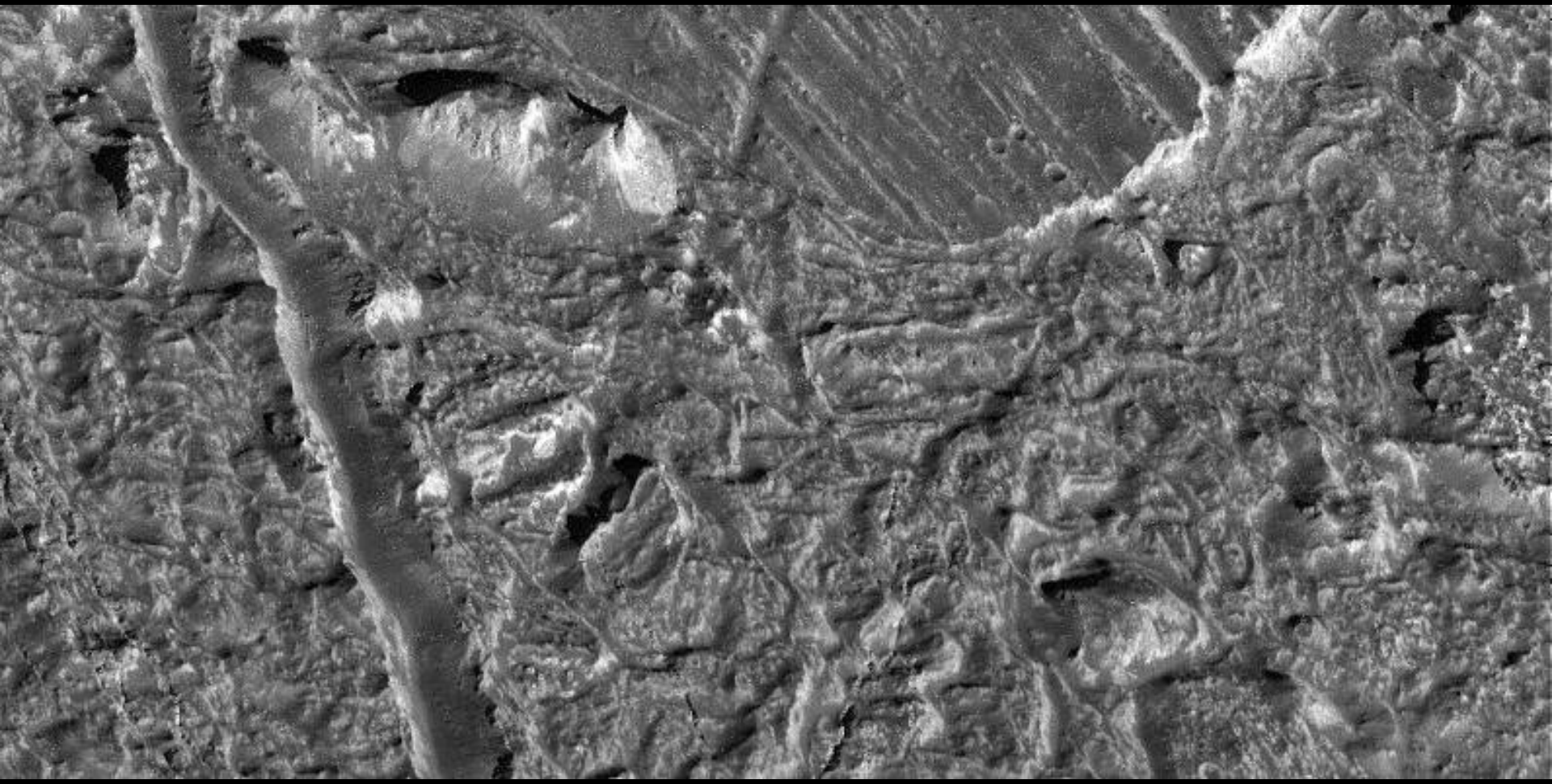


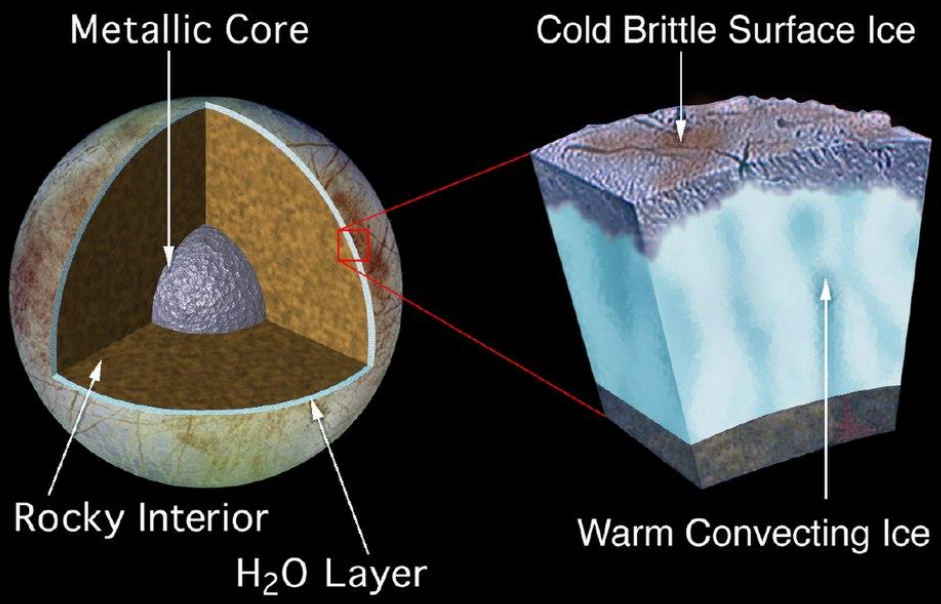
Europa: smallest of inner moons; ice world

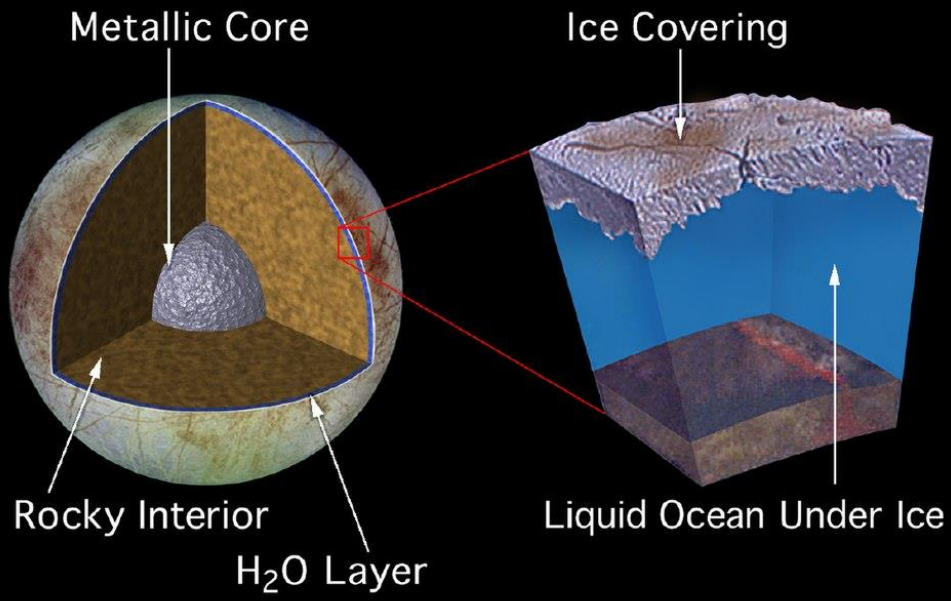


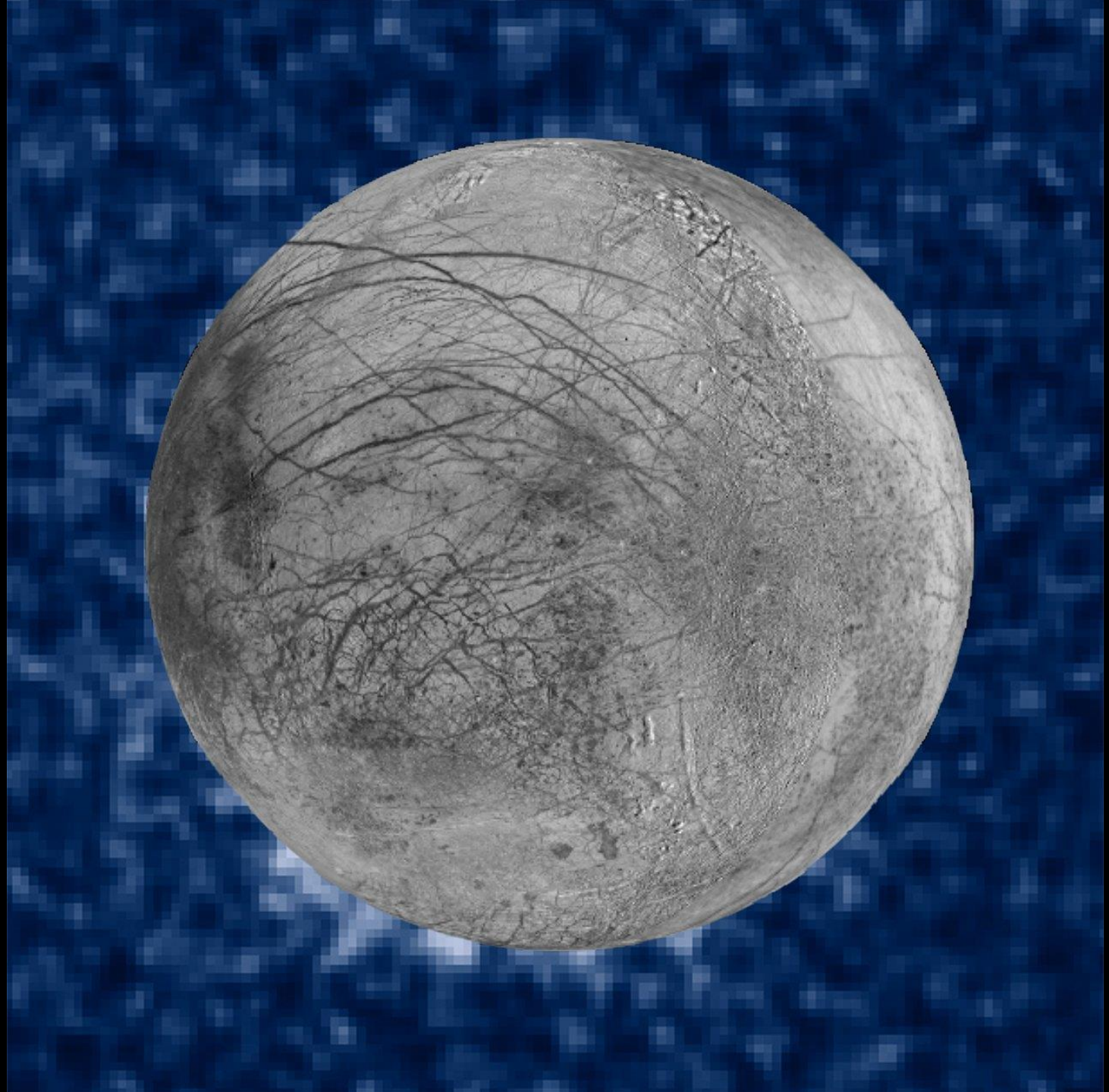


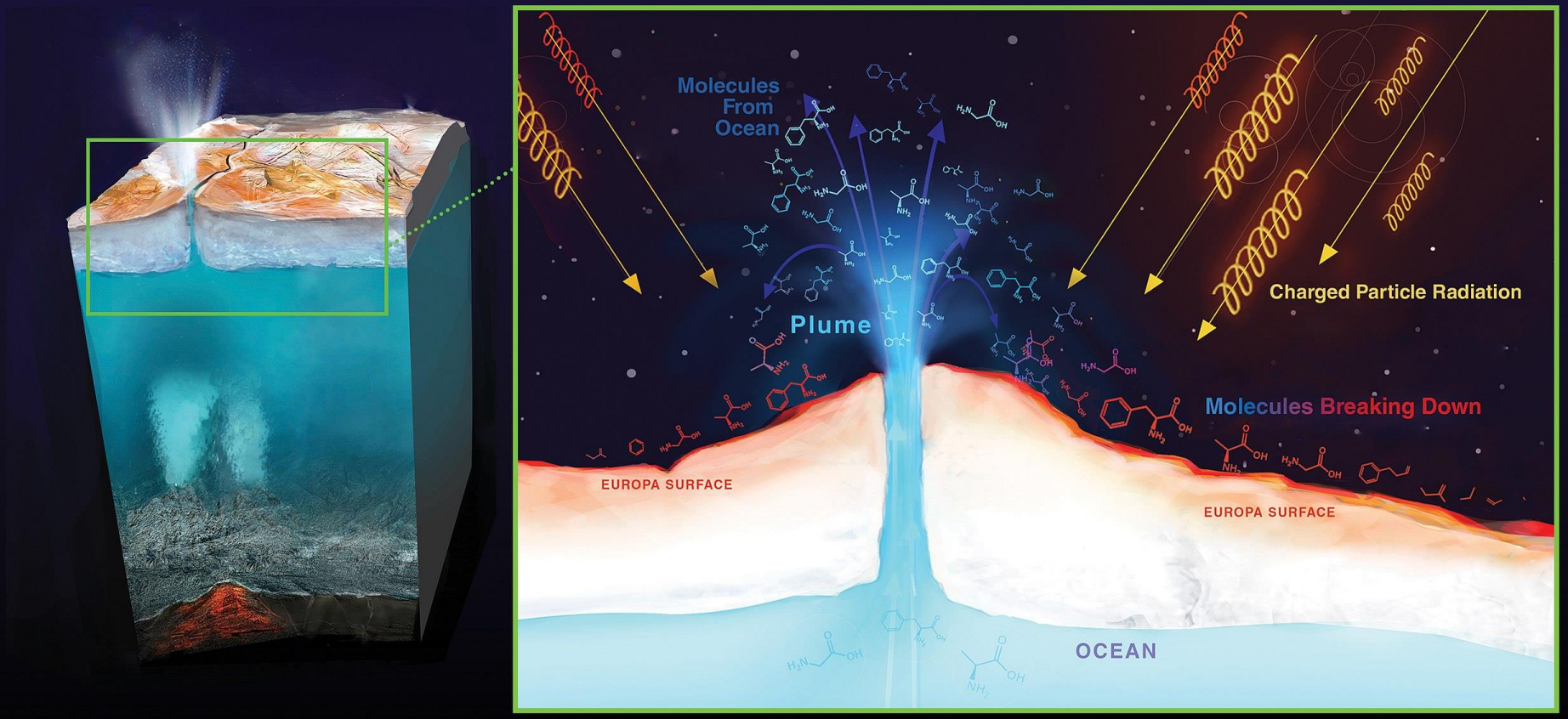




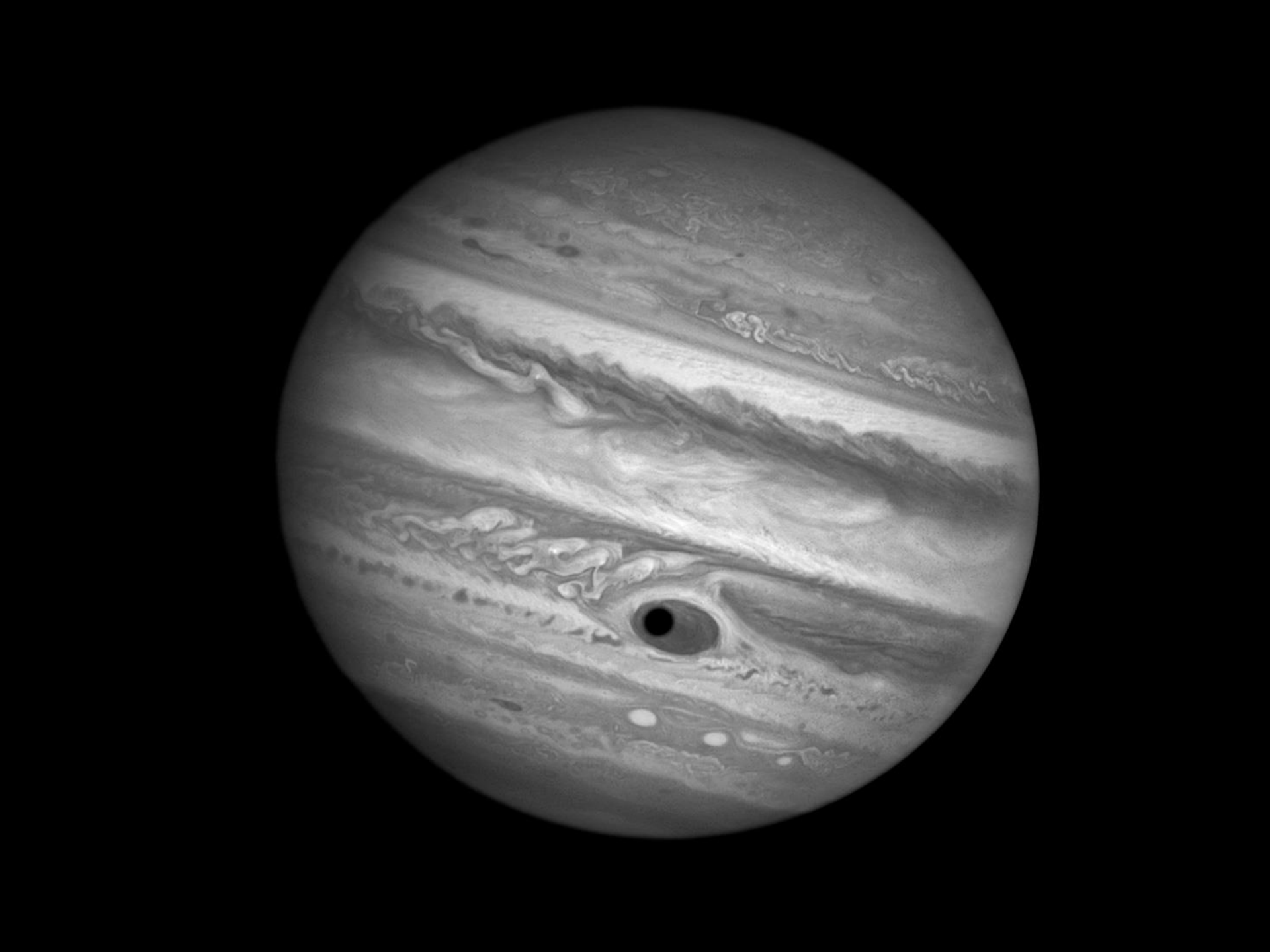

Metallic Core
Cold Brittle Surface Ice
Rocky Interior
H_2O Layer
Warm Convecting Ice

