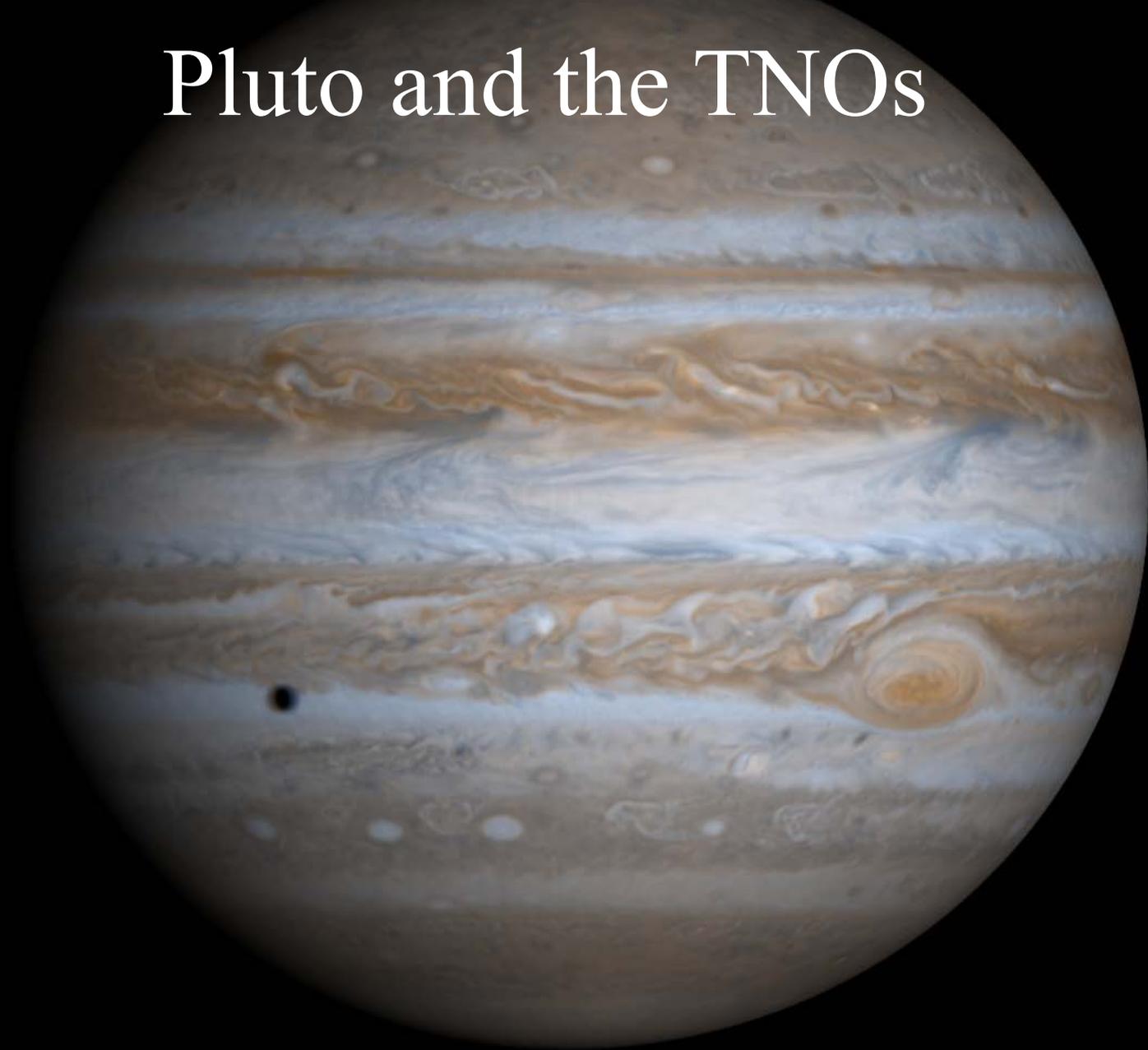
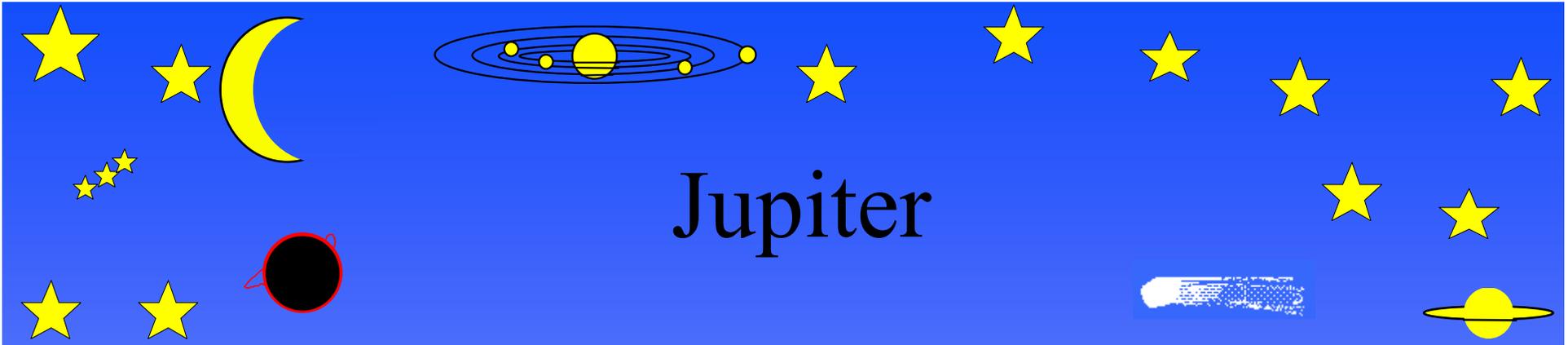


# The Jovian Planets + Pluto and the TNOs





# Jupiter

☀ **Jupiter** easily seen with naked eye; doesn't twinkle

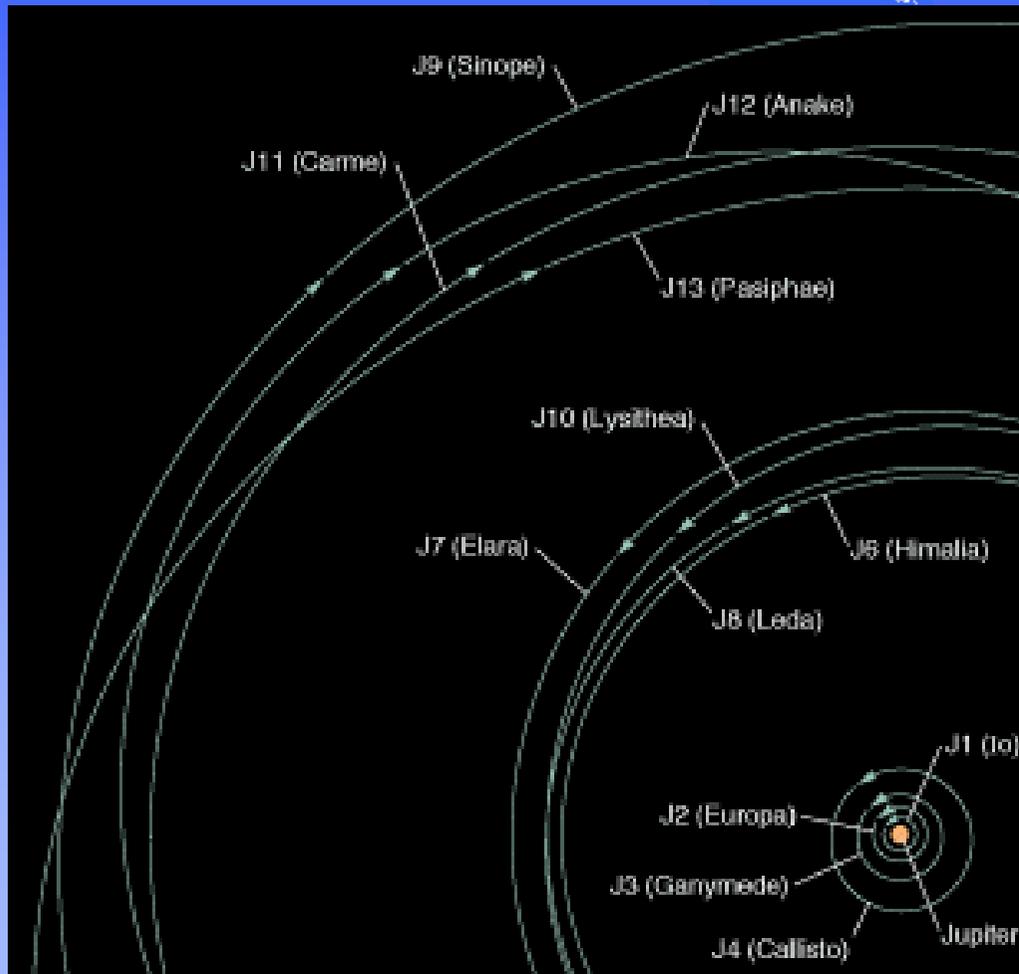
★ telescope for Io, Europa, Ganymede & Callisto  
| | | |  
*I Eat Green Carrots*