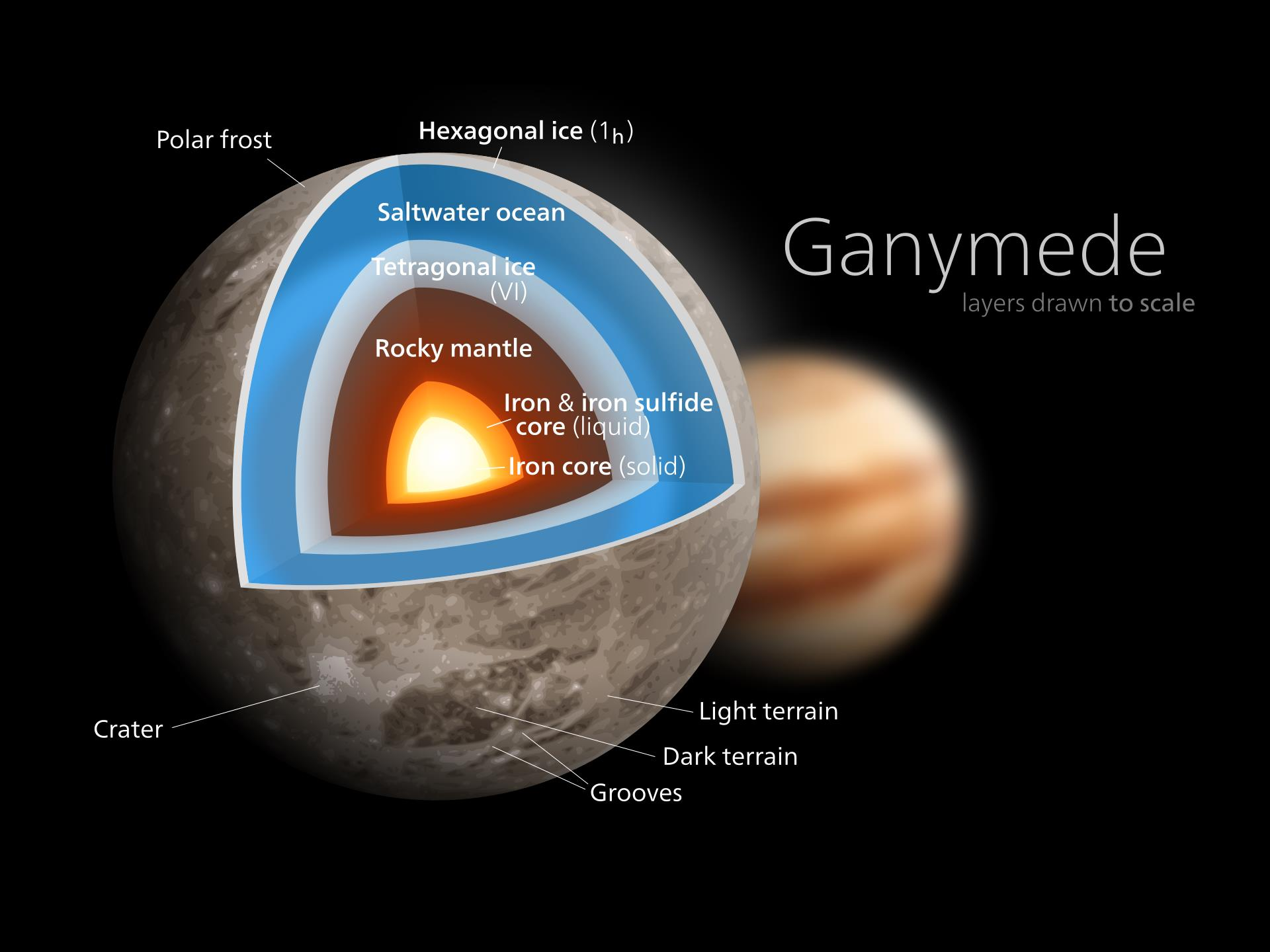

Metallic Core
Ice Covering
Rocky Interior
H_2O Layer
Liquid Ocean Under Ice

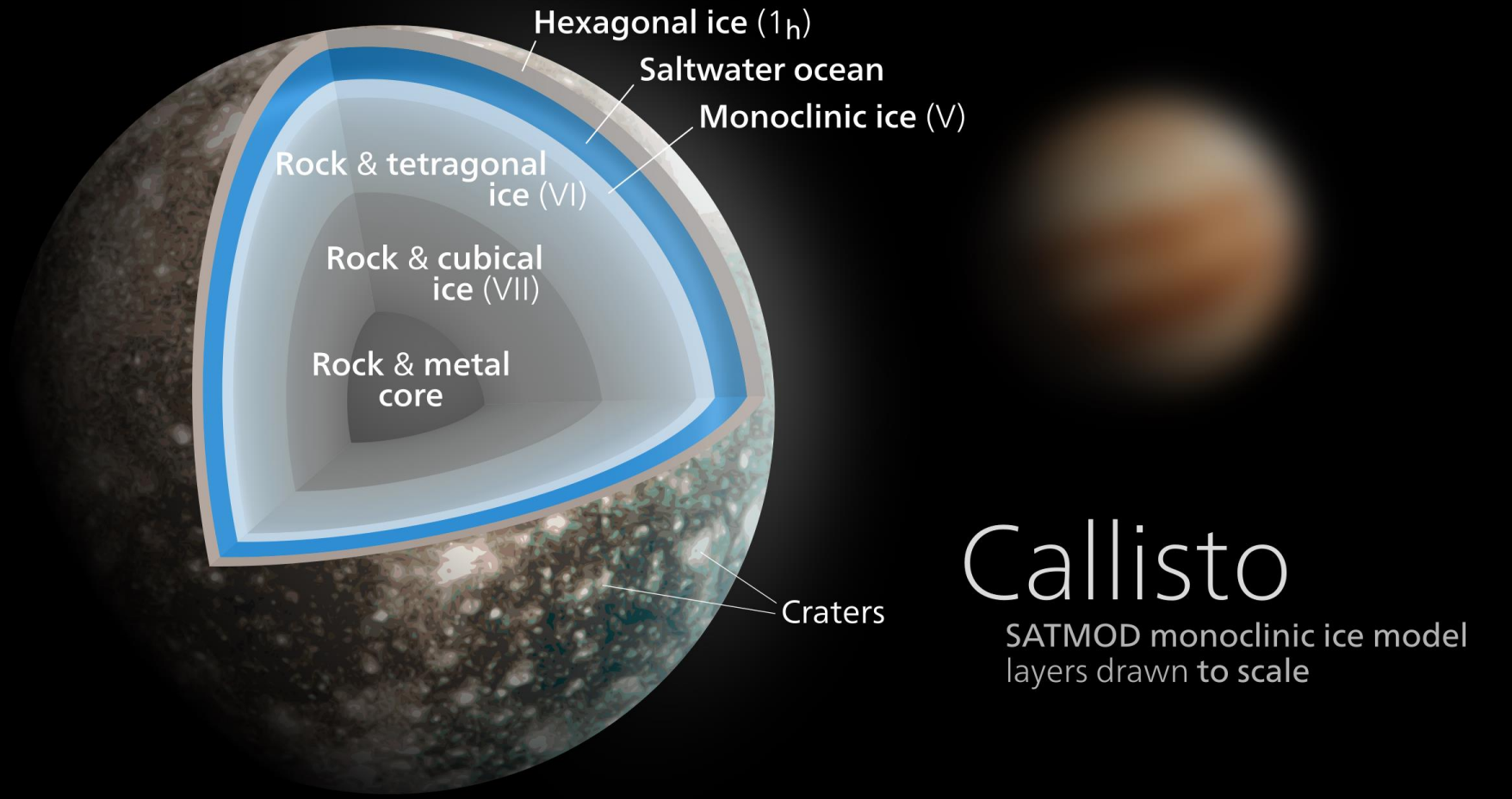



Molecules From Ocean
Plume
Charged Particle Radiation
Molecules Breaking Down
EUROPA SURFACE
EUROPA SURFACE
OCEAN

Ganymede and Callisto



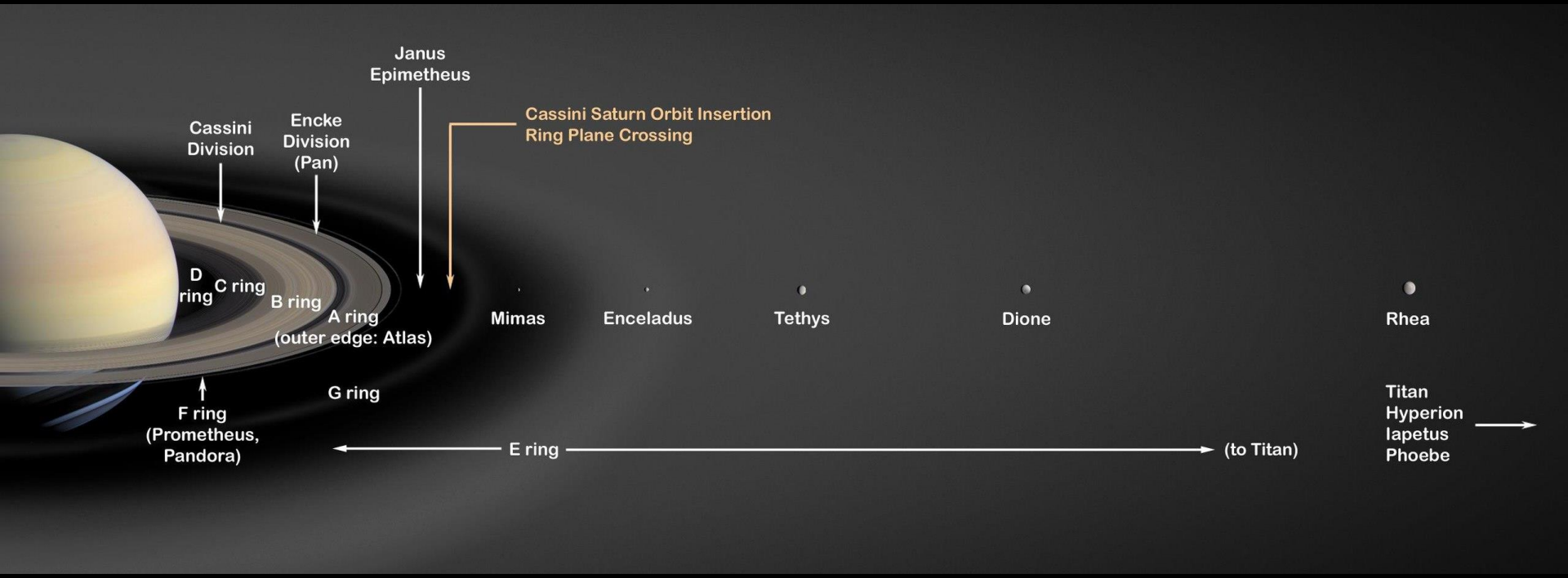

Polar frost
Hexagonal ice (1h)
Saltwater ocean
Tetragonal ice (VI)
Rocky mantle
Iron & iron sulfide core (liquid)
Iron core (solid)
Ganymede
layers drawn to scale
Crater
Light terrain
Dark terrain
Grooves



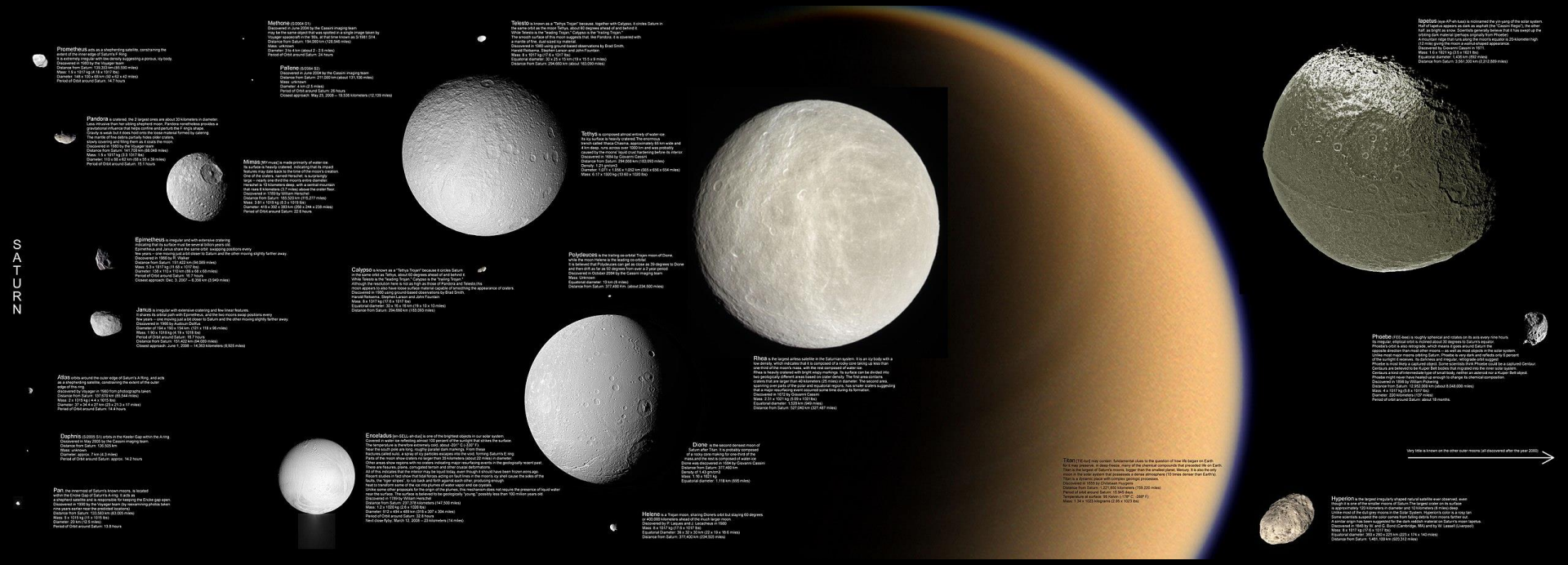
Callisto

SATMOD monoclinic ice model
layers drawn to scale

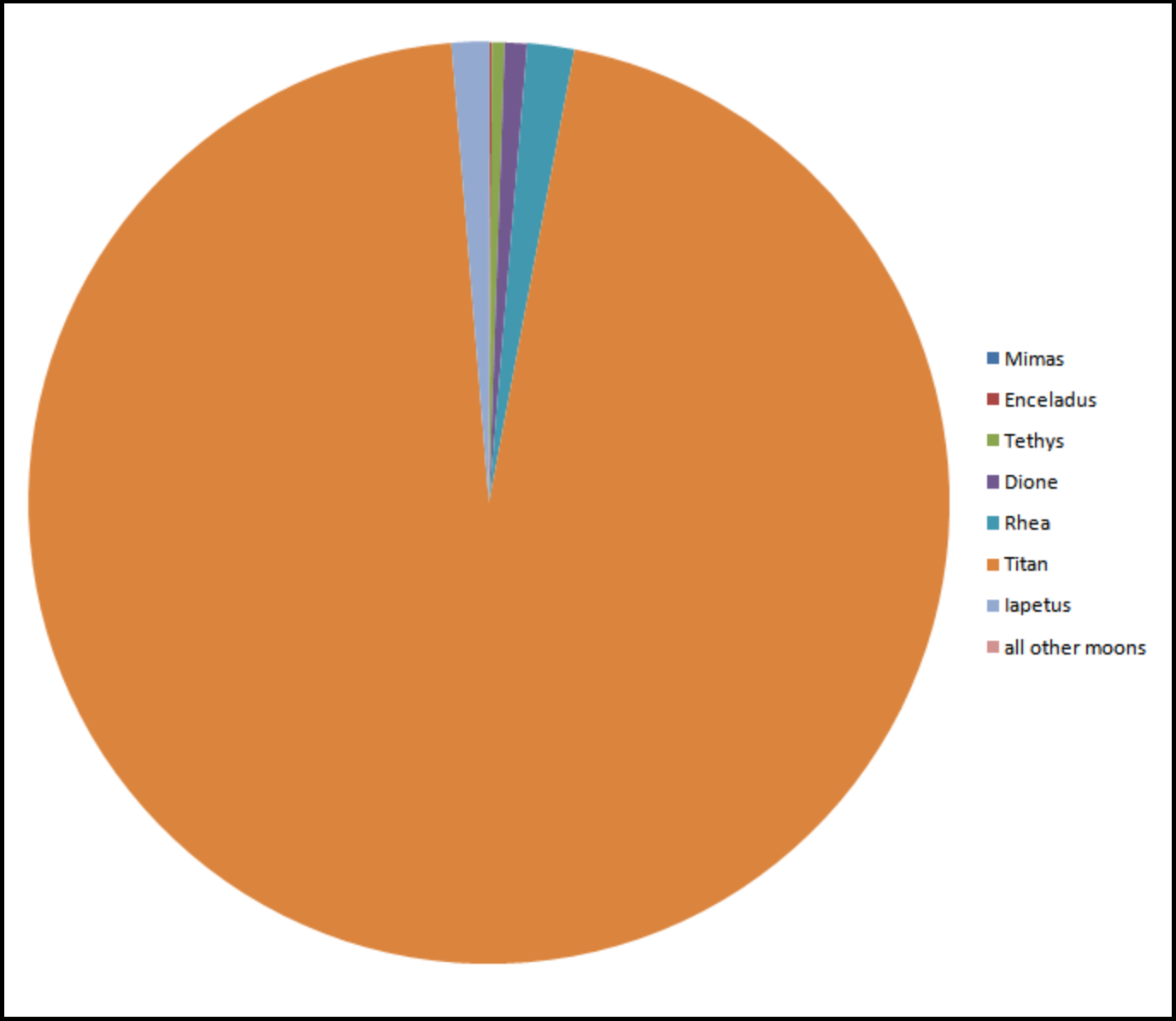
Moons of Saturn



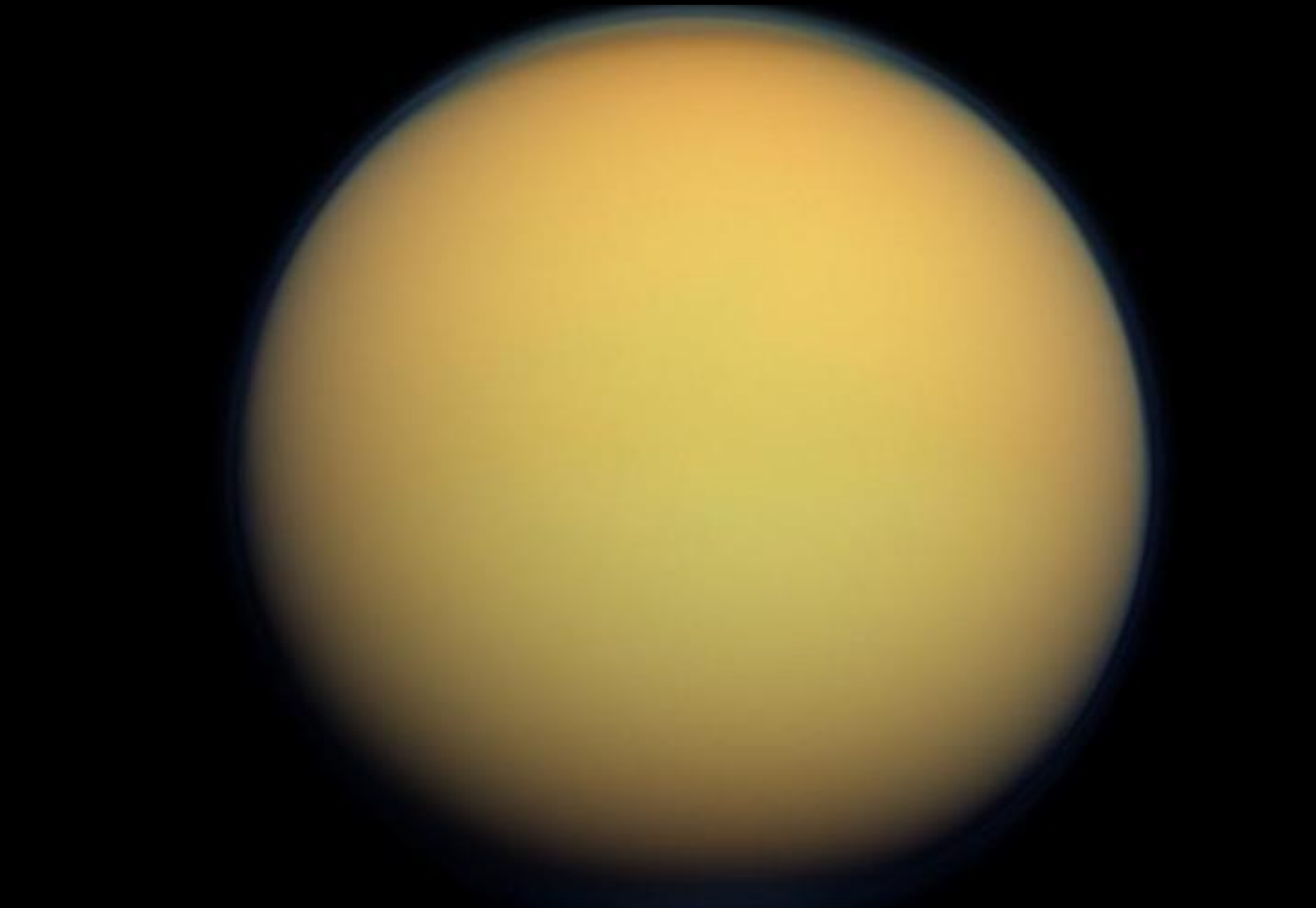
Moons of Saturn

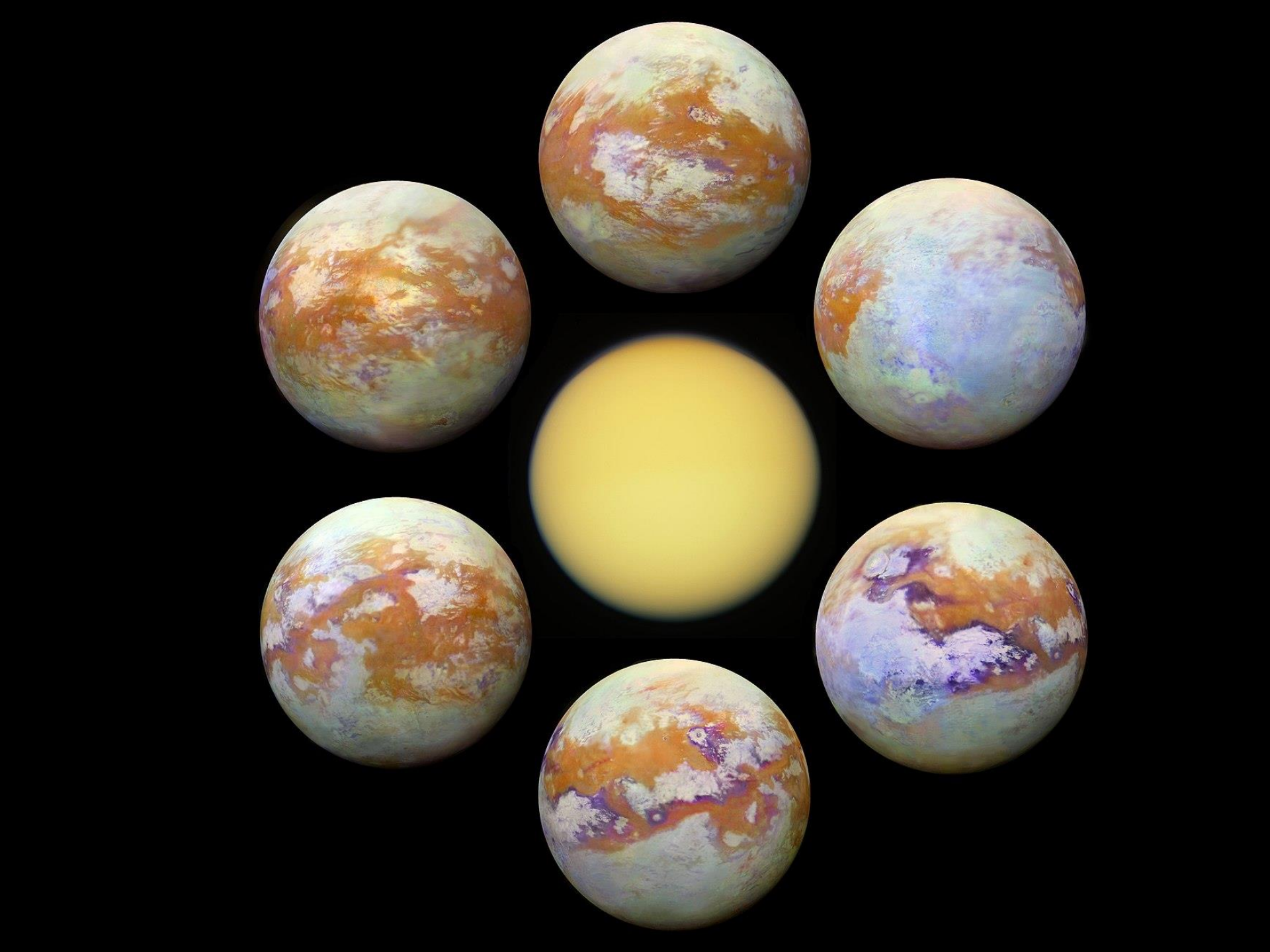


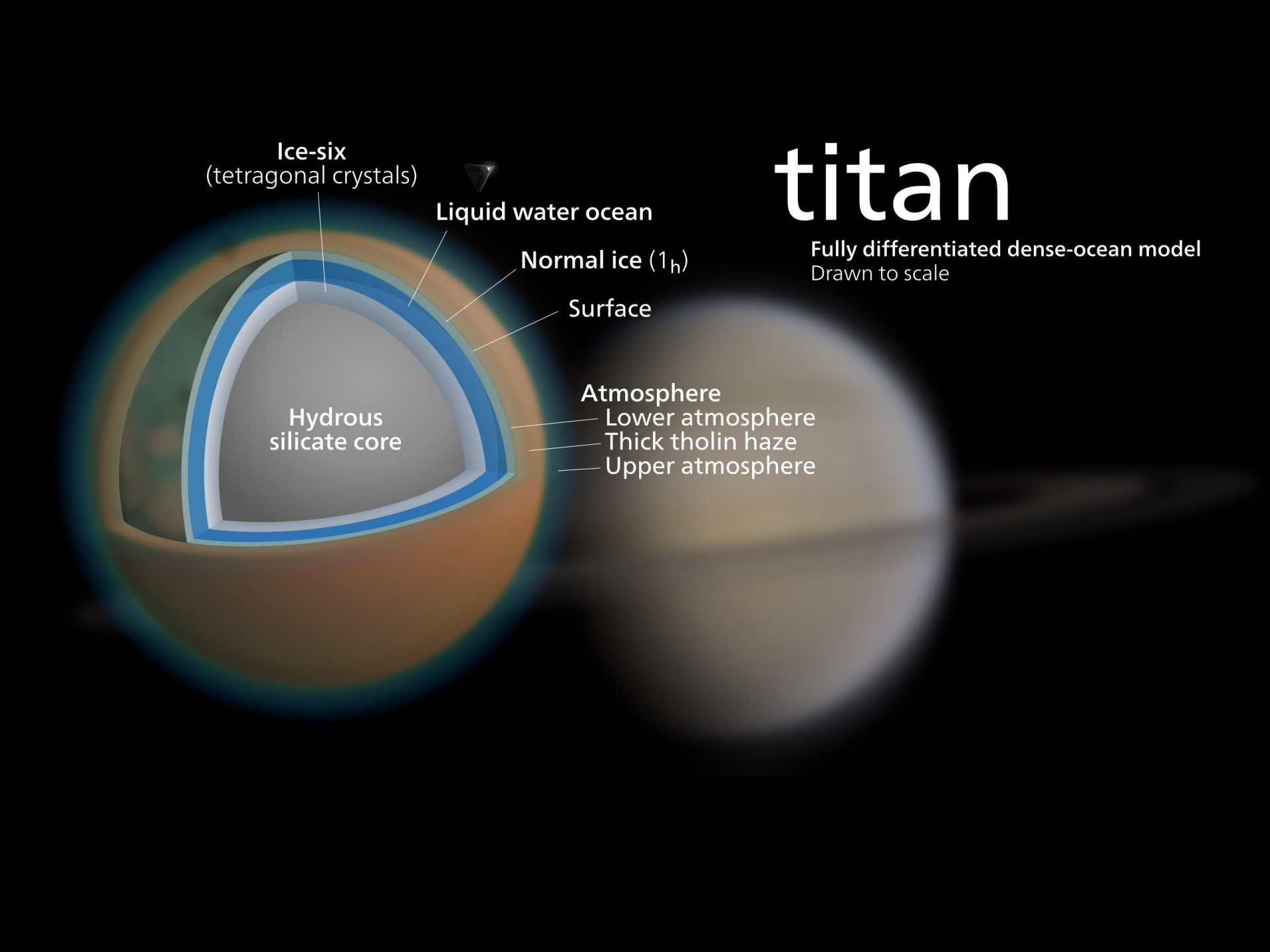
Moons of Saturn

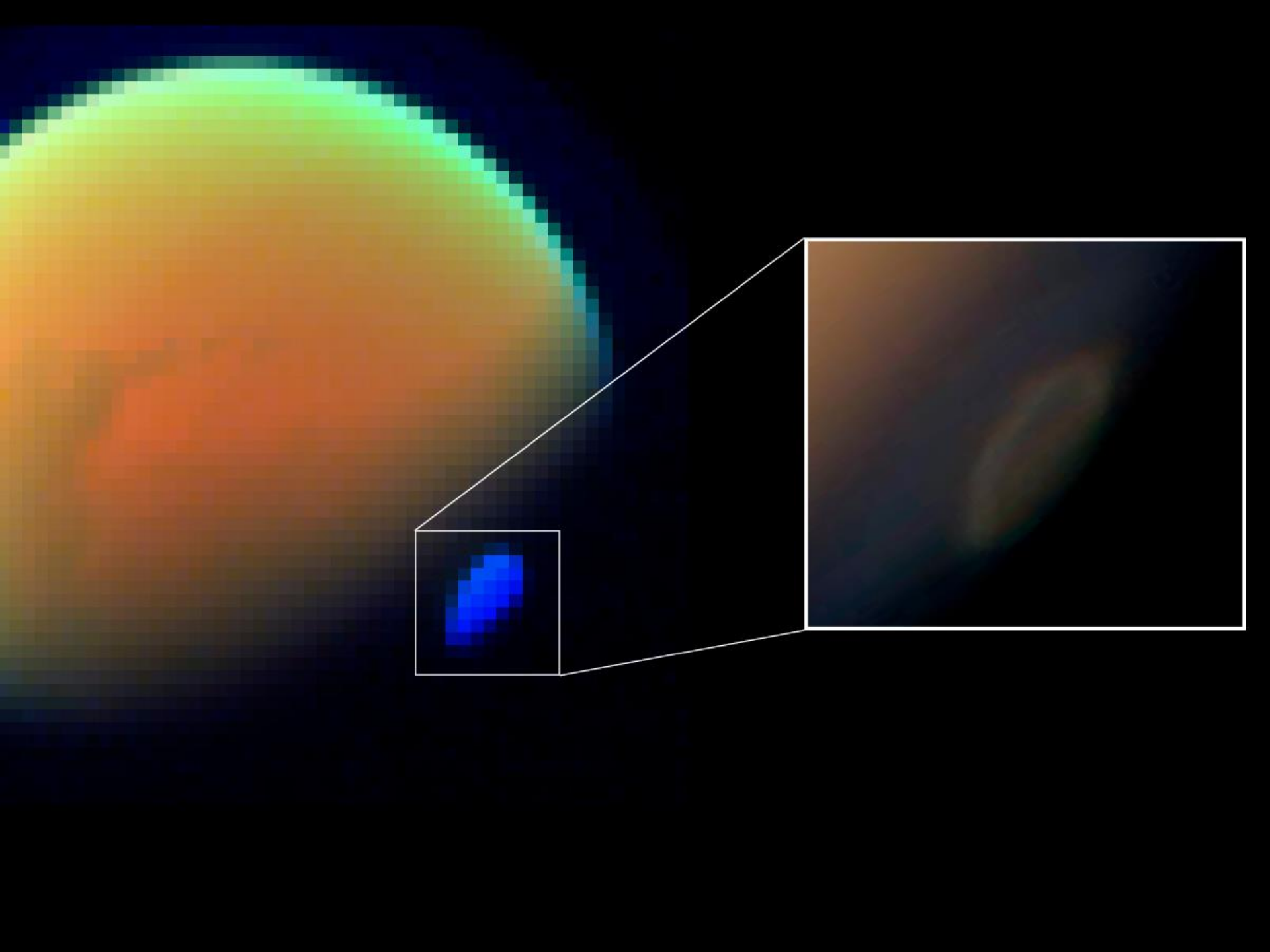


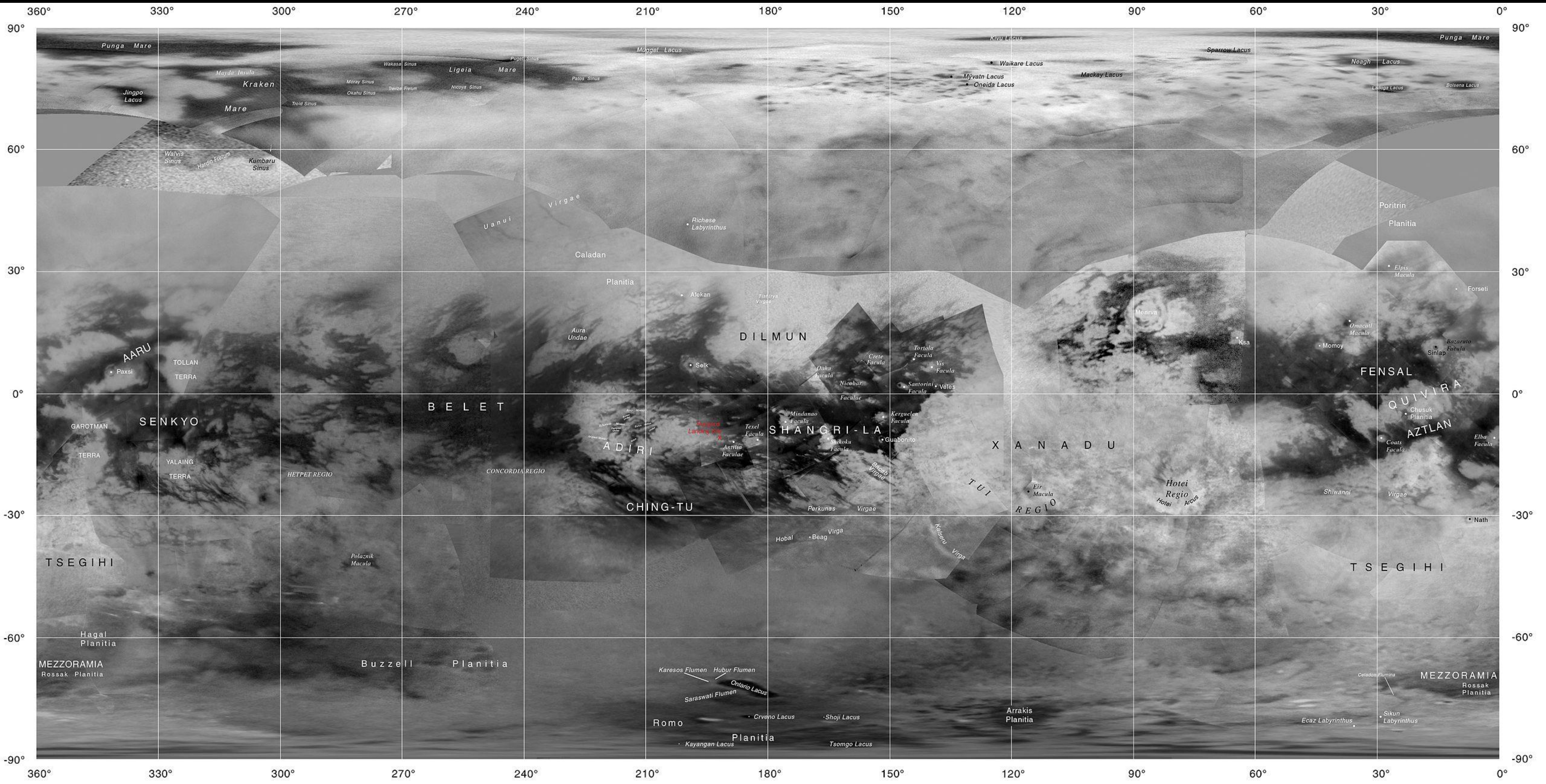
Titan: the main moon of Saturn



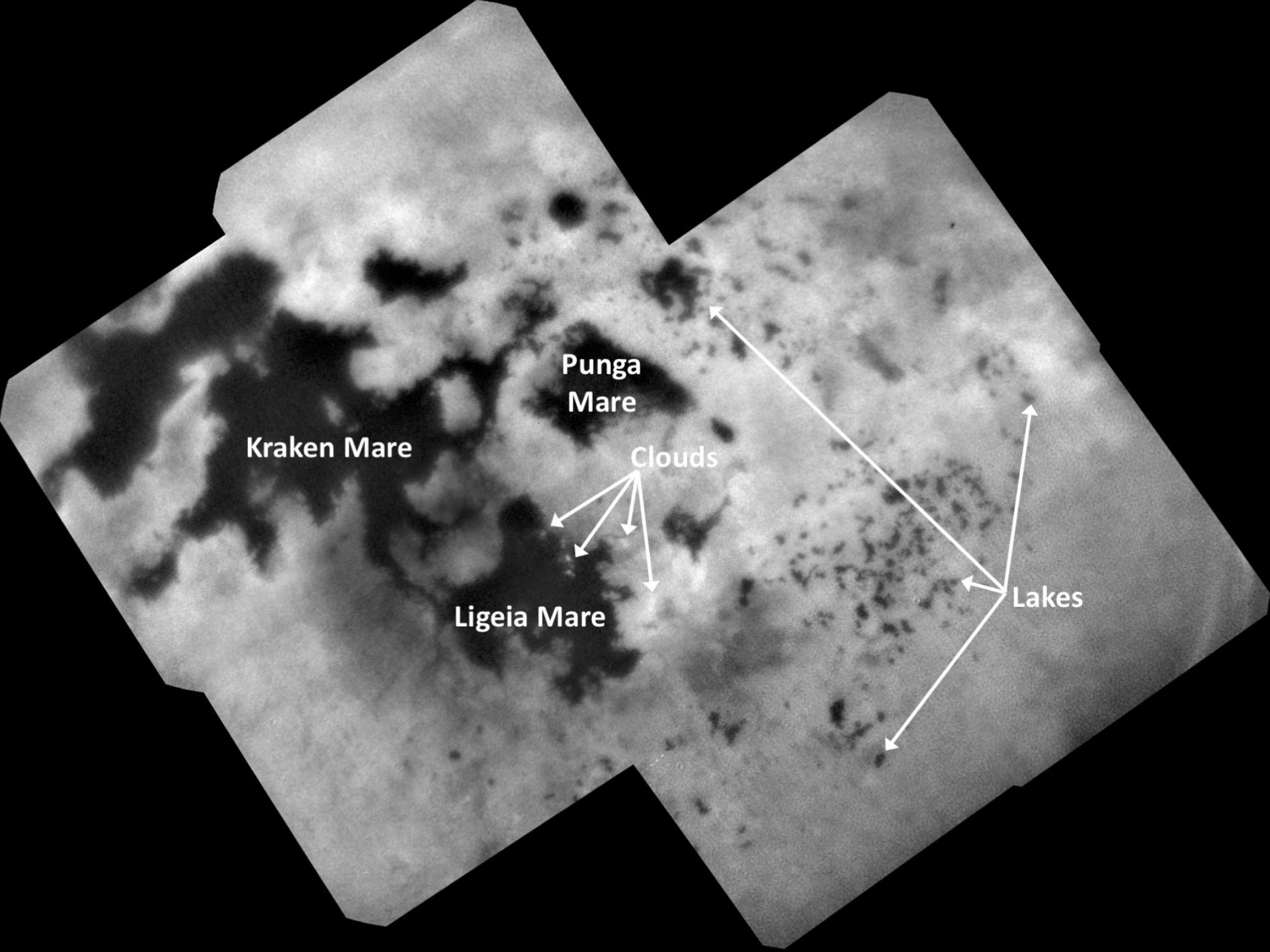


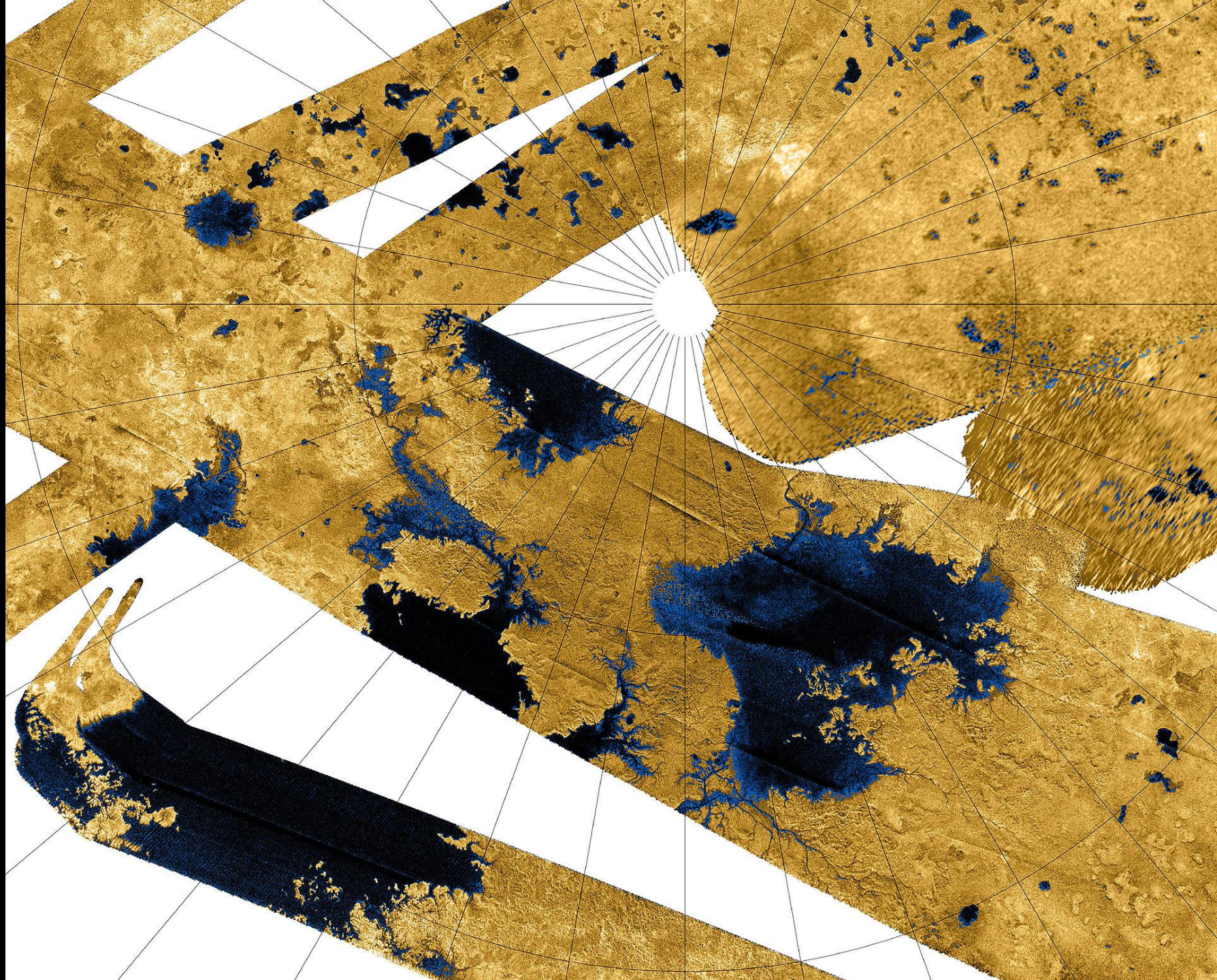

titan
Fully differentiated dense-ocean model
Drawn to scale
Ice-six
(tetragonal crystals)
Liquid water ocean
Normal ice (1_h)
Surface
Atmosphere
Lower atmosphere
Thick tholin haze
Upper atmosphere
Hydrous
silicate core

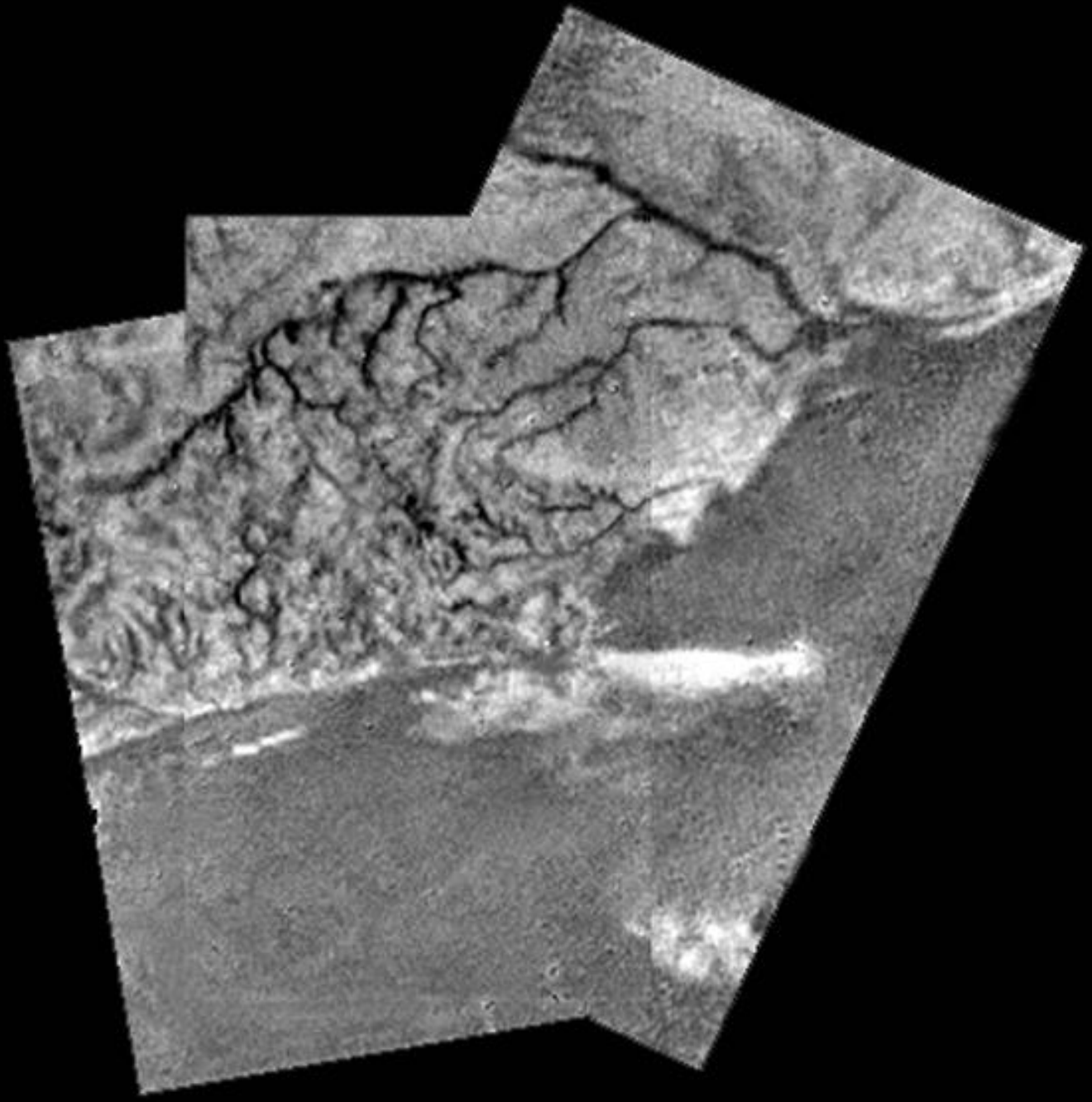


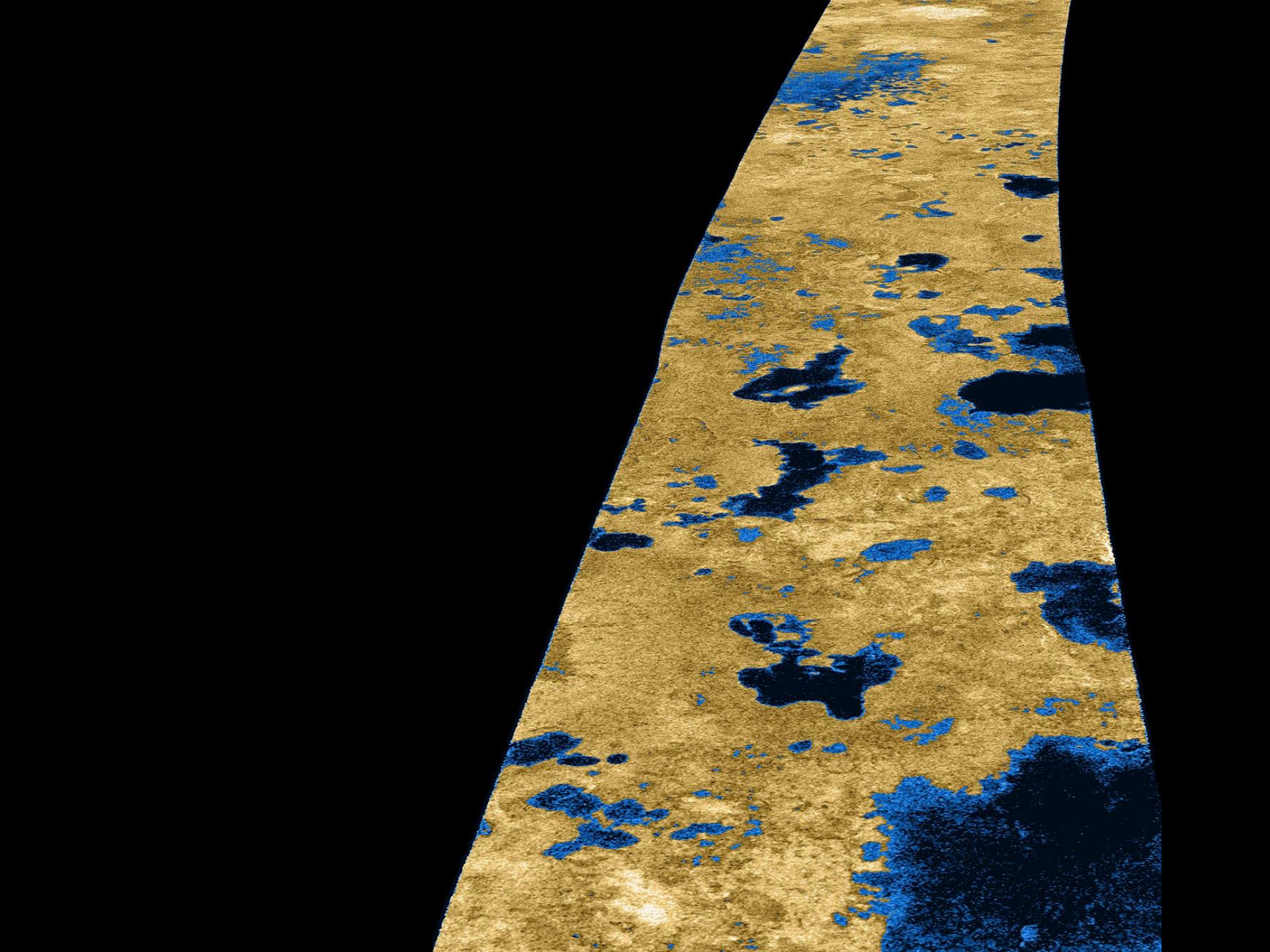


360° 330° 300° 270° 240° 210° 180° 150° 120° 90° 60° 30° 0°
90° 60° 30° 0° -30° -60° -90°
Punga Mare
Kraken Mare
Ligeia Mare
Jingpo Lacus