★ inner two moons are about the size of the Earth's moon

★ outer two moons are even larger, about size of Mercury

# 12 of Jupiter's Moons

☀ 3 of 4 even closer moons discovered as recently as 1979, along with a ring system



Courtesy: K & K

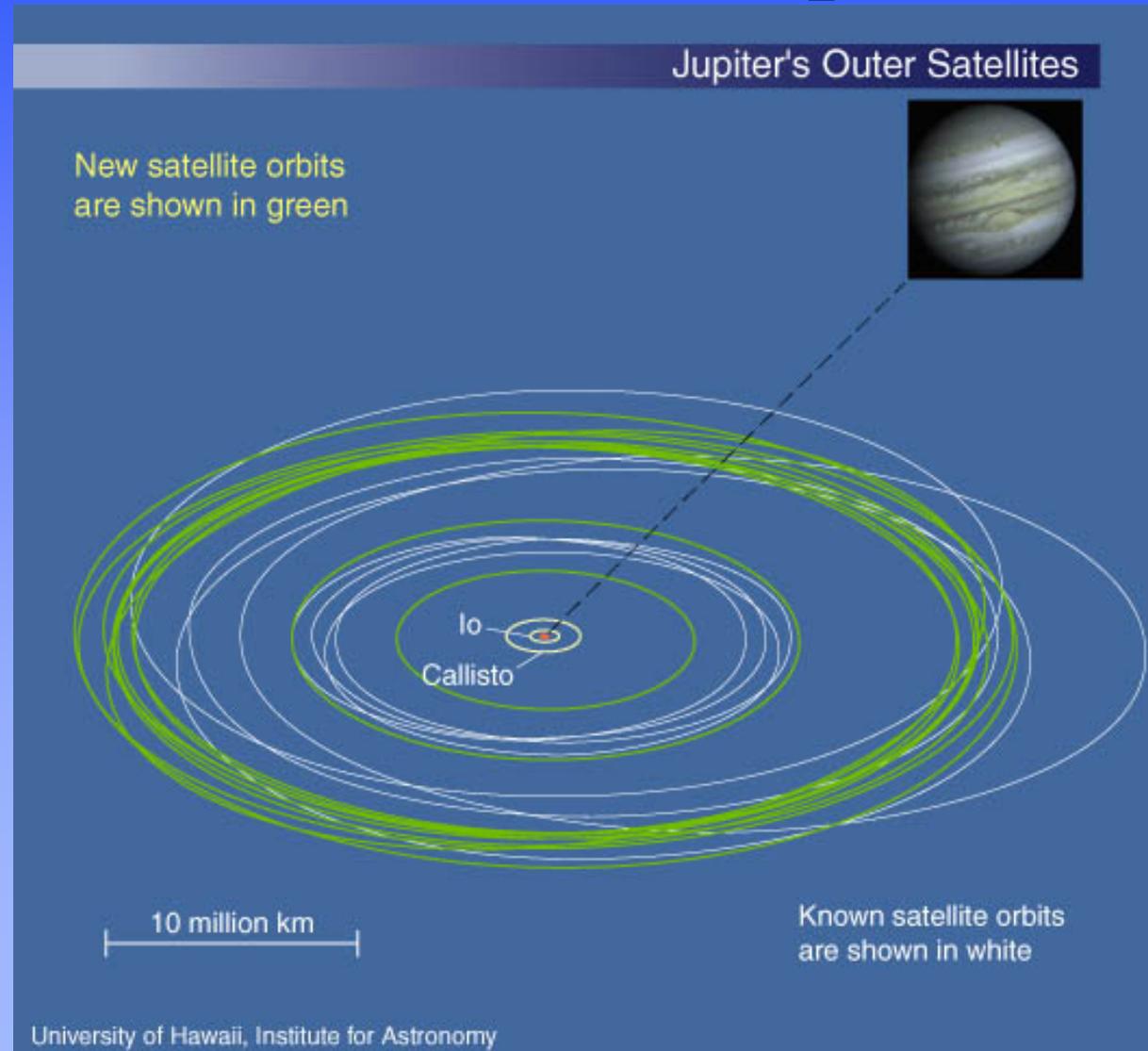
# Yet more Moons of Jupiter

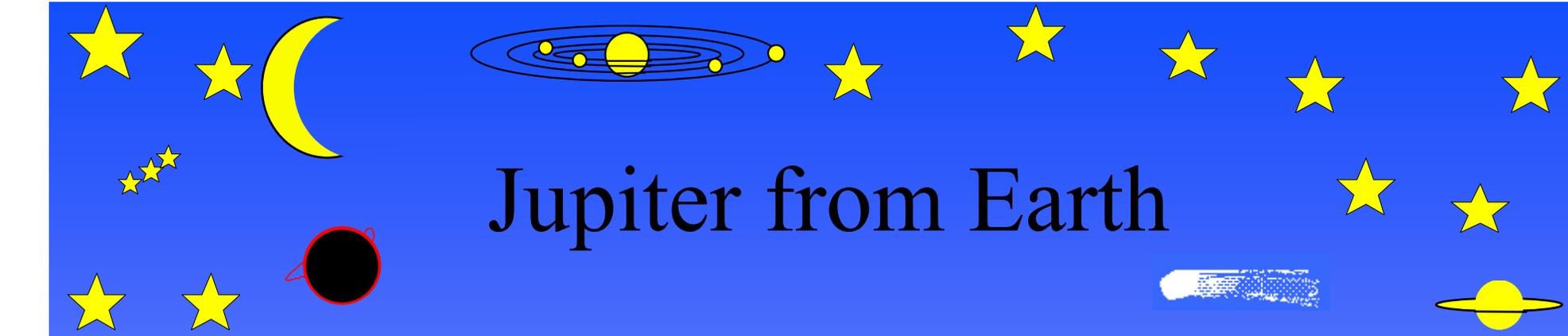
☀ 11 further moons announced in 2001

★ all small (~5 km)

★ most are retrograde

☀ More moons in 2003 (total of 50+ so far)





# Jupiter from Earth

☀ Orbital period 11.86 yr; av. solar dist. (from Kepler's 3rd law) 5.2 AU; day lasts 9.84 hr

🌟 diam. (from angular size and distance) 142,800 km; mass (from 3rd law)  $318 \times M_{\text{earth}}$

☀ Large mass perturbs interplanetary debris

🌟 Jupiter is the Hoover of the solar system

☀ 6% out-of-round; differential rotation; banded clouds; great red spot

☀ Hubble telescope follows planetary weather

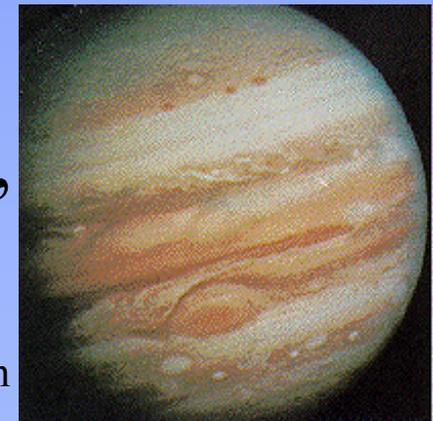
# Jupiter from Space

☀️ *Voyager 1 & 2* produced astonishing pictures in 1979, and made many measurements

✪ *Galileo* probe has improved our knowledge

☀️ Red spot is a stable, storm system rotating counterclockwise about once every 6 days

☀️ Magnetic field ( $20,000 \times$  Earth's) with poles off-set from rotation poles, as on Earth. Influence extends  $15 \times 10^6$  km from planet



animation



# Jupiter's Bands

- ☀ Bands represent a series of equator → pole vertical circulation cells, like the Earth's global weather system
- ☀ Convection currents rise from the equator through Jupiter's troposphere, clouds condensing out when conditions are right
- ☀ In the descending regions, the atmosphere warms and the high  $\text{NH}_3$  cloud evaporates
  - ★ we see lower level clouds here



# Jupiter's Atmosphere

- ☀ Abundant elements present mostly in fully hydrogenated form:  $\text{CH}_4$ ,  $\text{NH}_3$ ,  $\text{H}_2\text{O}$ ,  $\text{PH}_3$ , etc.
- ☀ Outer atmosphere contains stratospheric haze
  - ★ condensed products of UV dissociation of  $\text{CH}_4$
  - ★ lower haze could be  $\text{N}_2\text{H}_4$  (hydrazine) or  $\text{P}_2\text{H}_4$
- ☀ Upper white clouds  $\text{NH}_3$  (~750 mbar)
- ☀ Lower cloud  $\text{NH}_4\text{SH}$  (ammonium hydrosulphide), (~1.5 bar) probably with colouring from S and P
  - ★  $\text{H}_2\text{O}$  cloud (~5 bar) visible through filters