Mayda Insula
Walvis Sinus
Kumbaru Sinus
Mungel Lacus
Waikare Lacus
Mývatn Lacus
Oneida Lacus
Mackay Lacus
Sparrow Lacus
Neagh Lacus
Uanui Virgae
Richese Labyrinthus
Caladan Planitia
Poritrin Planitia
AARU
Paxsi
TOLLAN TERRA
Afekan
Aura Undae
Selk
DILMUN
Menrva
Ksa
Momoy
FENSAL
QUIVIRA
AZTLAN
Forseti
GAROTMAN TERRA
SENKYO
YALAING TERRA
BELET
HETPET REGIO
CONCORDIA REGIO
ADIRI
SHANGRI-LA
Guabonito
XANADU
TUI REGIO
Hotei Regio
Hotei Arcus
CHING-TU
Perkunas Virgae
Hobal
Beag
Shiwanni
Nath
TSEGIHI
Polaznik Macula
Hagal Planitia
MEZZORAMIA
Rossak Planitia
Buzzell Planitia
Karesos Flumen
Hubur Flumen
Ontario Lacus
Saraswati Flumen
Romo Planitia
Crveno Lacus
Shoji Lacus
Kayangan Lacus
Tsomgo Lacus
Arrakis Planitia
Ecaz Labyrinthus
Sikun Labyrinthus


Punga
Mare
Kraken Mare
Clouds
Ligeia Mare
Lakes

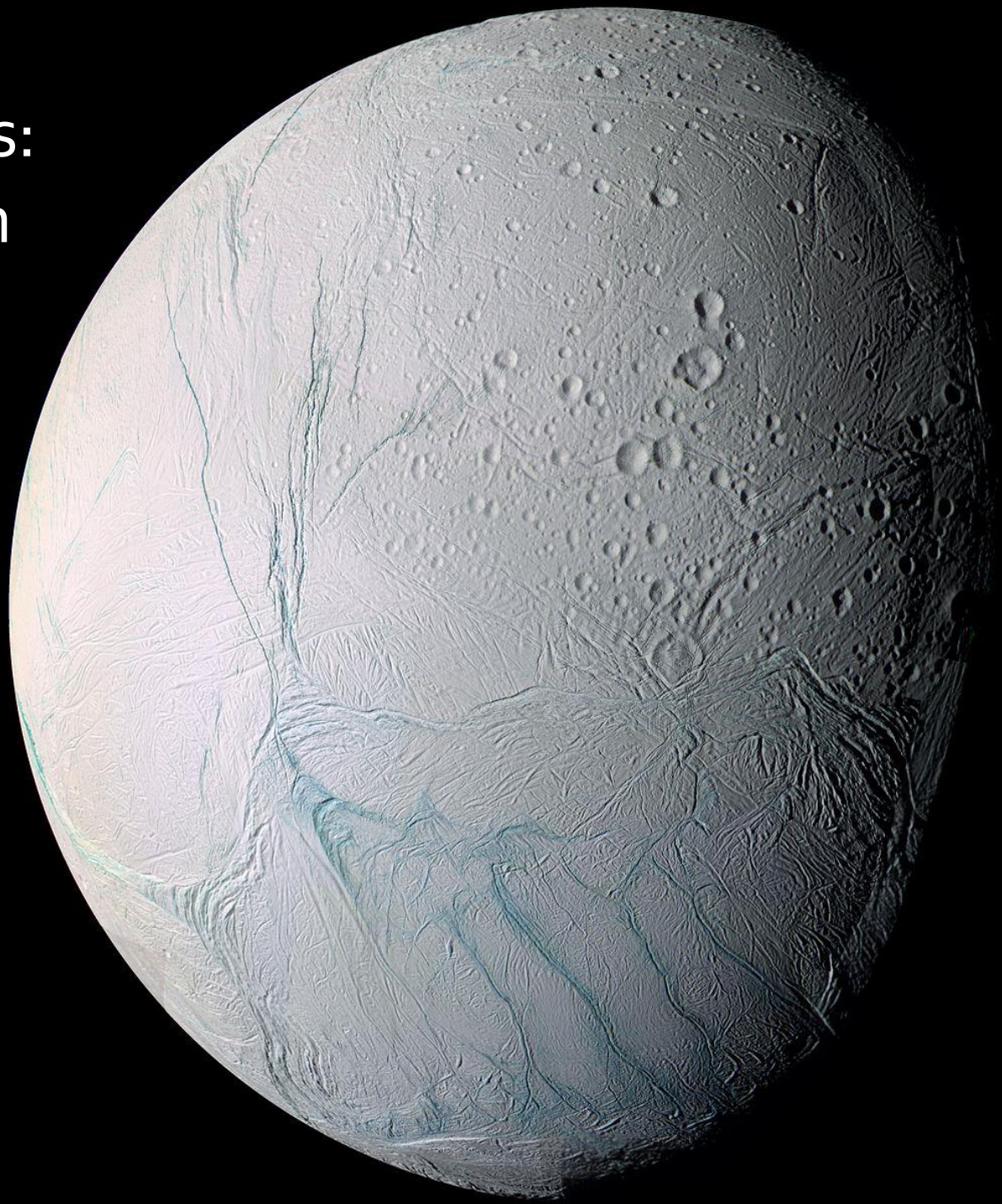


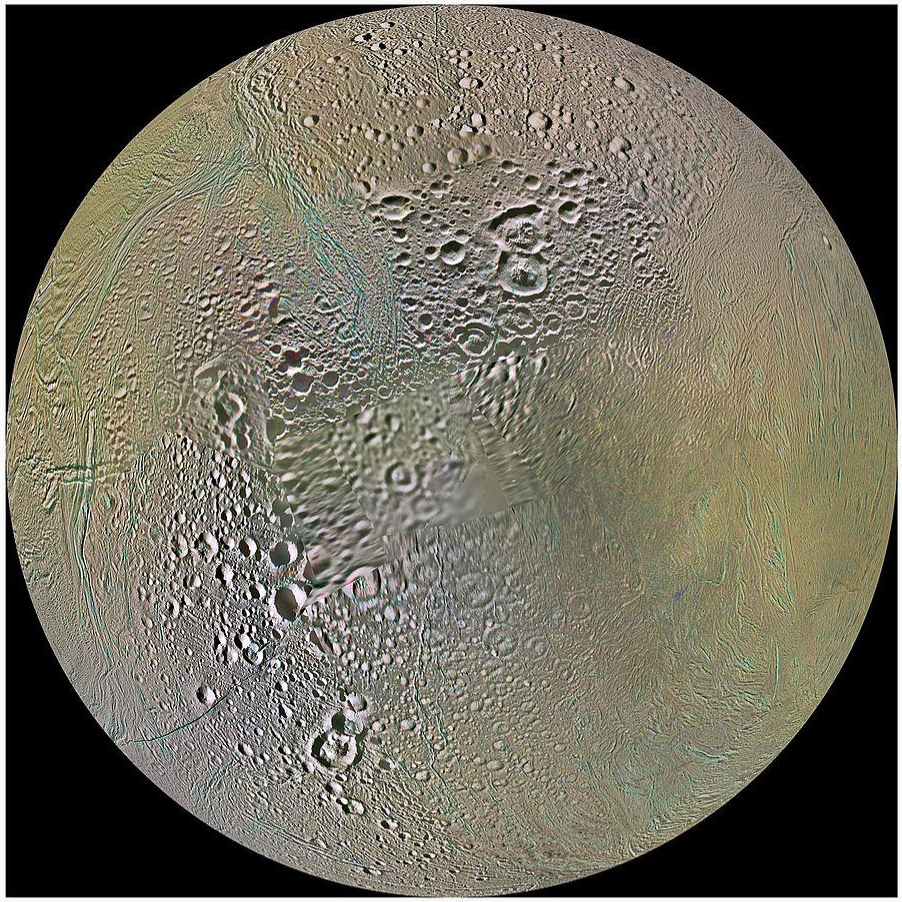




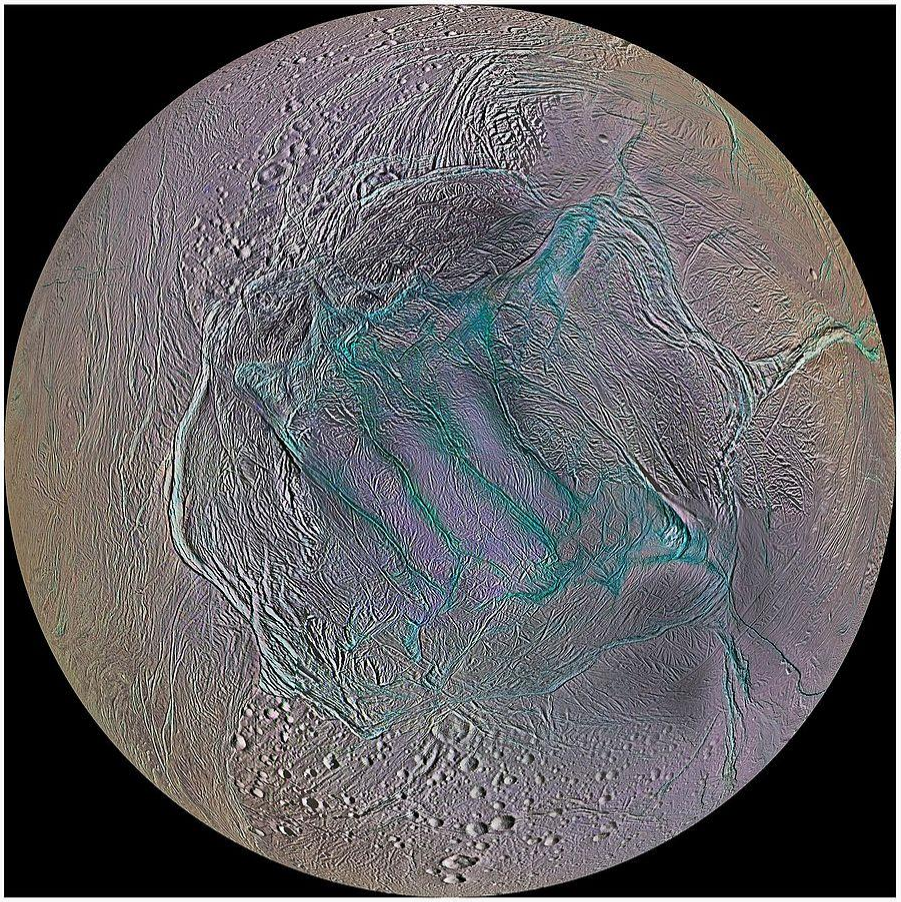

NASA/Dragonfly Mission:
drone to Titan!

Enceladus: ice moon





Northern Hemisphere
Orthographic map projection at 100 meters/pixel



Southern Hemisphere
Orthographic map projection at 100 meters/pixel

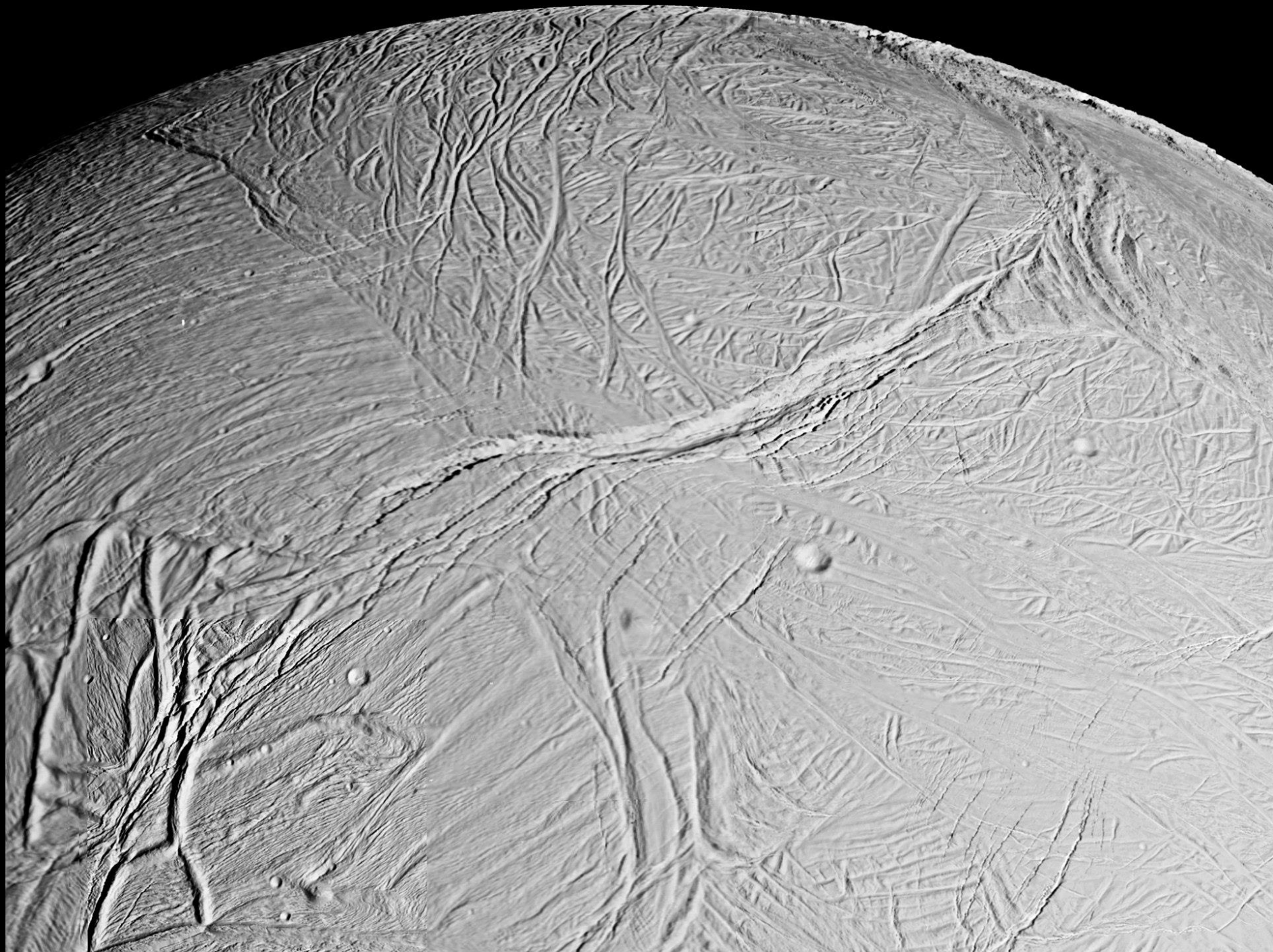
Global 3-Color Map of Enceladus (IR3-GRN-UV3)

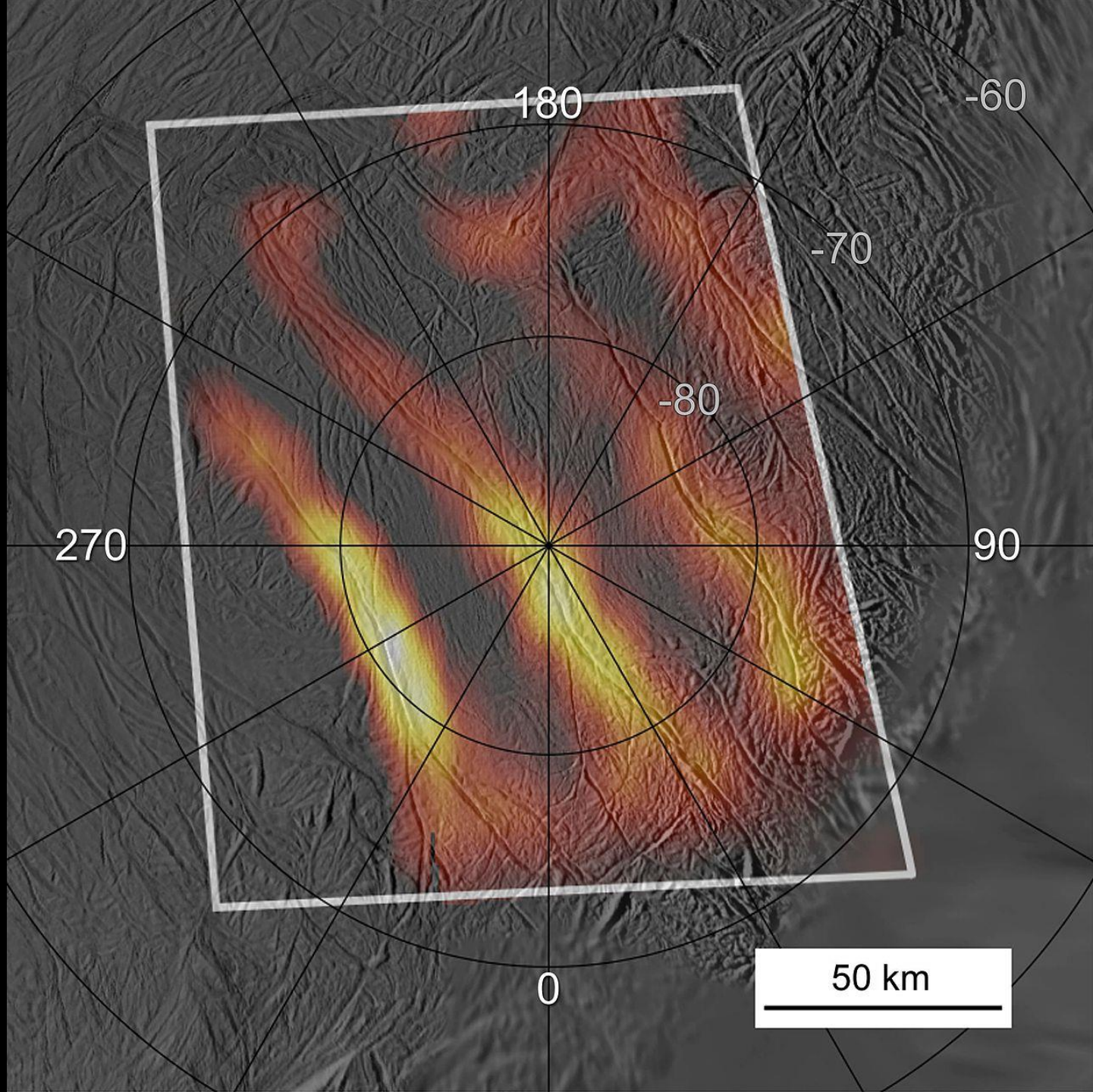
April 2014

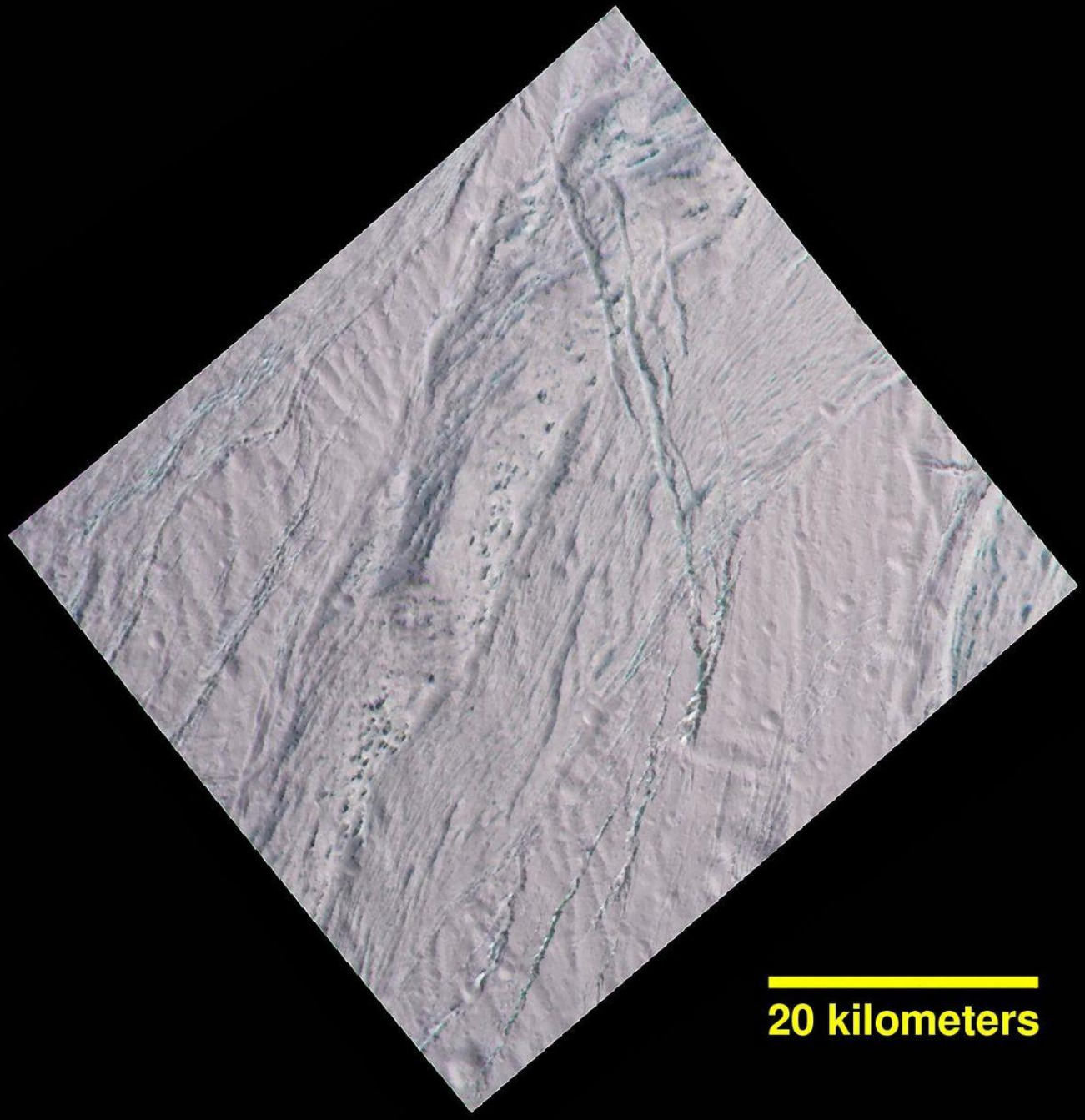
Scale bar = 100 km

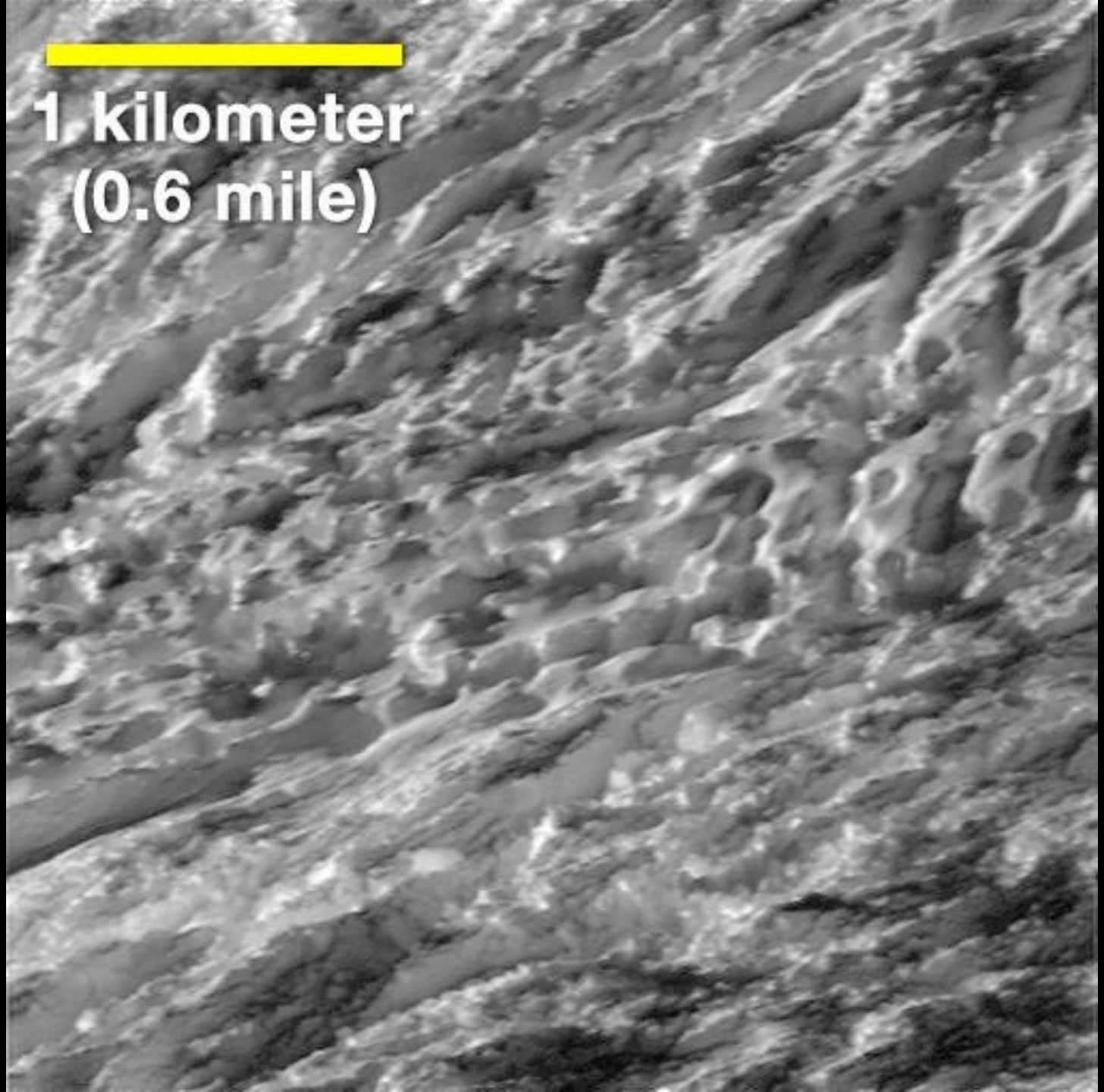
Cartographic control and digital mosaic construction by Dr. Paul Schenk (LPI, Houston)
Cassini ISS images acquired 2004-2014