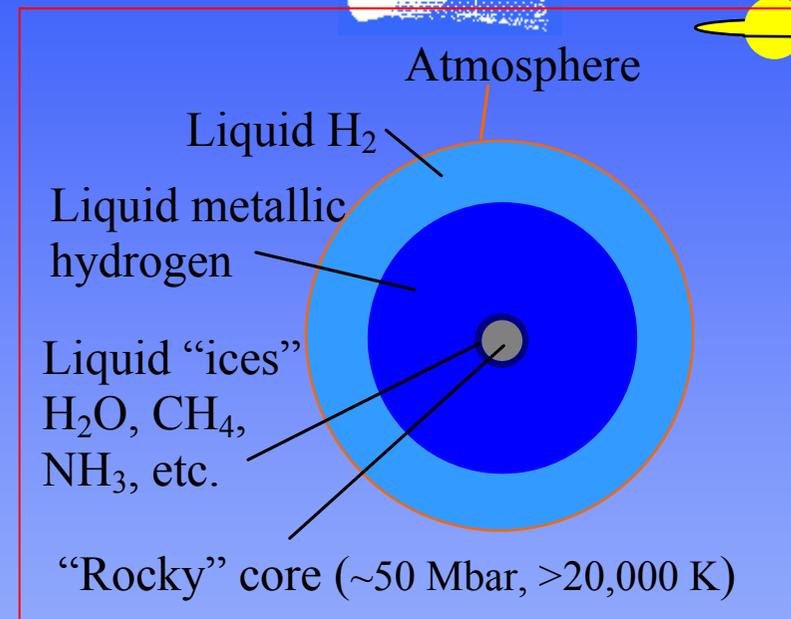
# Jupiter's Structure: the Liquid Giant

 The atmosphere consists mostly of  $H_2$ , in which the clouds float

 it is immensely active, both horizontally and vertically, and inhomogeneous

 Jupiter's activity is driven by the interior heat

 Atmosphere merges into  $\sim 20,000$  km of liquid  $H_2$ , then 40,000 km of metallic liquid hydrogen, then liquid "ices" and, finally, core  $<10,000$  km radius





# Jupiter's Own Energy

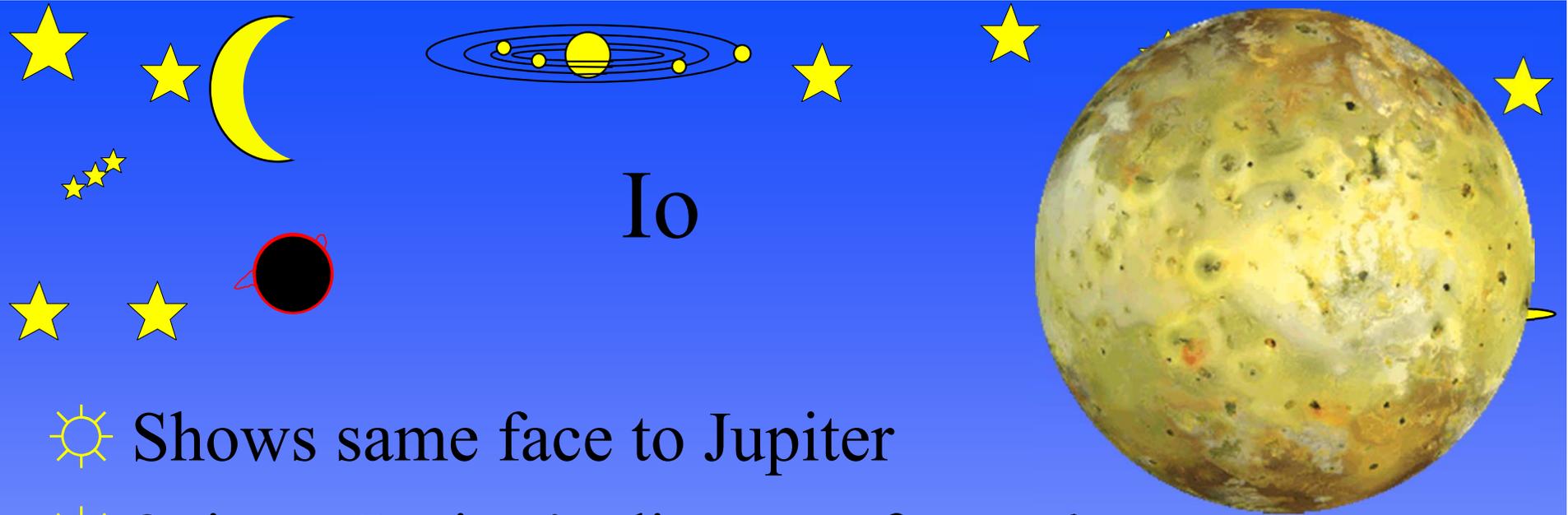
☀ Jupiter emits about twice energy it gets from the Sun

☀ Discarded ideas for source of energy:

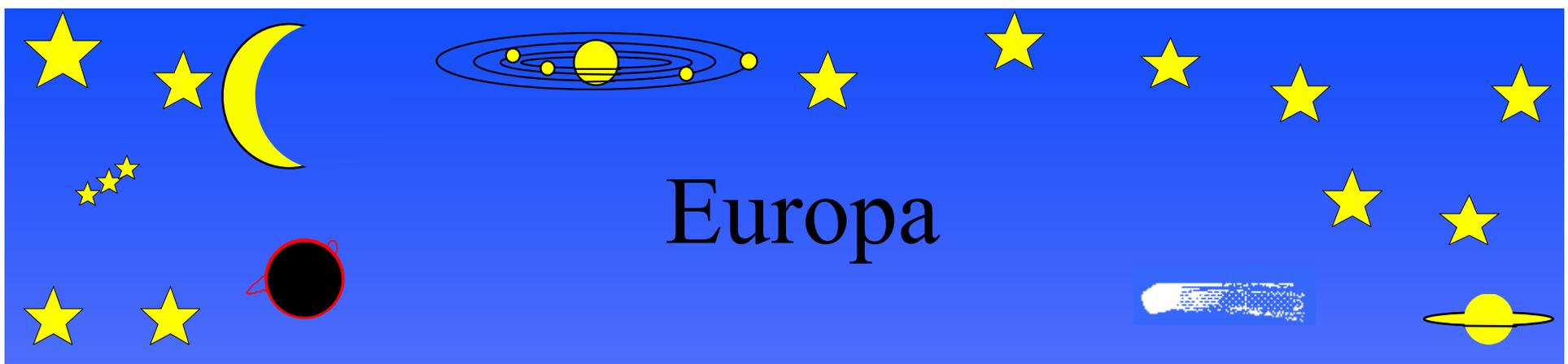
- ★ nuclear fusion in core:- temperature and pressure aren't high enough

- ★ fuelled by gravitational collapse:- like the Sun, Jupiter is too old for this mechanism to still work

☀ Current thinking: residual energy of formation still leaking out

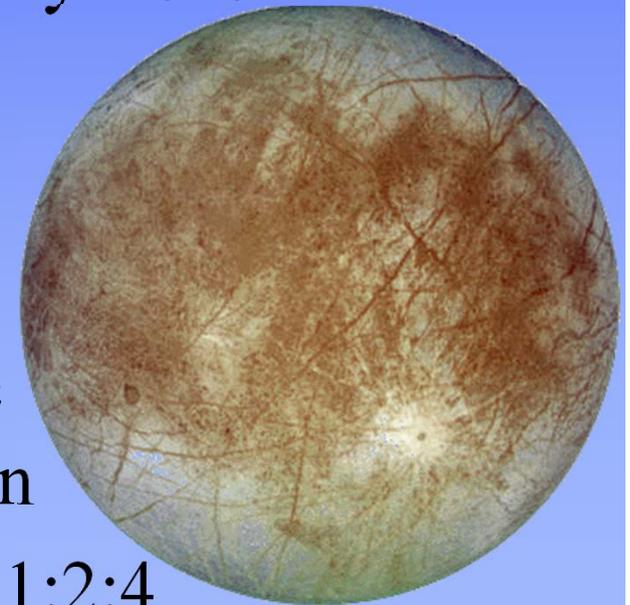


- ☀ Shows same face to Jupiter
- ☀ 3 times Jupiter's diameter from planet
- ☀ Dry - volcanic, with lavas much hotter than on Earth - sulphurous
- ☀ Too small to have retained primordial heat
- ☀ Heated by strong tidal deformation that varies around Io's elliptical orbit
- ☀ Surrounded by a halo of Na (sodium) atoms



# Europa

- ☀ Looks like a cracked billiard ball from a distance
- ☀ Mainly rock, covered by an ocean ~100 km deep; more water than all oceans on Earth, partly frozen
- ☀ Tidal flexure acts on a thin ice cap
- ☀ Meteoric matter is slowly taken below surface by water breaking through ice
- ☀ Ingredients for life: water, heat, organic compounds all present → NASA mission
- ☀ Periods Io, Europa, Ganymede in ratio 1:2:4