LUNAR AND PLANETARY INSTITUTE

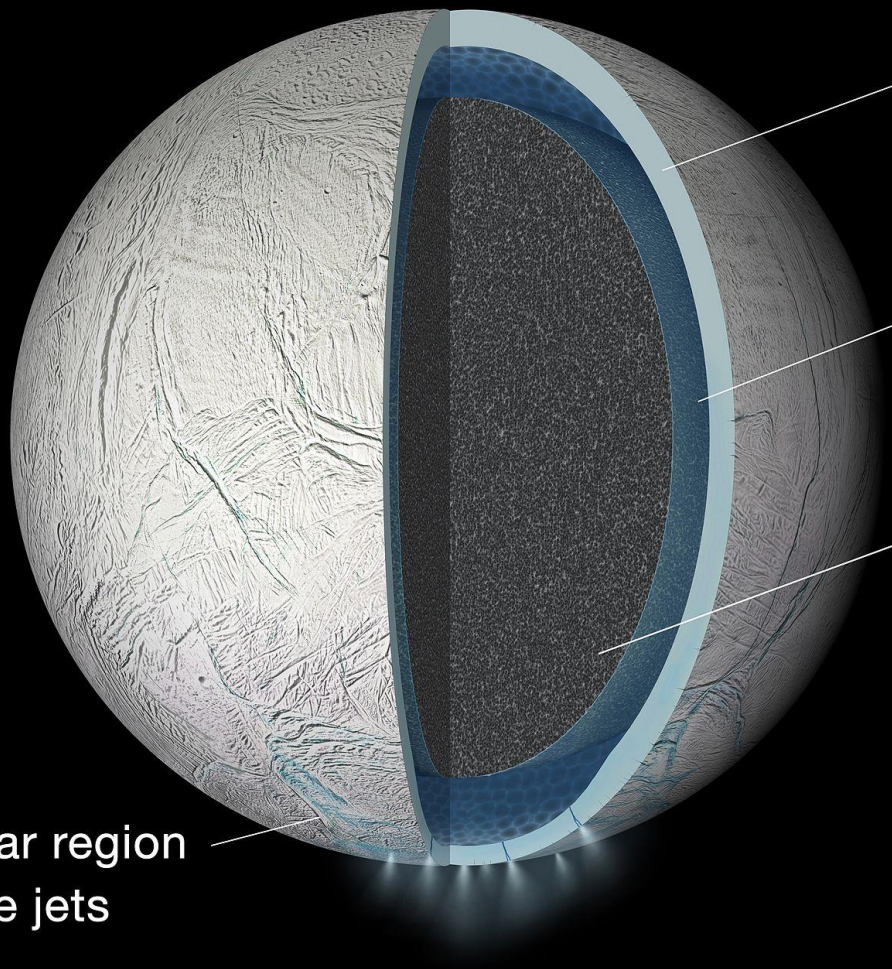



180
-60
-70
-80
270
90
0
50 km


20 kilometers

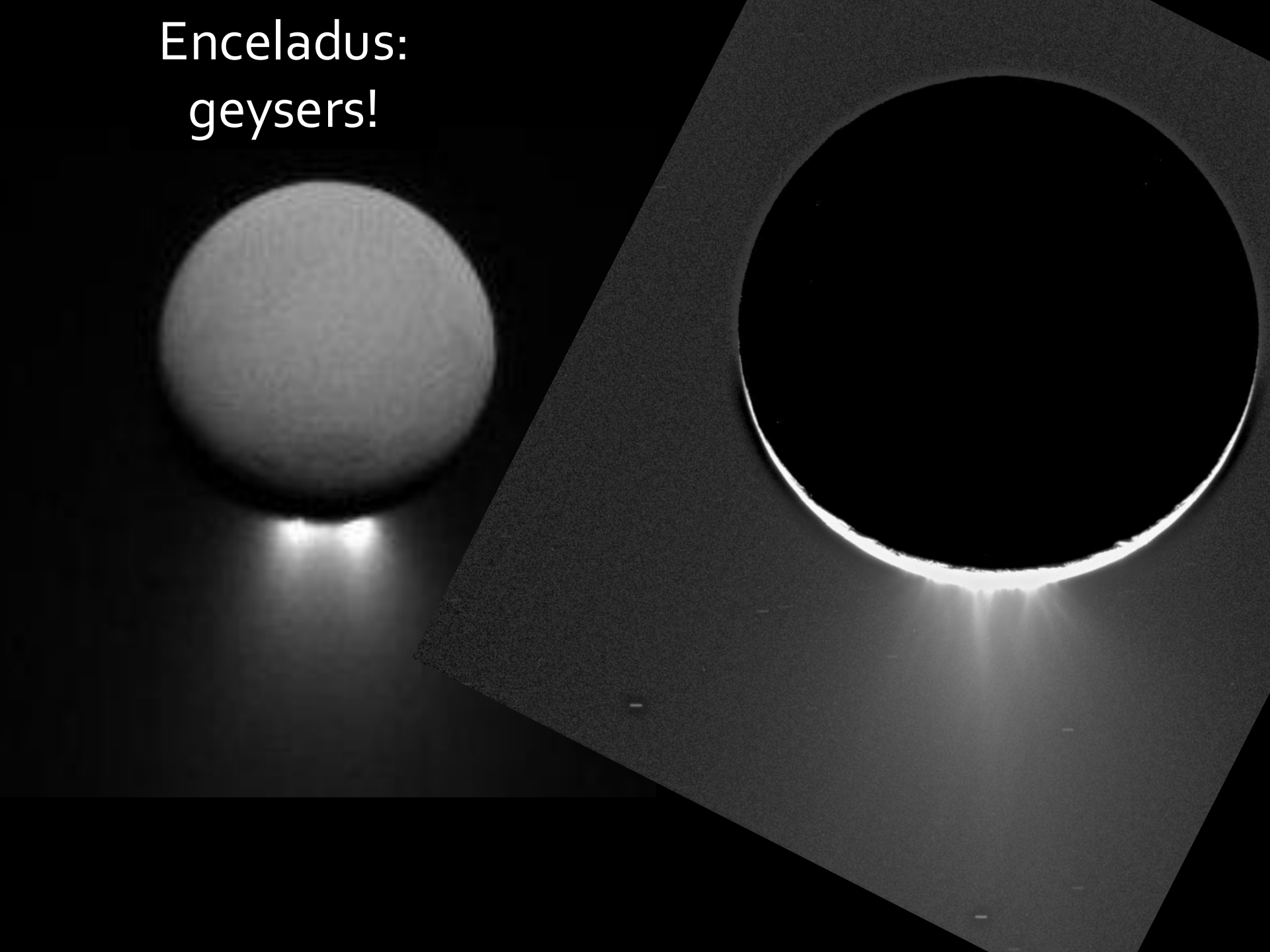

1 kilometer
(0.6 mile)

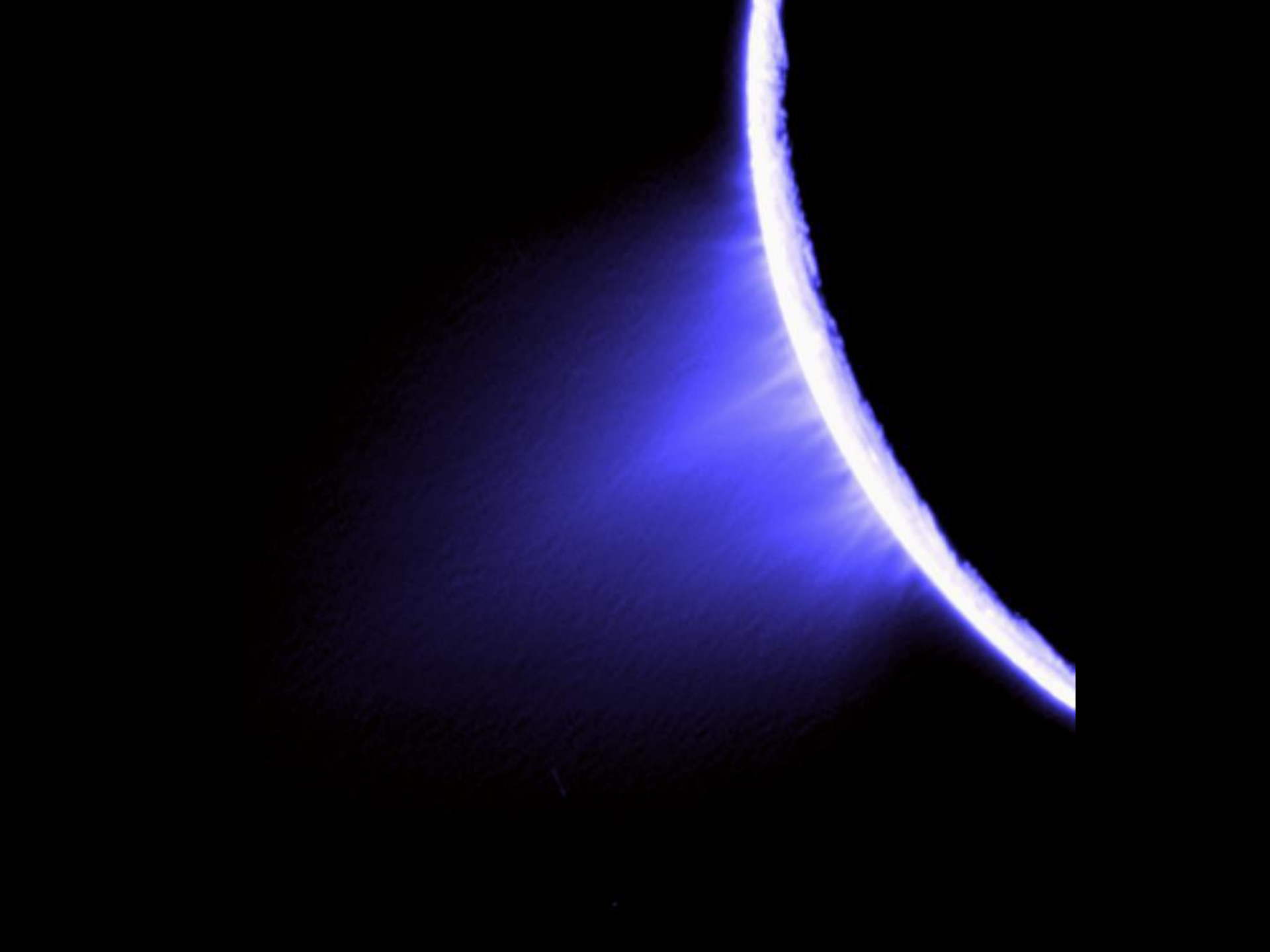
Global Ocean on
Saturn's Moon
ENCELADUS

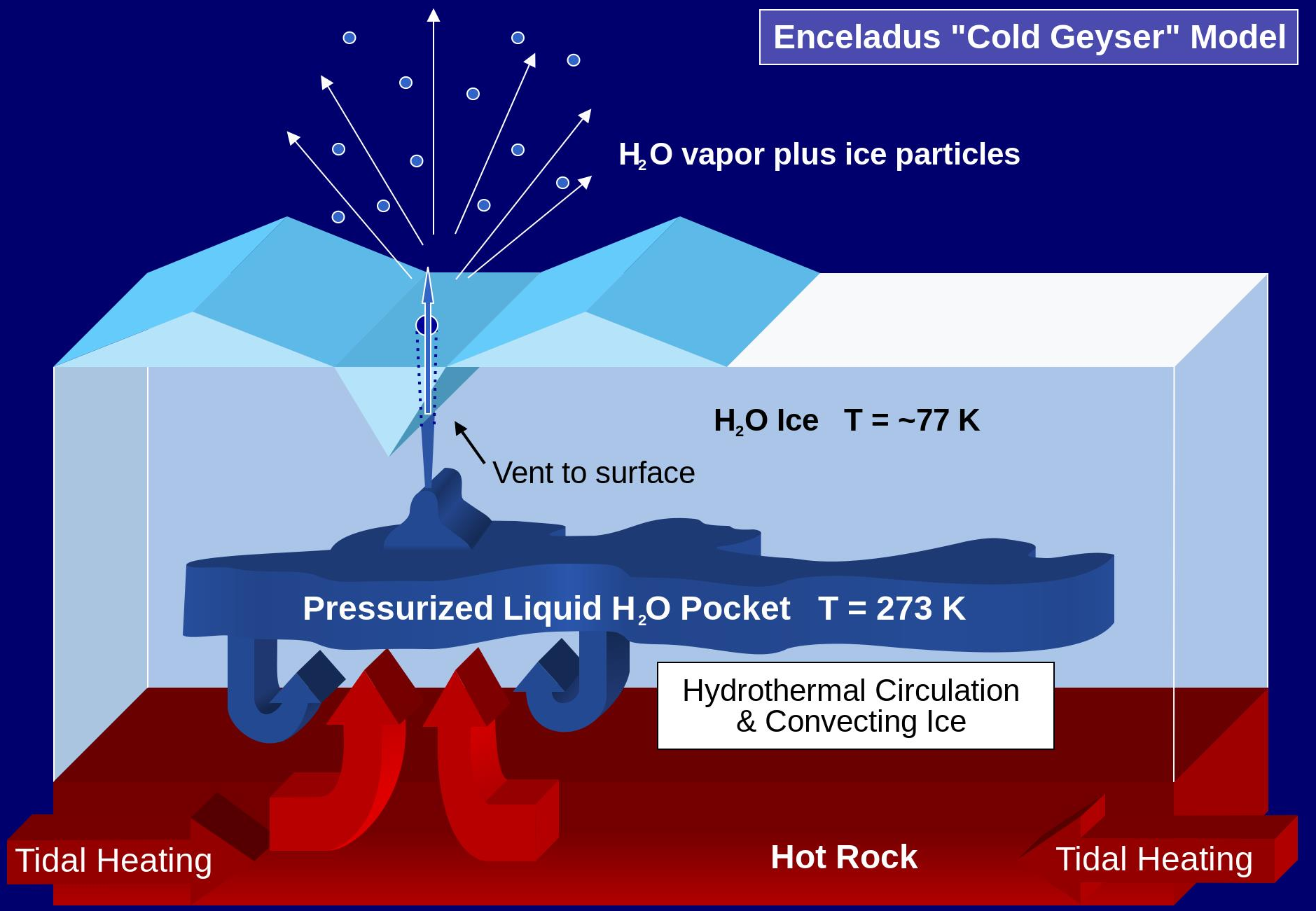


* Thickness of layers is not to scale

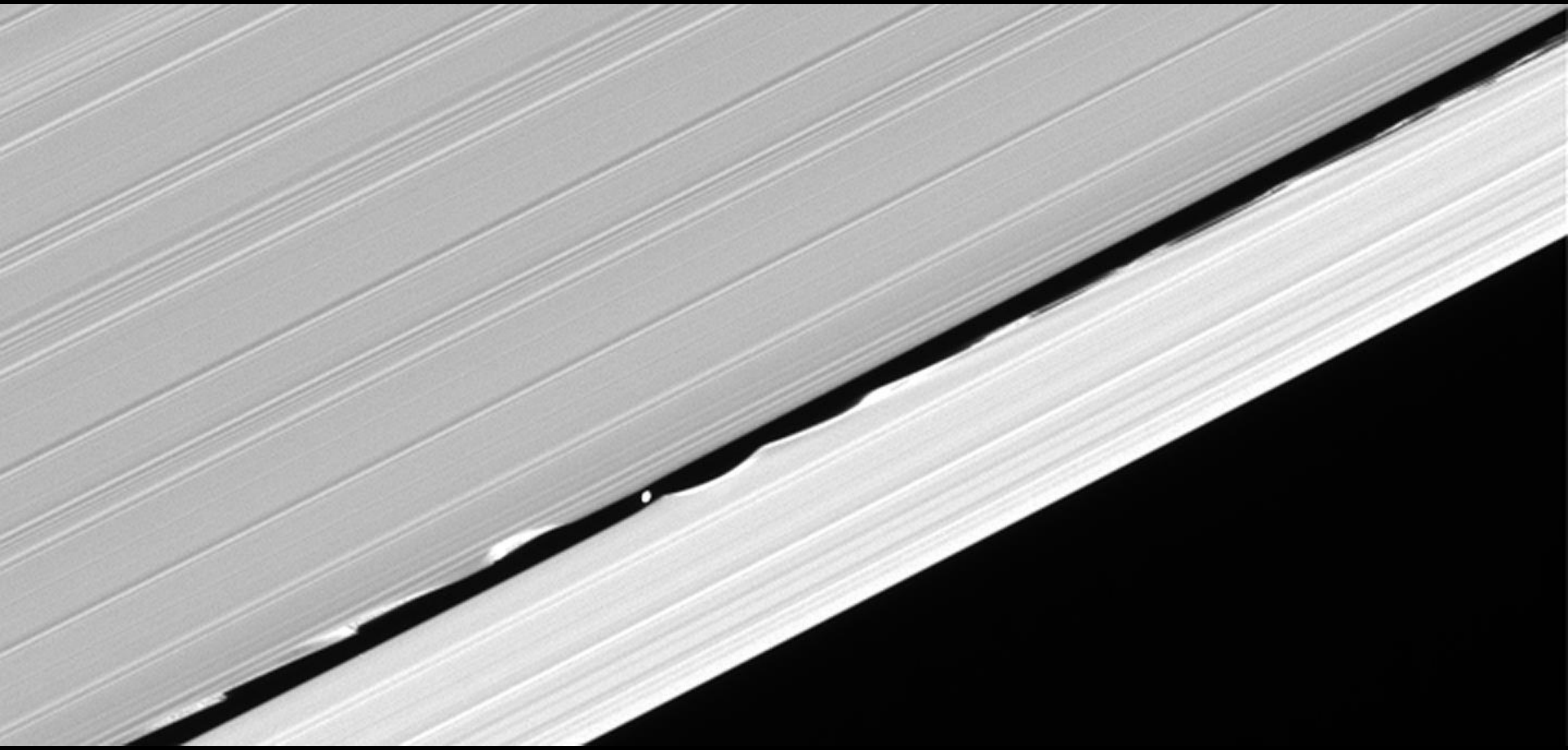
Enceladus: geysers!



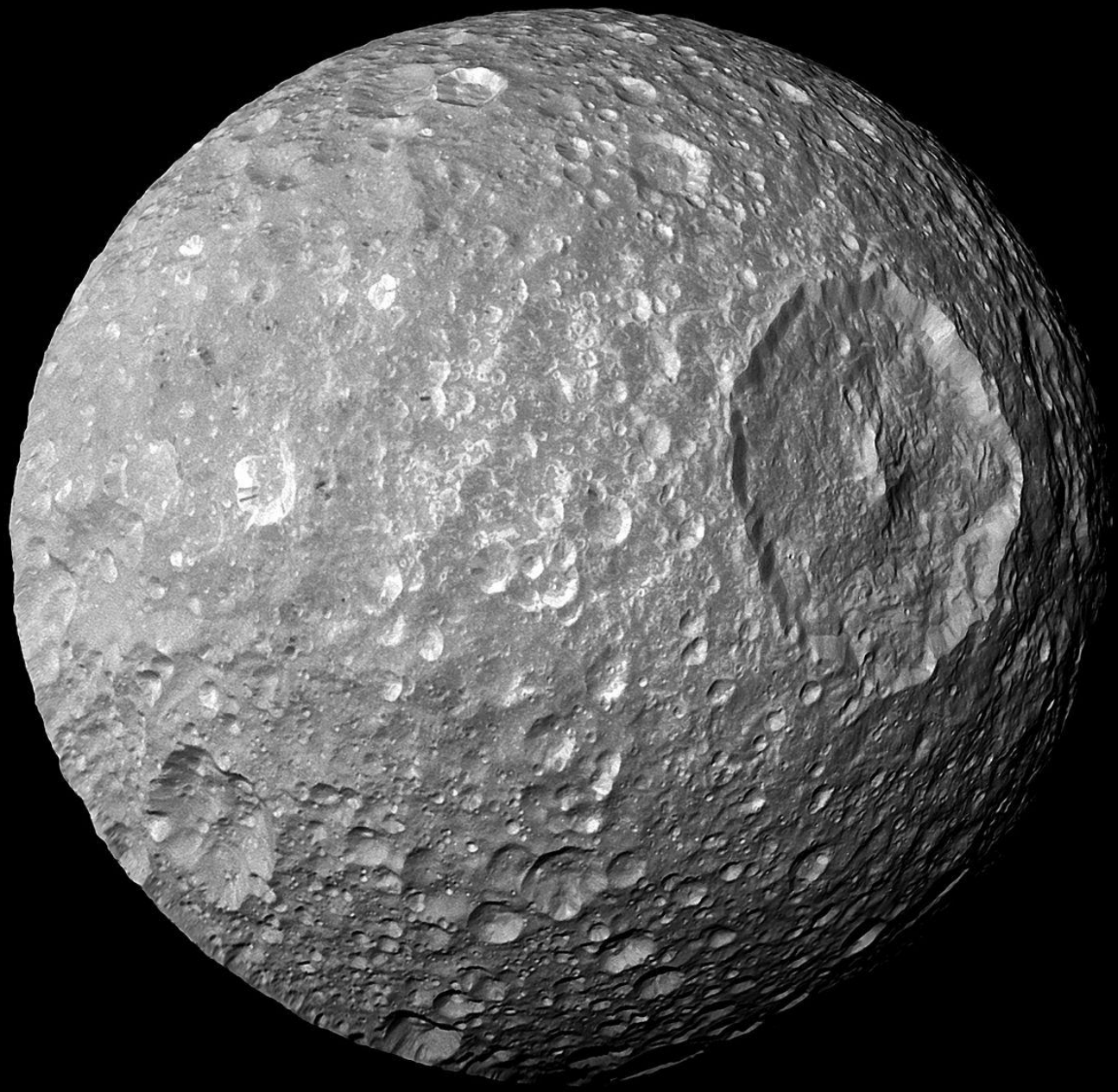



Enceladus "Cold Geyser" Model
H2O vapor plus ice particles
H2O Ice T = ~77 K
Vent to surface
Pressurized Liquid H2O Pocket T = 273 K
Hydrothermal Circulation
& Convecting Ice
Tidal Heating
Hot Rock
Tidal Heating