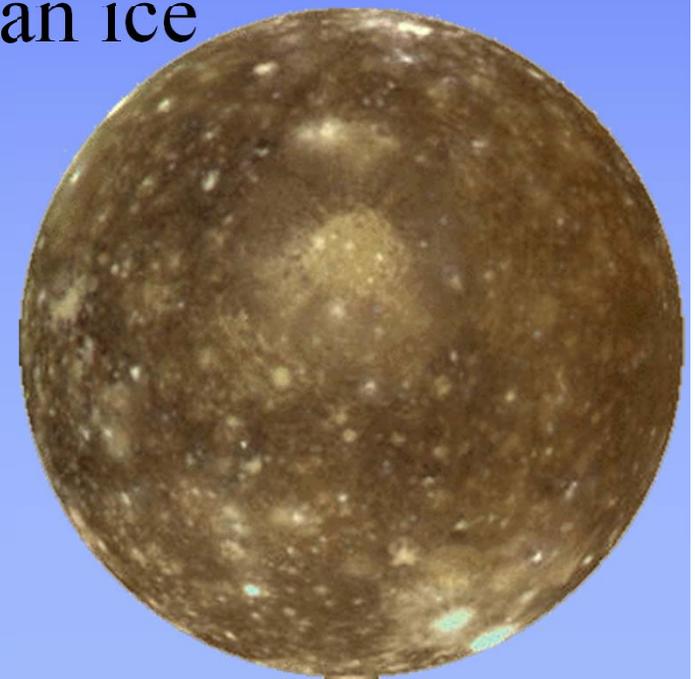




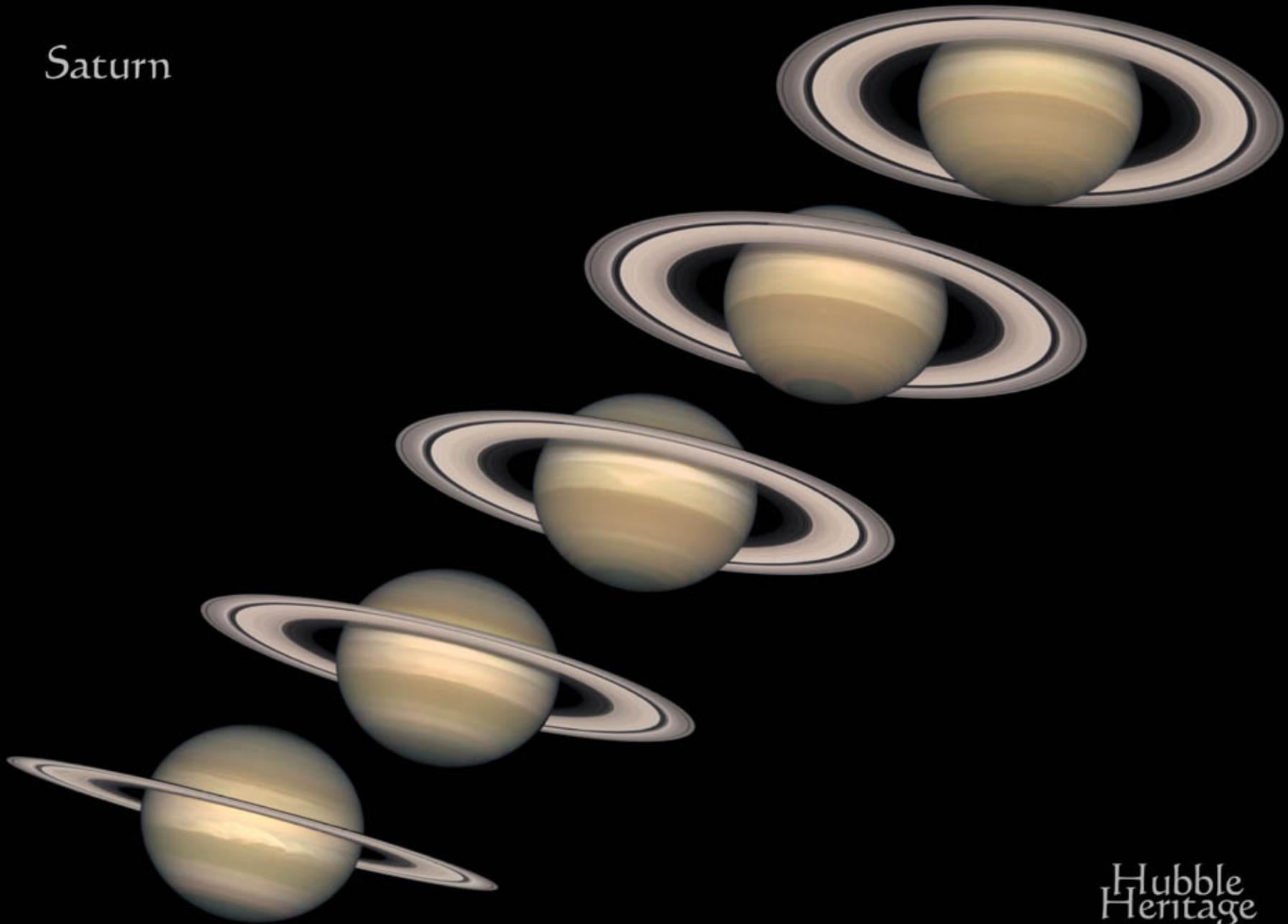


# Callisto

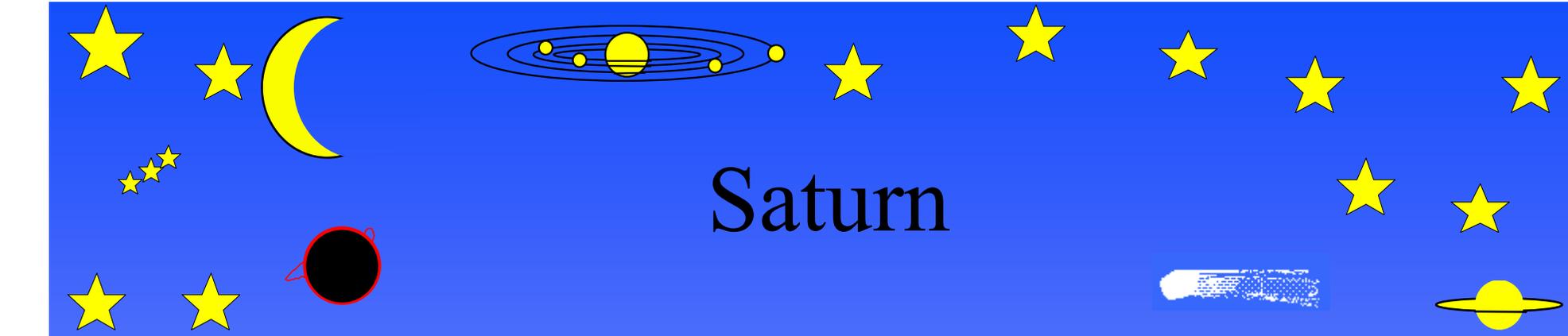
- ☀ Average densities of the Galilean satellites decrease with distance from Jupiter. This is taken as evidence that they are composed of increasing amounts of ice
- ☀ White spots considered to be clean ice exposed by meteoric impact
- ☀ Few craters smaller than 1 km
- ☀ Shows the largest impact crater in the solar system (Valhalla)



# Saturn

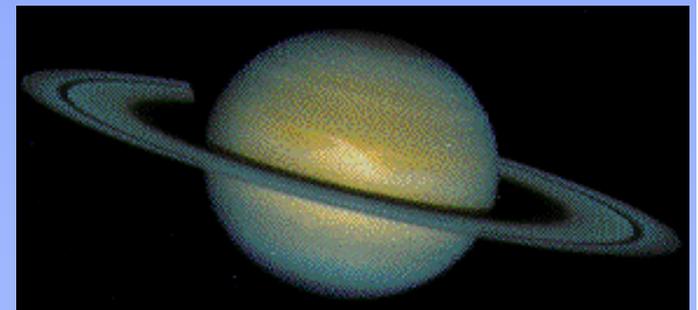


Hubble  
Heritage



# Saturn

- ☀ Planet itself (120,000 km diameter) like a slightly smaller, blander version of Jupiter
- ☀ Banded cloud system of whitish clouds
- ☀ Intermittent giant storm spot
- ☀ General structure and composition similar to Jupiter
- ☀ Magnetic field  $\frac{1}{20}$  th Jupiter's
  - ☀ Aurora on Saturn has been
- ☀ Some internal heat



HST 1994

# Saturn's Appearance

(animated)

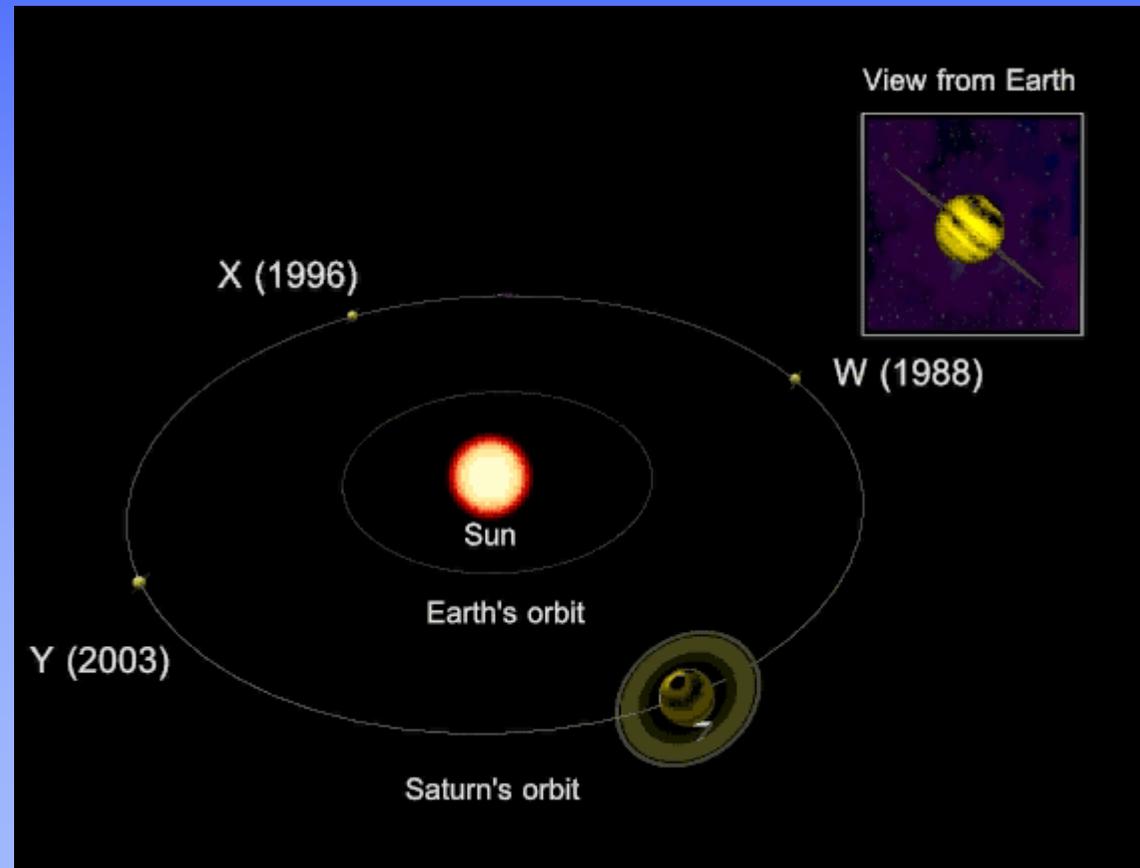
Ring inclination

$26.7^\circ$

Rings edge-on:

4<sup>th</sup> Sept. 2009

Courtesy: K & K





# Saturn's Rings

- ☀ James Clerk Maxwell, while at Aberdeen, showed they must be a myriad of small chunks
- ☀ A few rings visible from Earth, extending from 1.2 diameters of Saturn to 2.3 diameters
- ☀ *Voyager* probe showed highly complex ring structure, with thickness only ~100 m
- ☀ Notable dark band called the 'Cassini division'
  - 🌟 The Cassini-Huygens probe now circulating close to Saturn has returned stunning pictures and lots of data

# Cassini–Huygens Mission

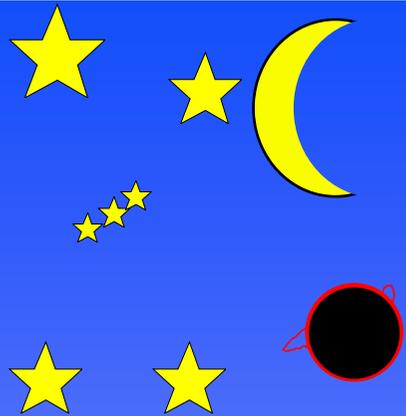
☀ Launched in 1997

- ★ last of the very large, conspicuously multi-purpose probes
- ★ several ‘gravity assists’ to get to Saturn in a reasonable time (VVEJ)

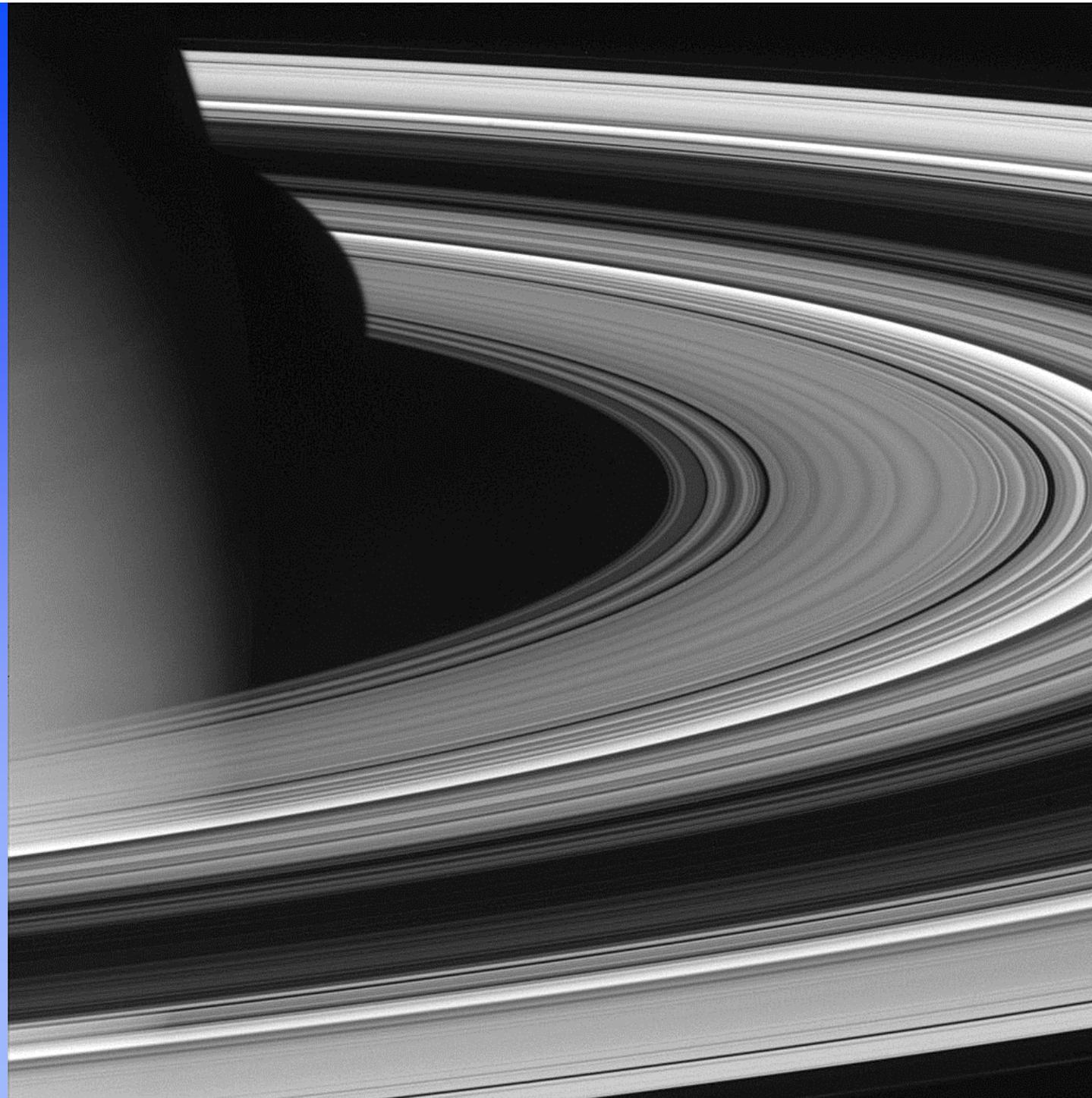
☀ 3D structure of Saturn’s rings;  
composition and history of moons;  
dynamics of Saturn’s clouds;  
variations of Saturn’s magnetosphere

☀ Huygens probe has been dropped onto Titan to examine atmospheric composition and nature of surface