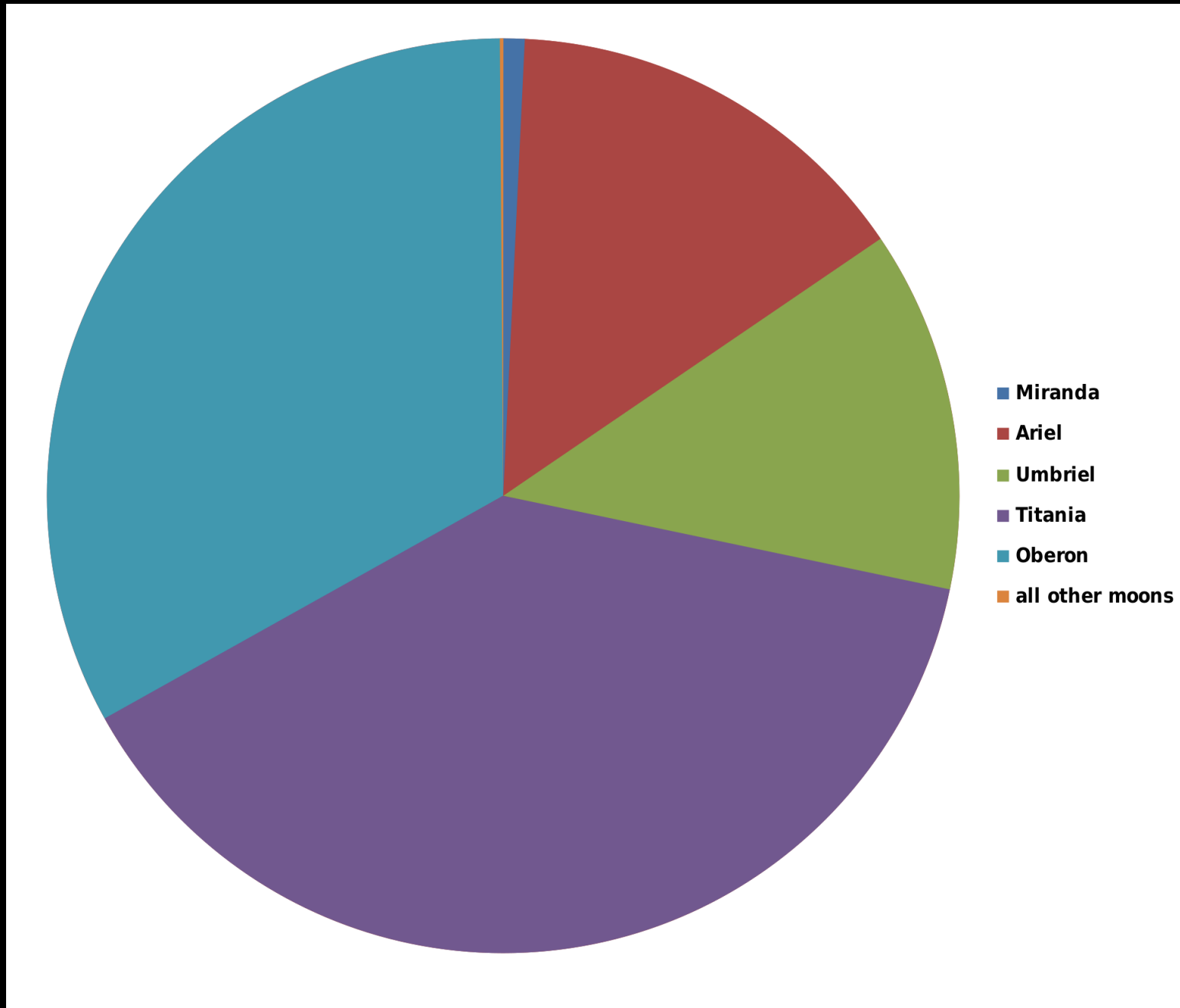
Daphnis: A shepherd moon

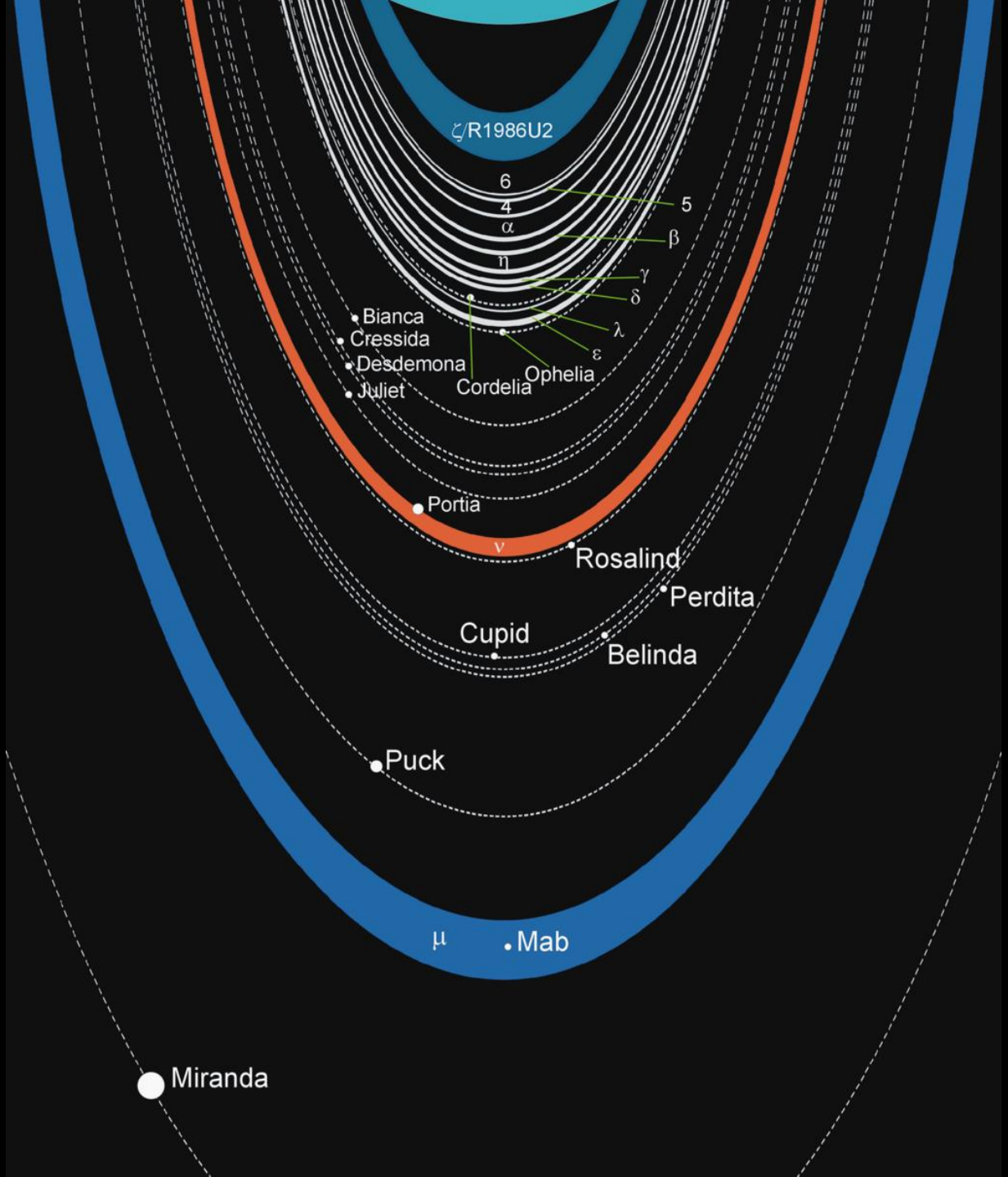


Mimas: the death star moon

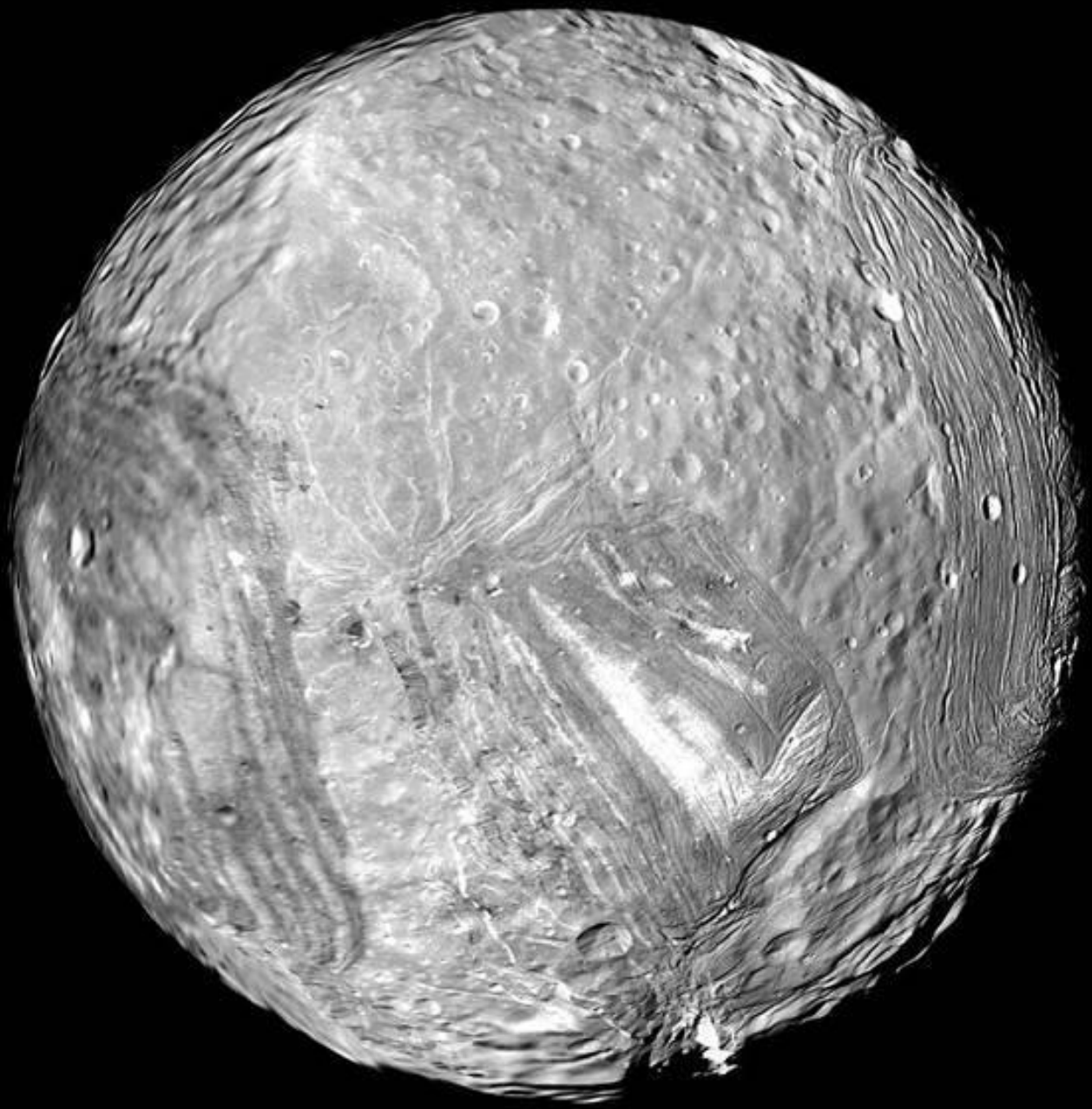


Moons of Uranus

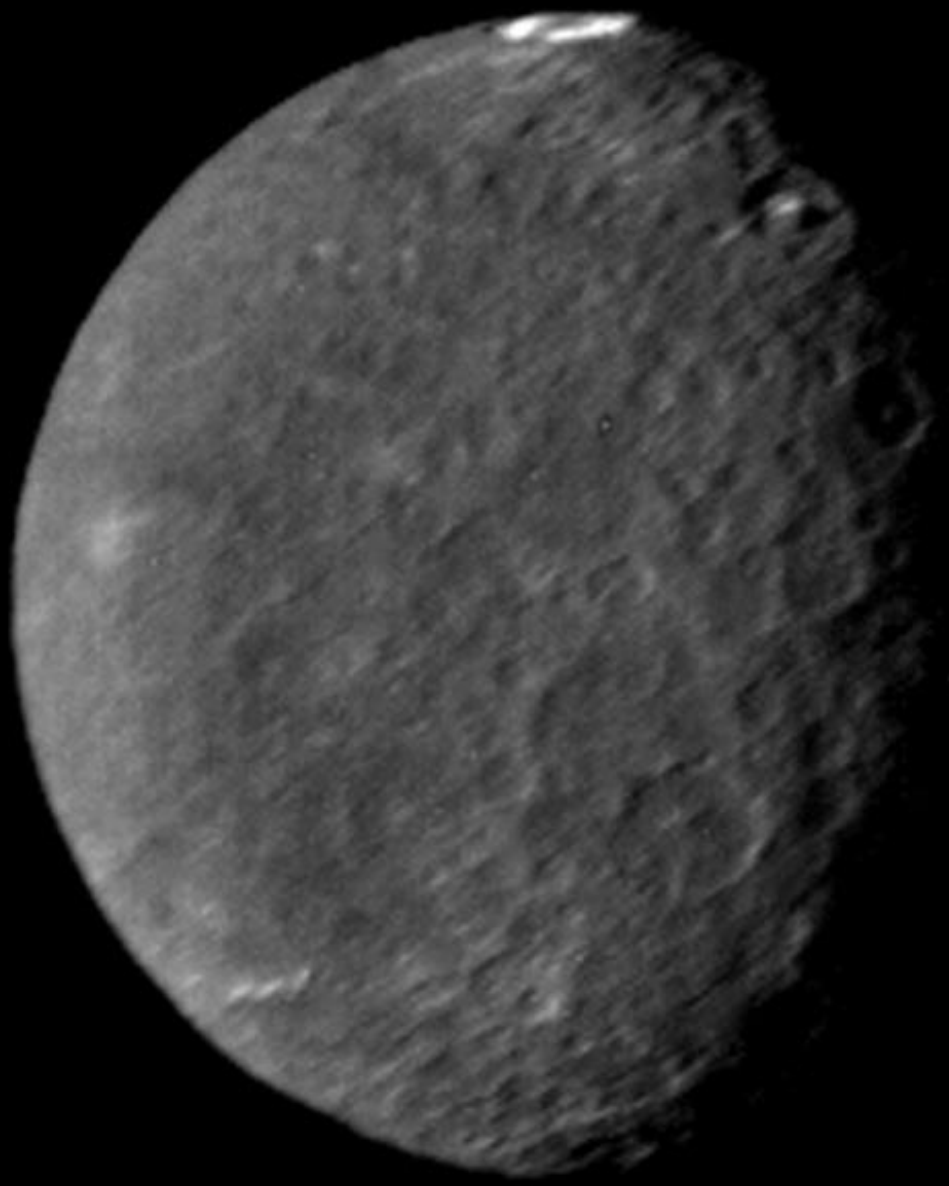


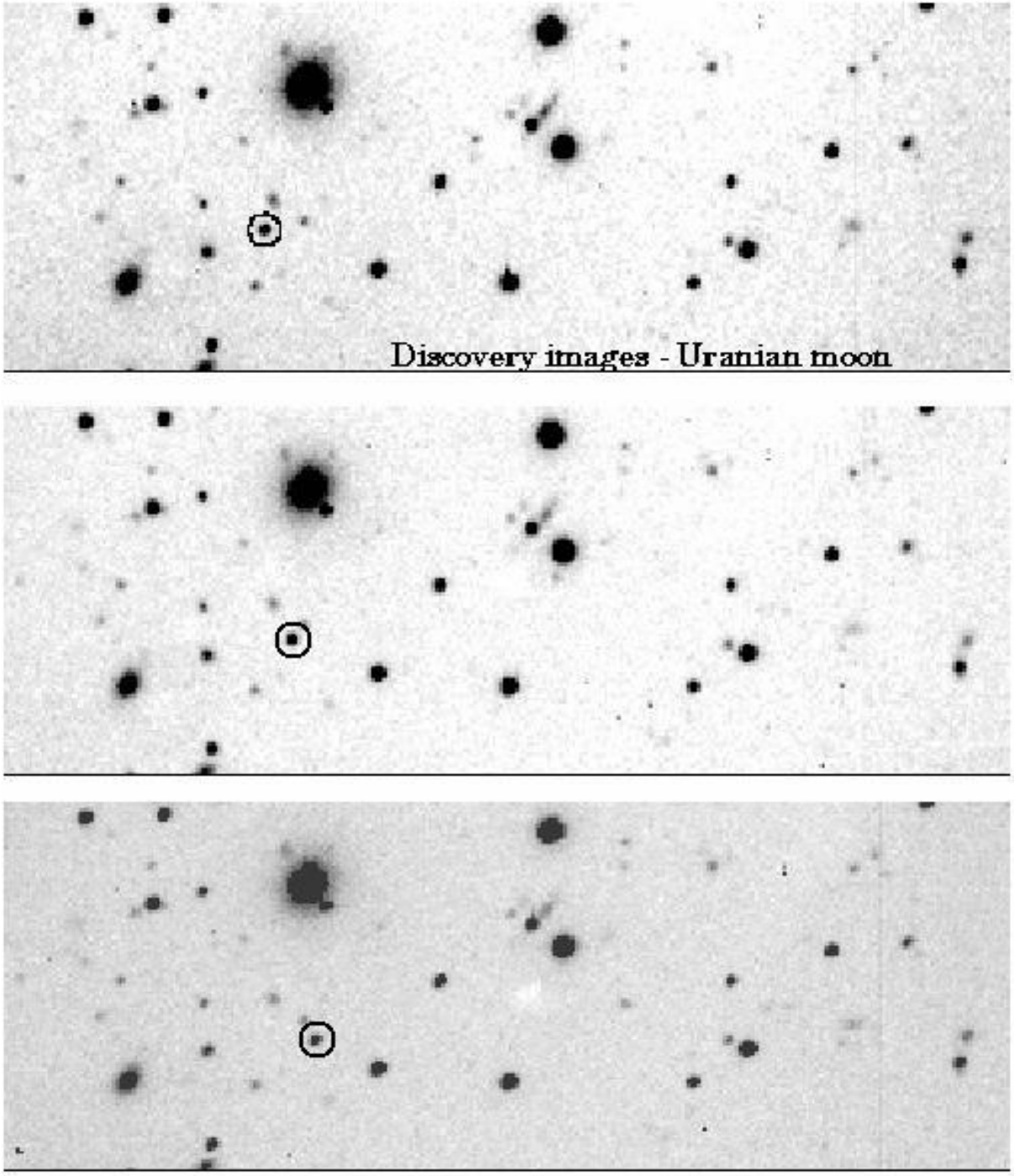

ζ/R1986U2
6
4
α
η
5
β
γ
δ
λ
ε
Bianca
Cressida
Desdemona
Juliet
Cordelia
Ophelia
Portia
ν
Rosalind
Perdita
Cupid
Belinda
Puck
μ
Mab
Miranda

Miranda: an ice world?