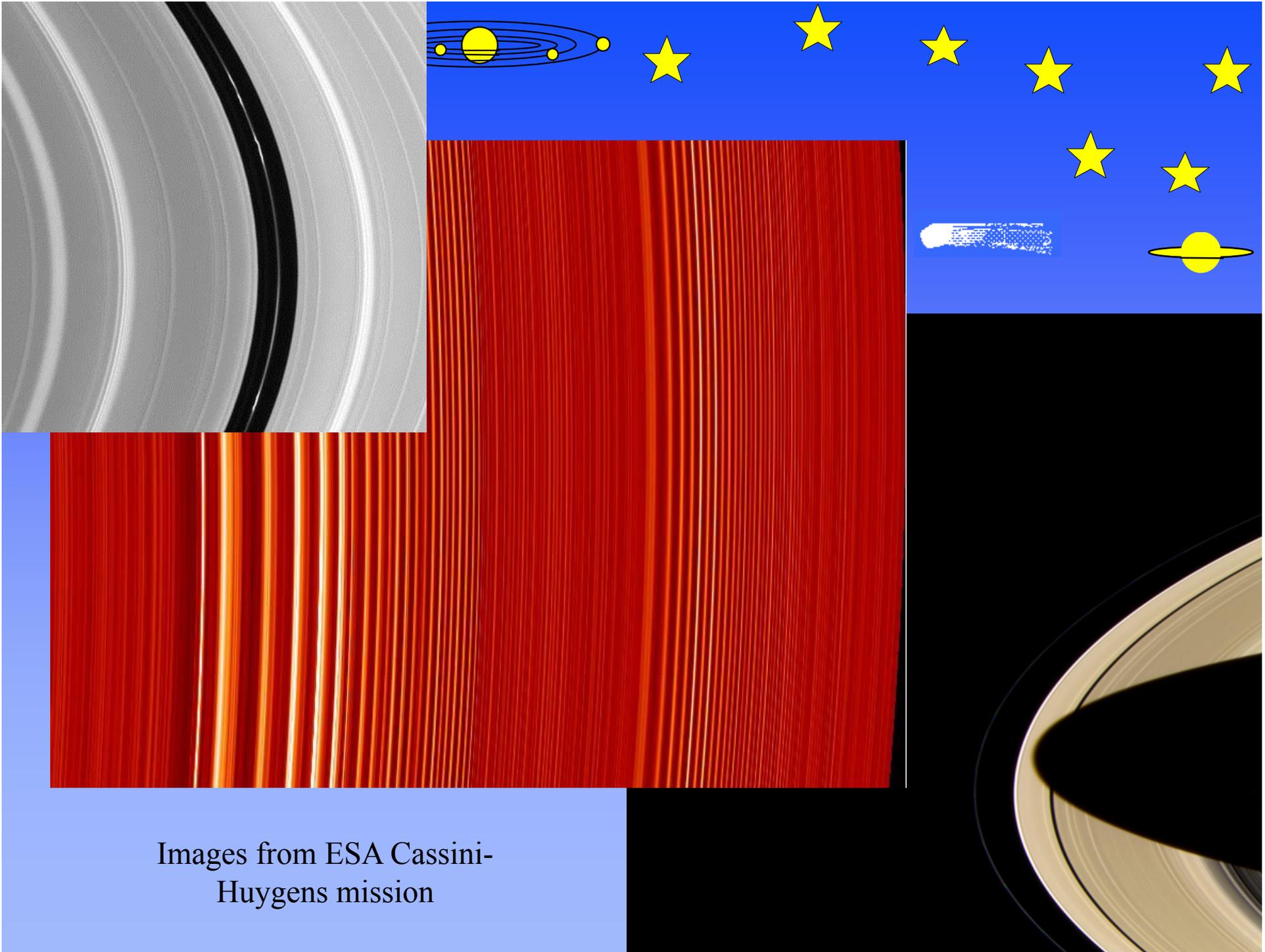


Saturn's rings seen  
by the approaching  
Cassini-Huygens  
mission

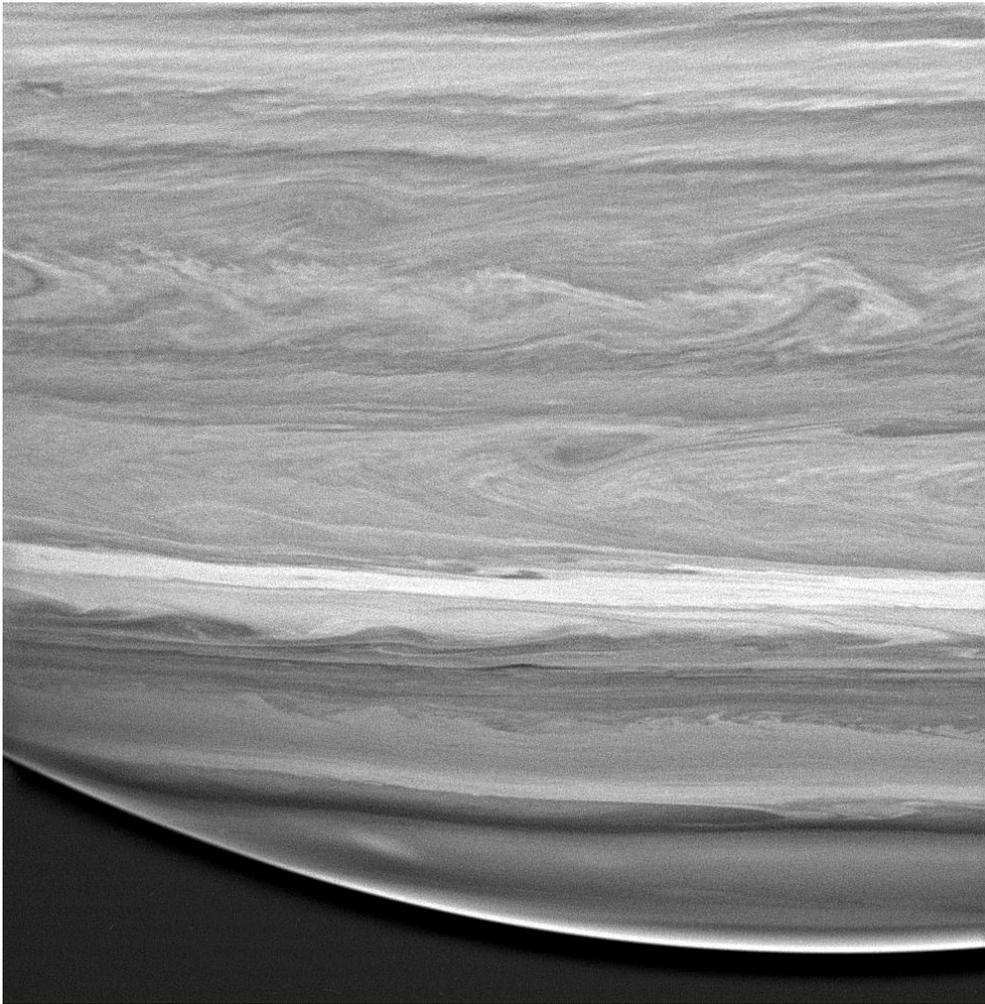


# Rings in natural colour

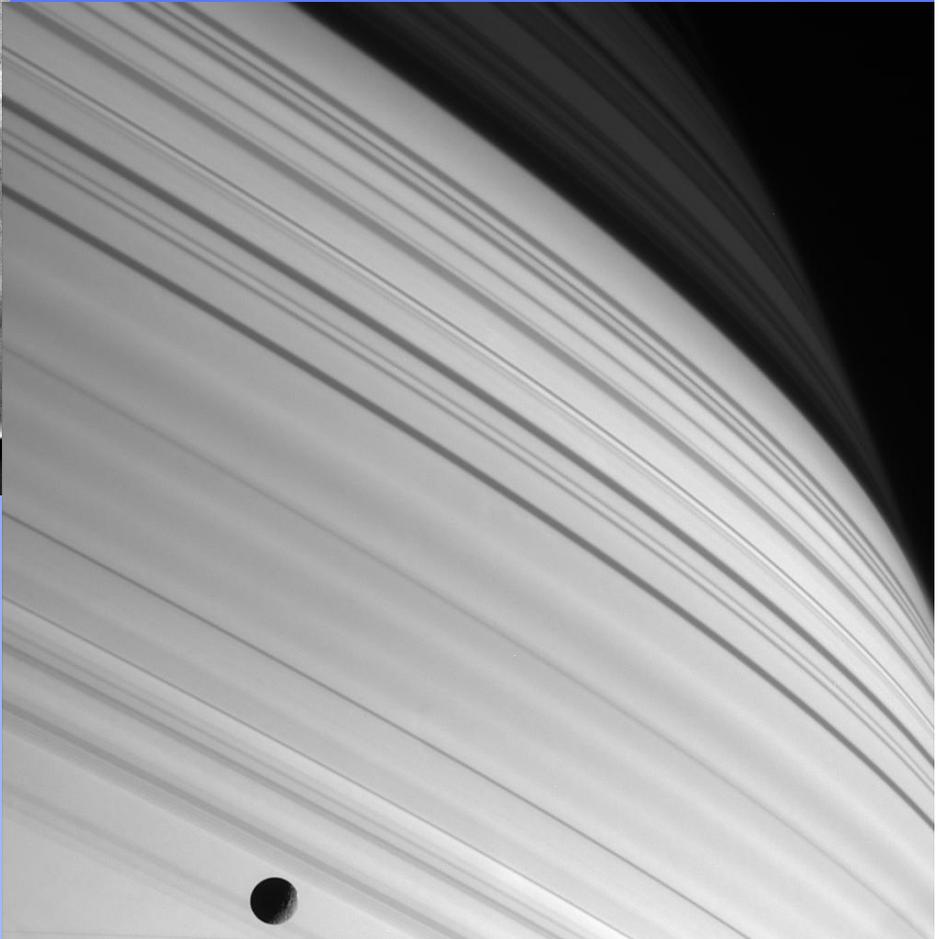
Courtesy: <http://antwrp.gsfc.nasa.gov/apod/ap040723.html>



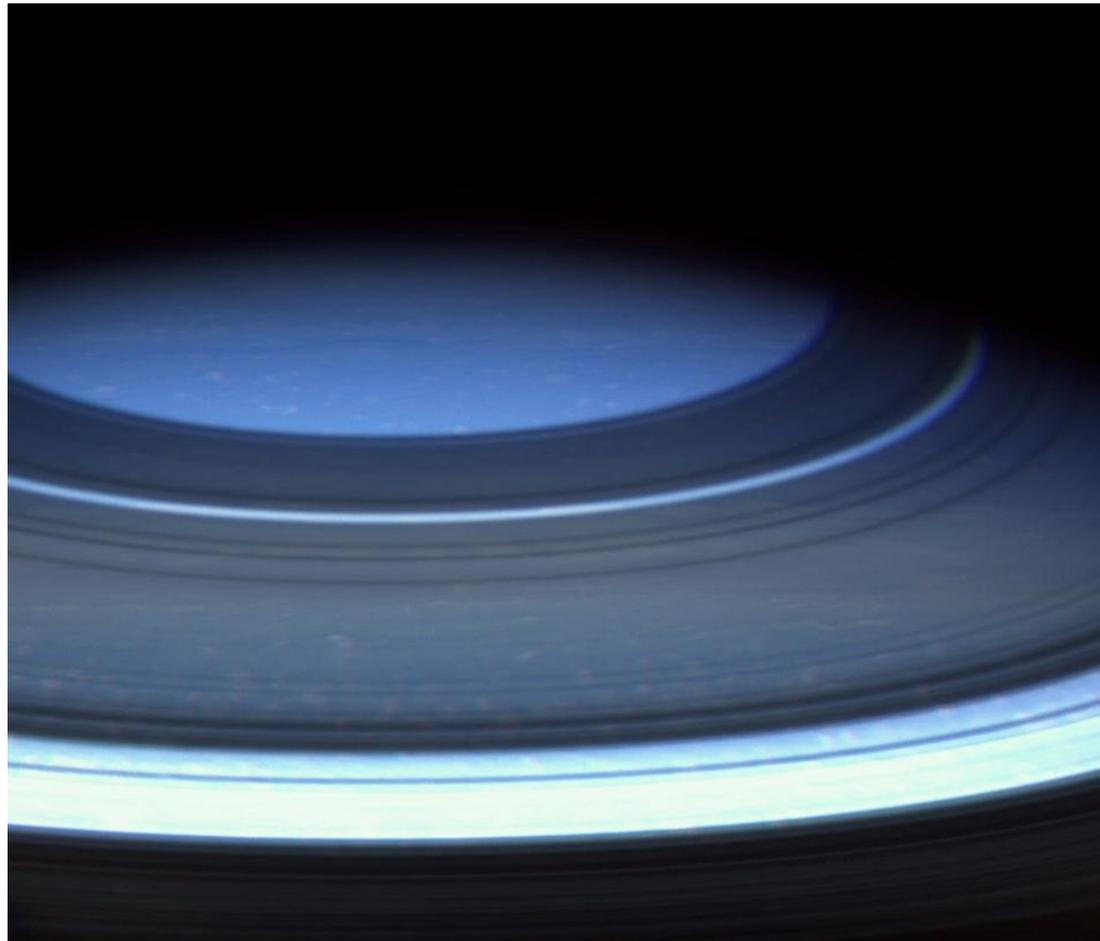
Images from ESA Cassini-Huygens mission



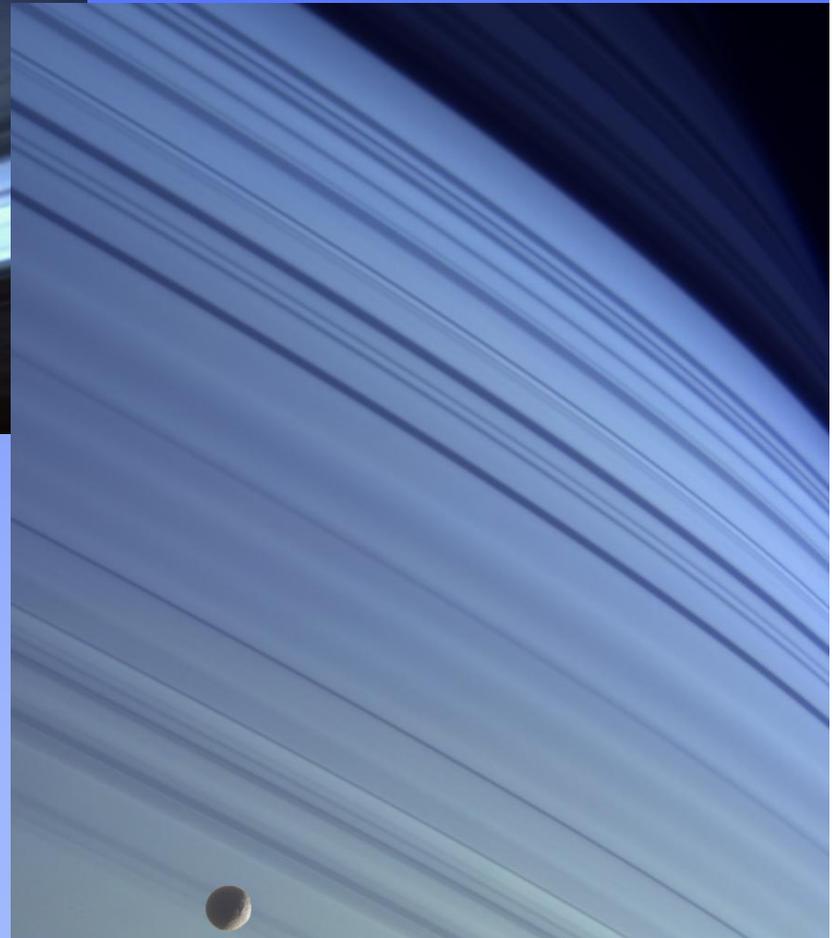
Swirling clouds

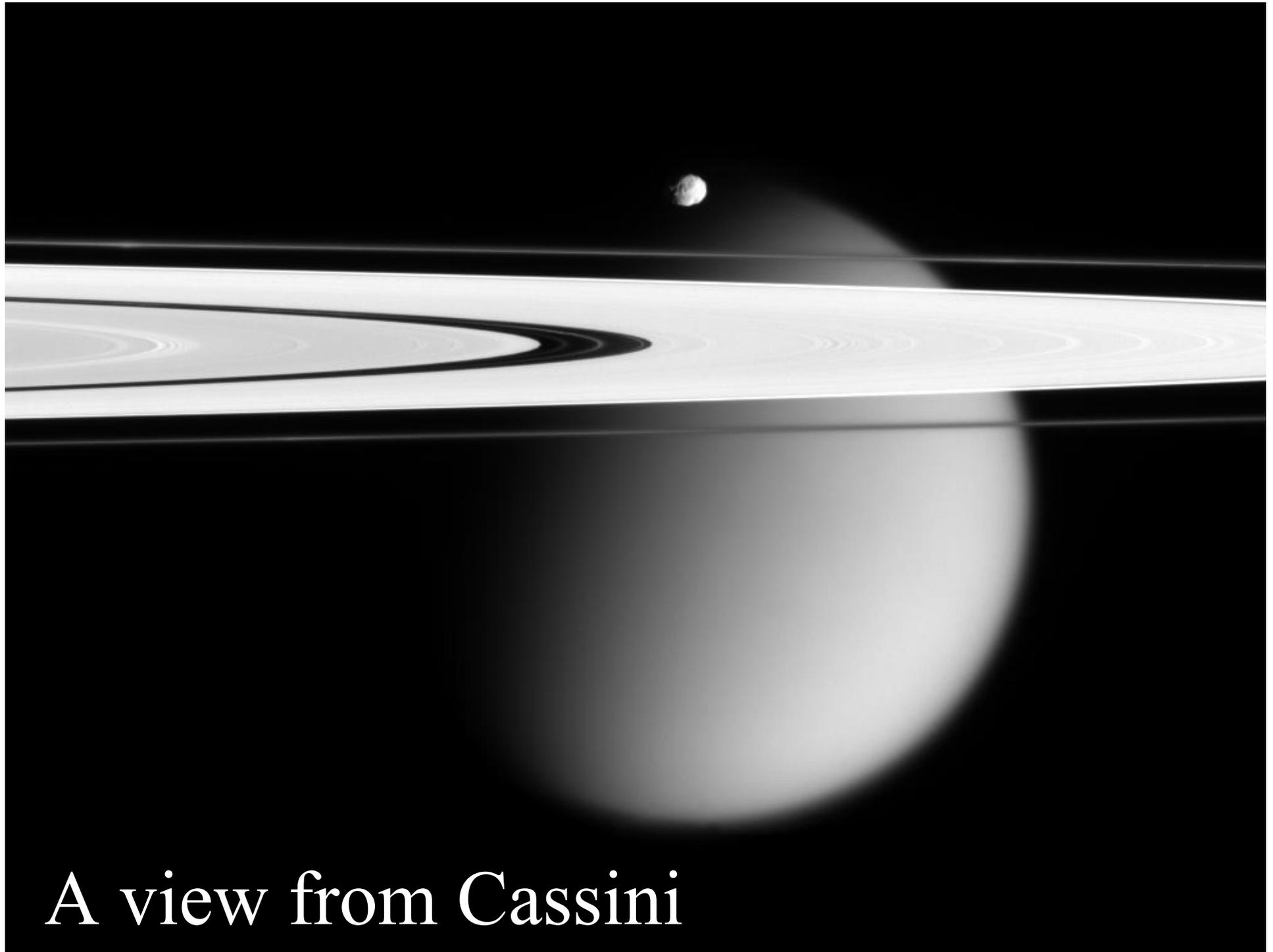


Shadow on the  
cloud tops



Cassini/Huygens pictures of the Northern hemisphere in natural colour in Dec 2004



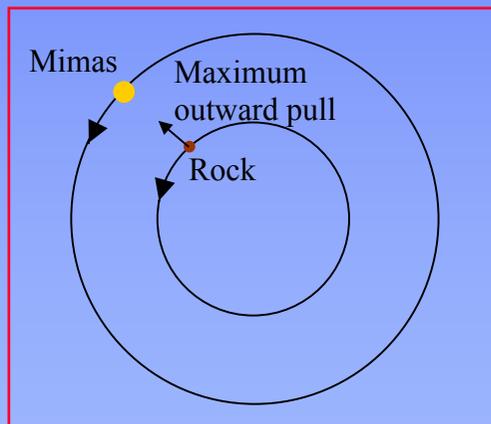


*A view from Cassini*

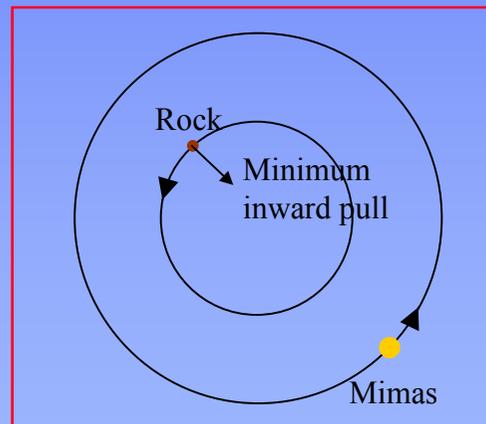
# Orbital resonance

A rock in the Cassini division has half the period of Mimas

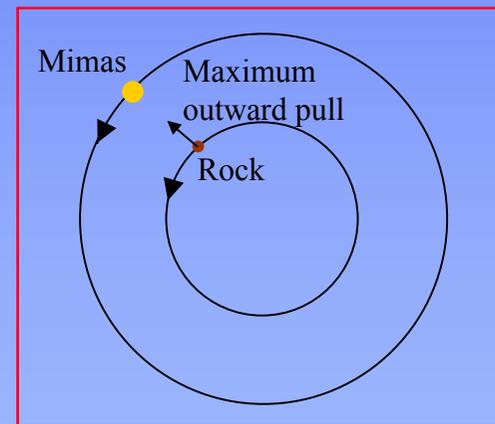
☼ outward pull cumulates in the same direction



Maximum pull  
on rock outward



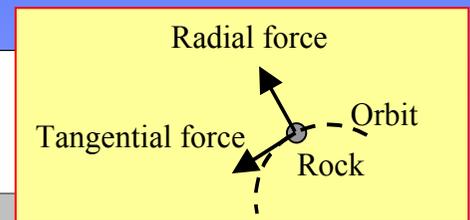
One period  
of rock later



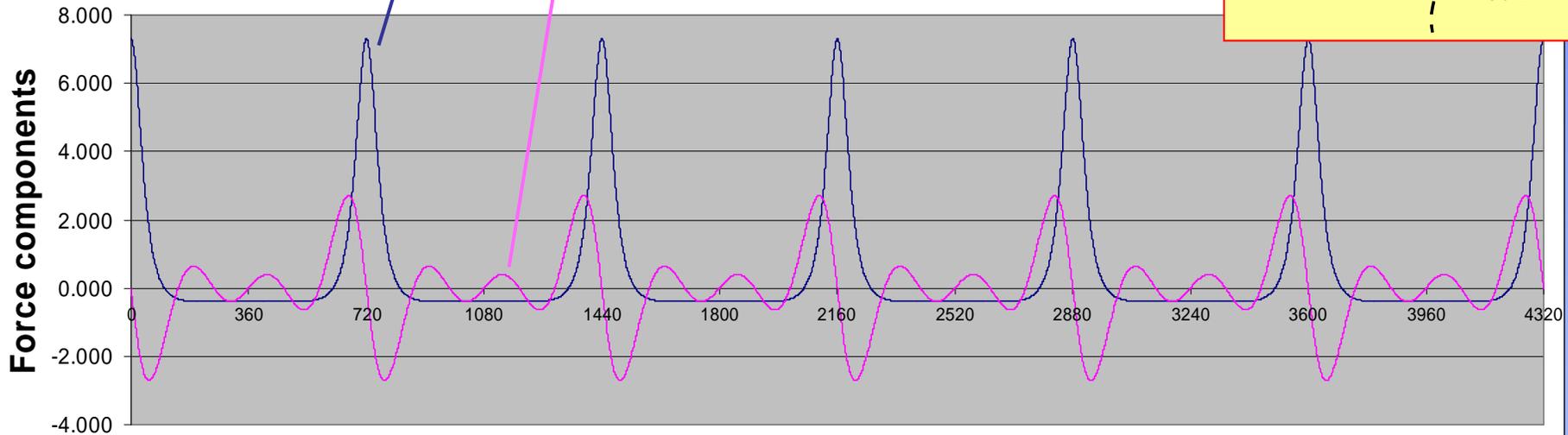
2 periods of  
rock later

# Forces on a rock

☀ Rock receives a repeated regular outward pull *in the same direction* every 2 orbits