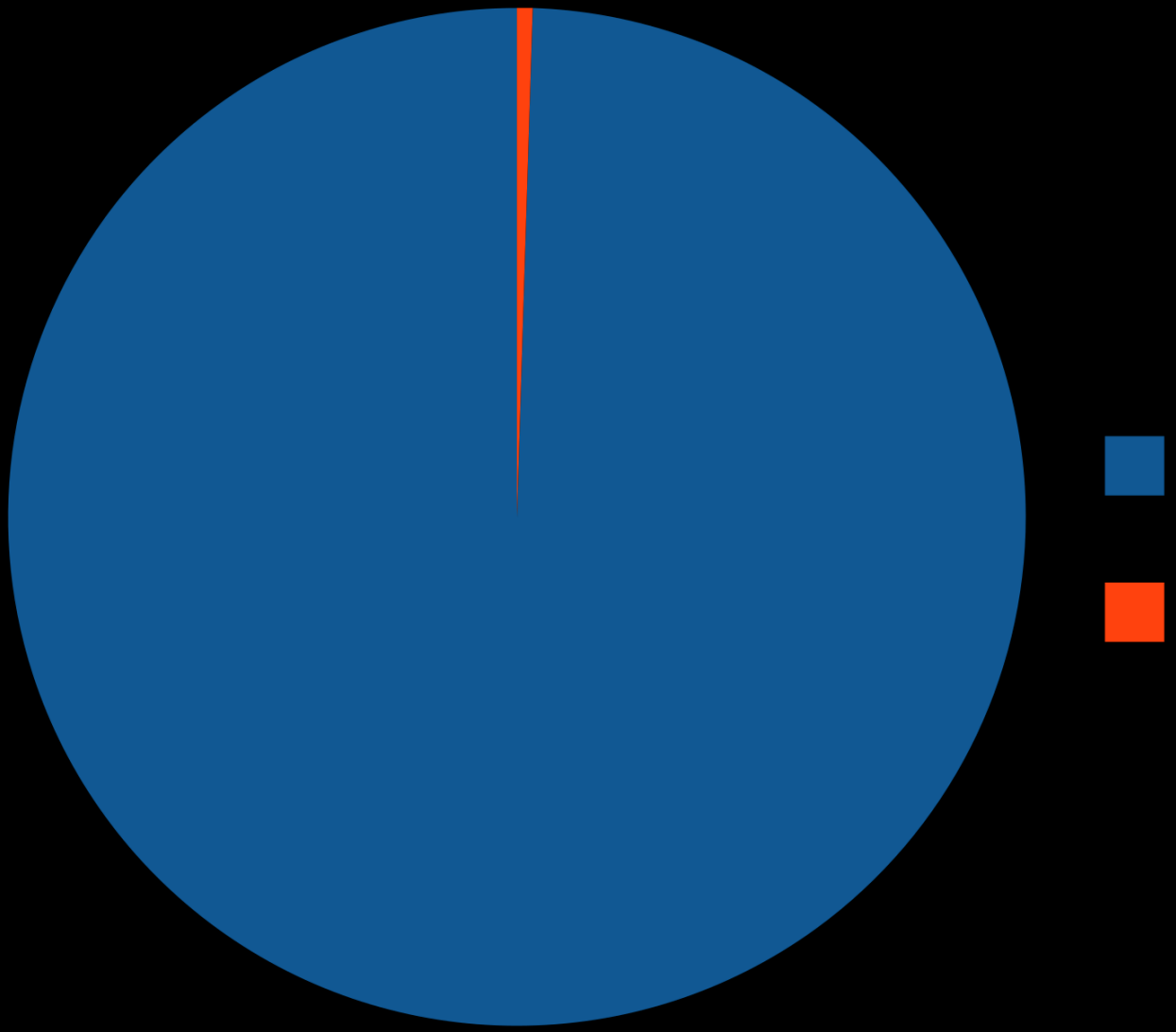
Umbriel: weird ring at the top



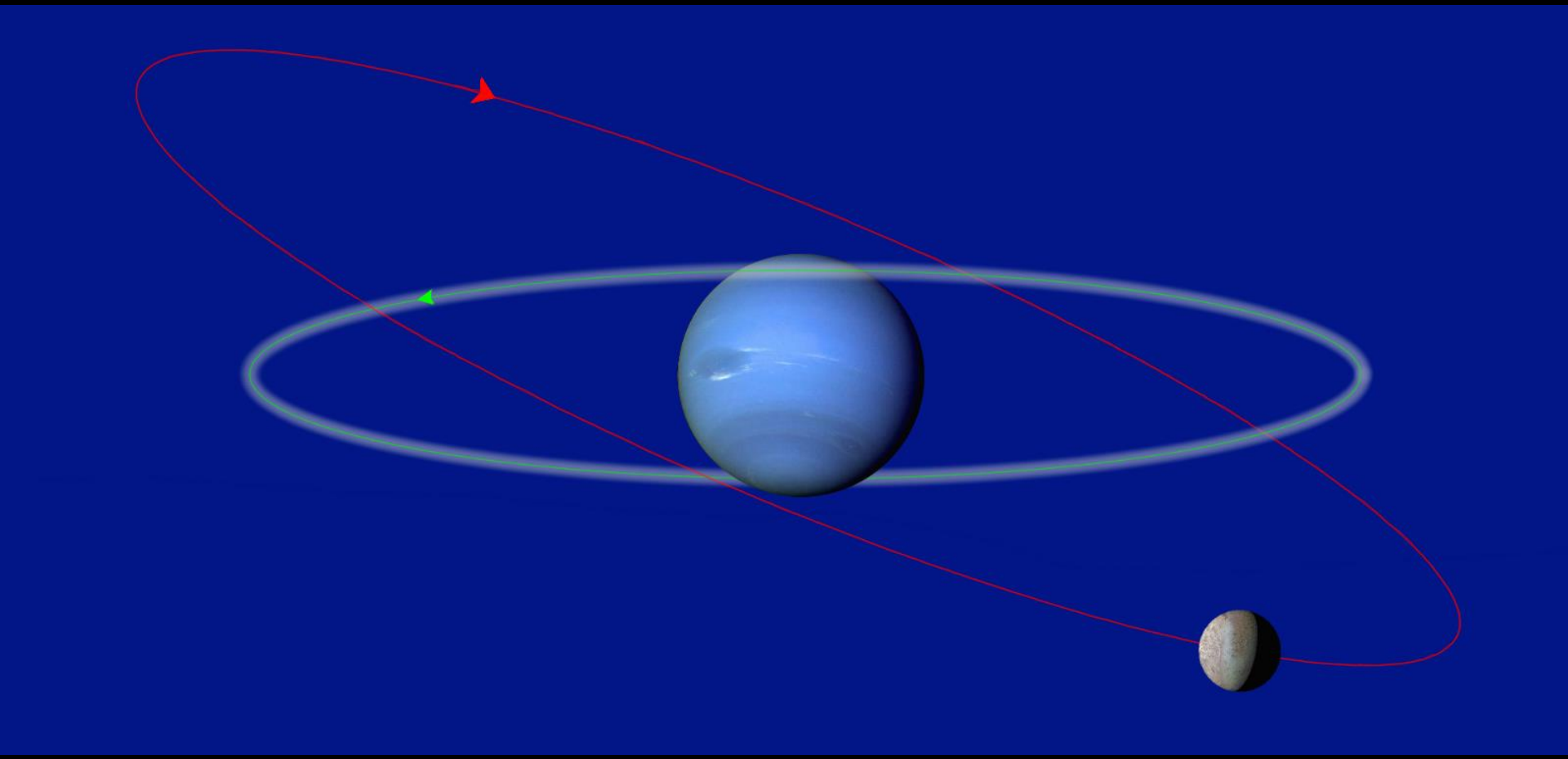


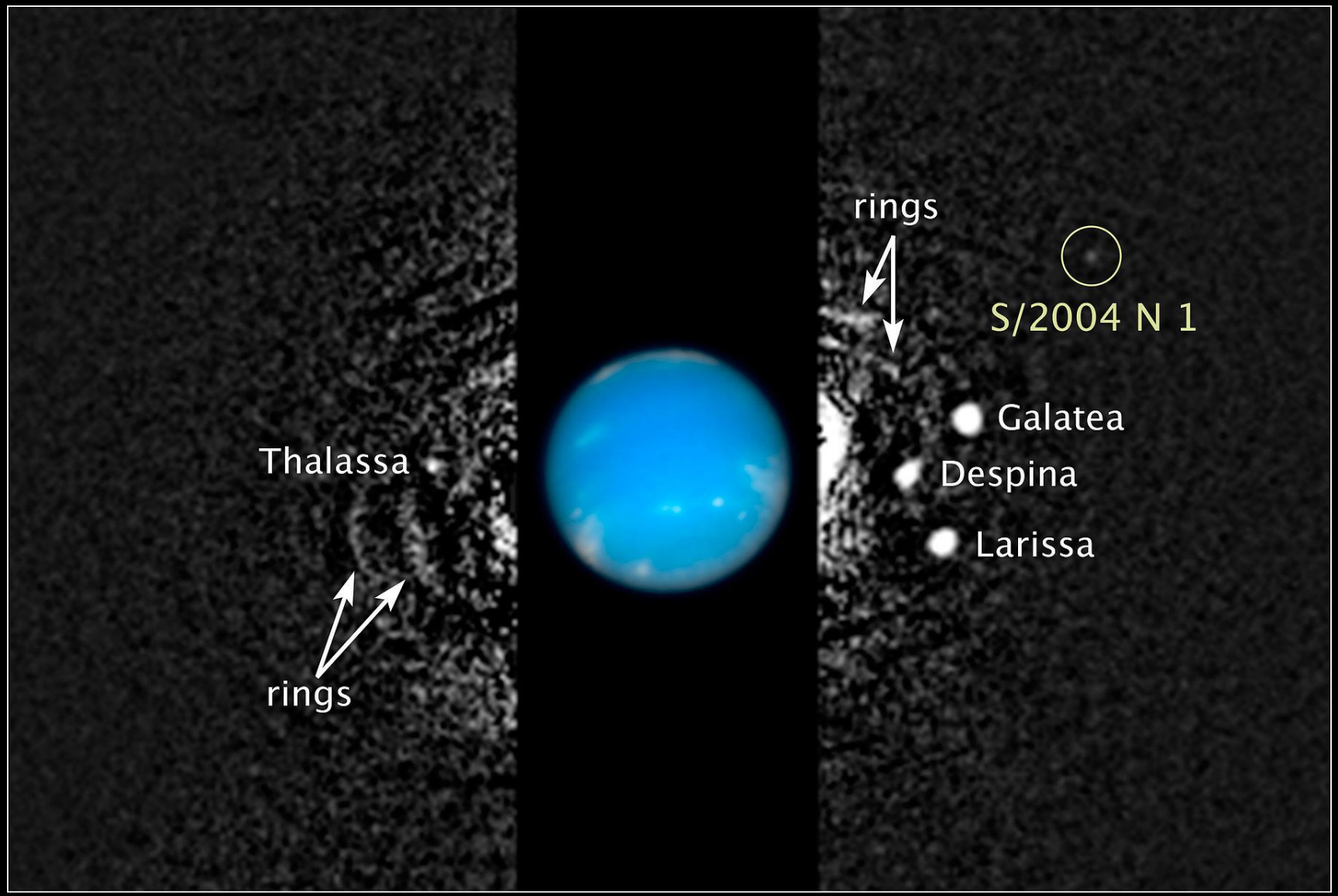
Sycorax: example of how the moons are found

Moons of Neptune



Triton: going in the wrong direction! captured Kuiper Belt Object?



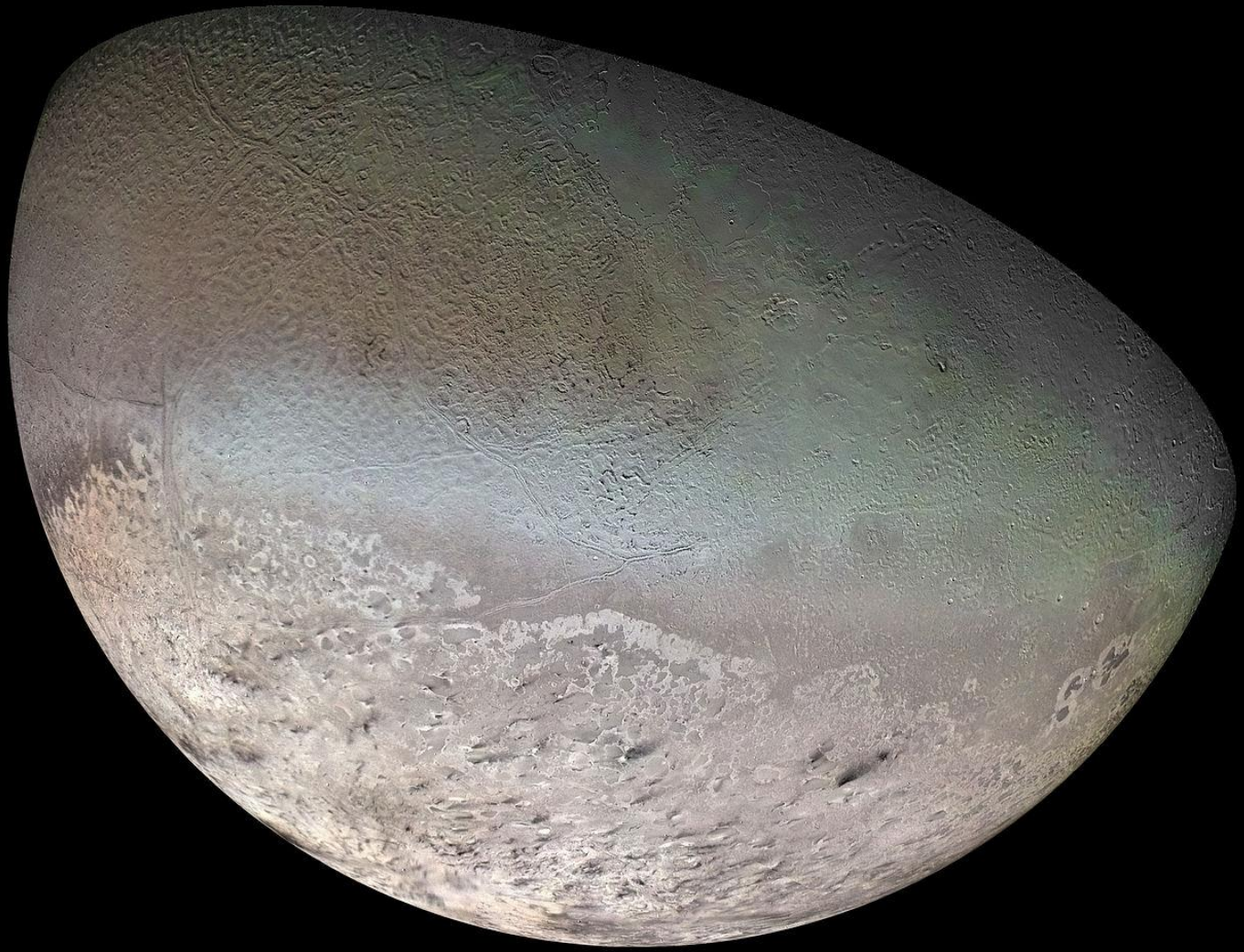


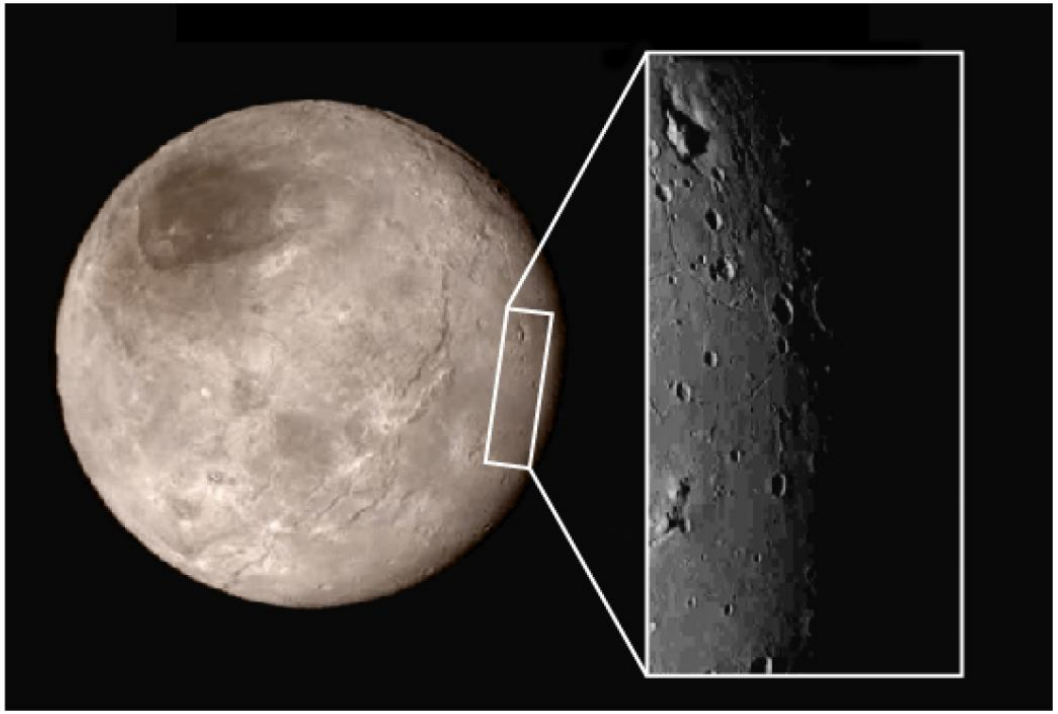
Neptune Satellites and Ring Arcs

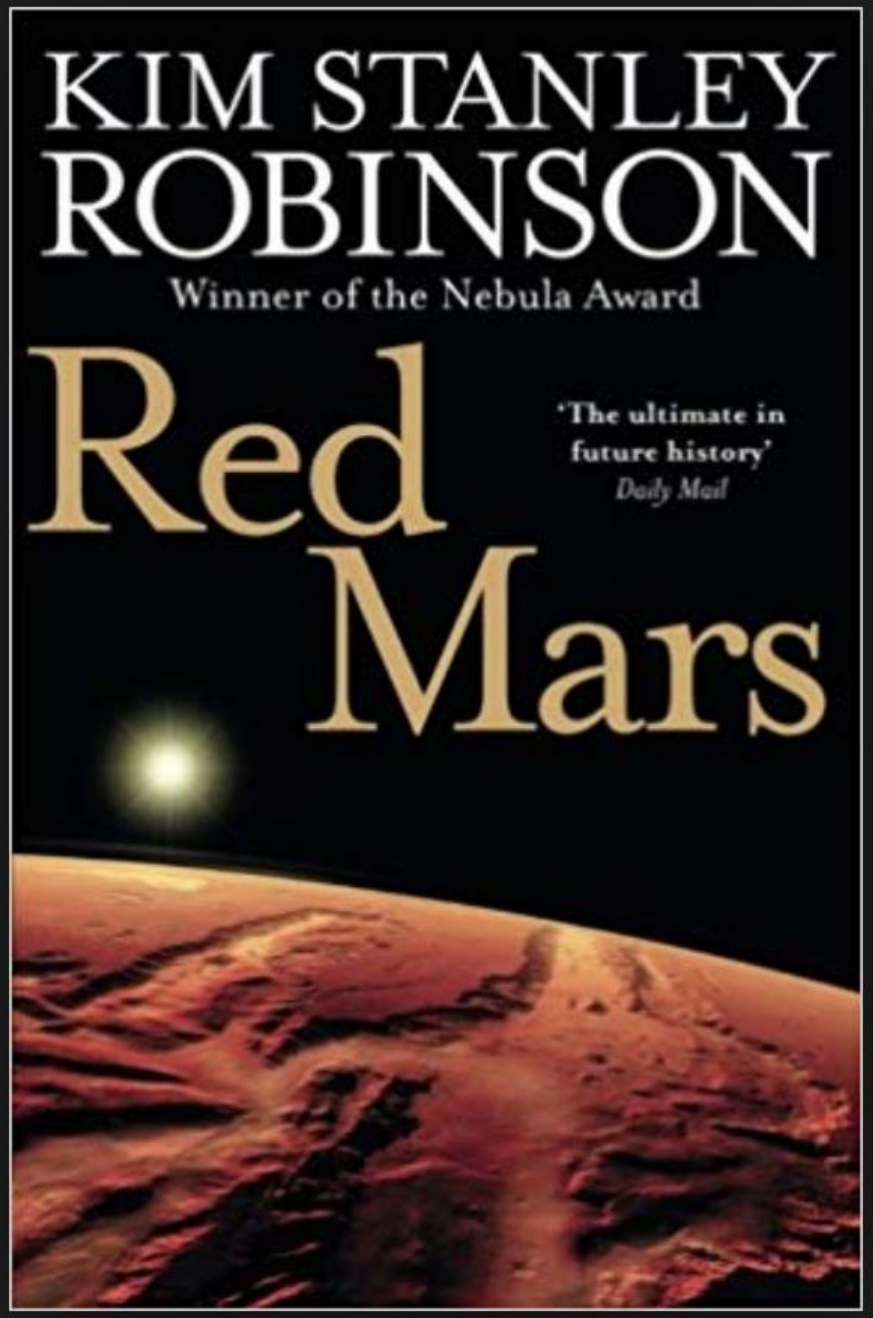
Hubble Space Telescope ▪ WFC3/UVIS

NASA and ESA

STScI-PRC13-30a



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