Radial and Tangential forces for 2:1 orbital resonance



Angular position of rock

Graph by Sarah-Emily Mutch

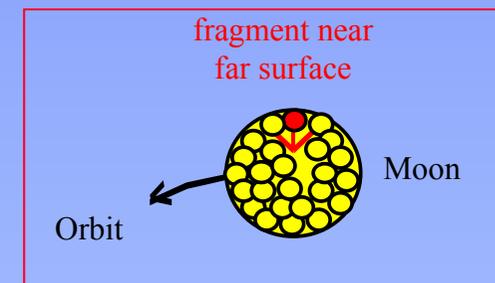
# Roche Limit

☀ Why hasn't Saturn's ring material coalesced into a moon?

☀ Rings are within the *Roche limit*

☀ A big body orbiting a planet needs strength to orbit at one speed

- ☀ gravity provides that strength
- ☀ consider a body of little intrinsic strength like a powdery snowball
- ☀ look at a fragment of it furthest from the planet



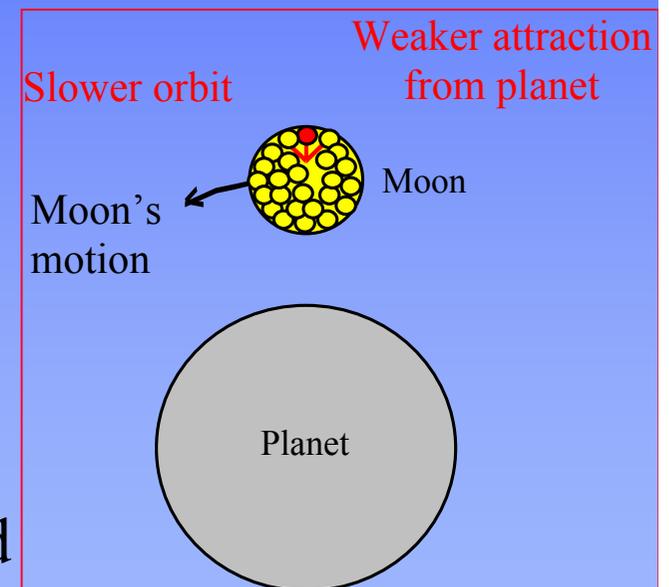
# The Roche limit effect

☀ Fragment ● has more acceleration than supplied by planet since it is travelling faster than it would do on its own

☀ Acceleration of ● as part of moon = acceleration of ● supplied by planet + gravitational acceleration of ● by moon

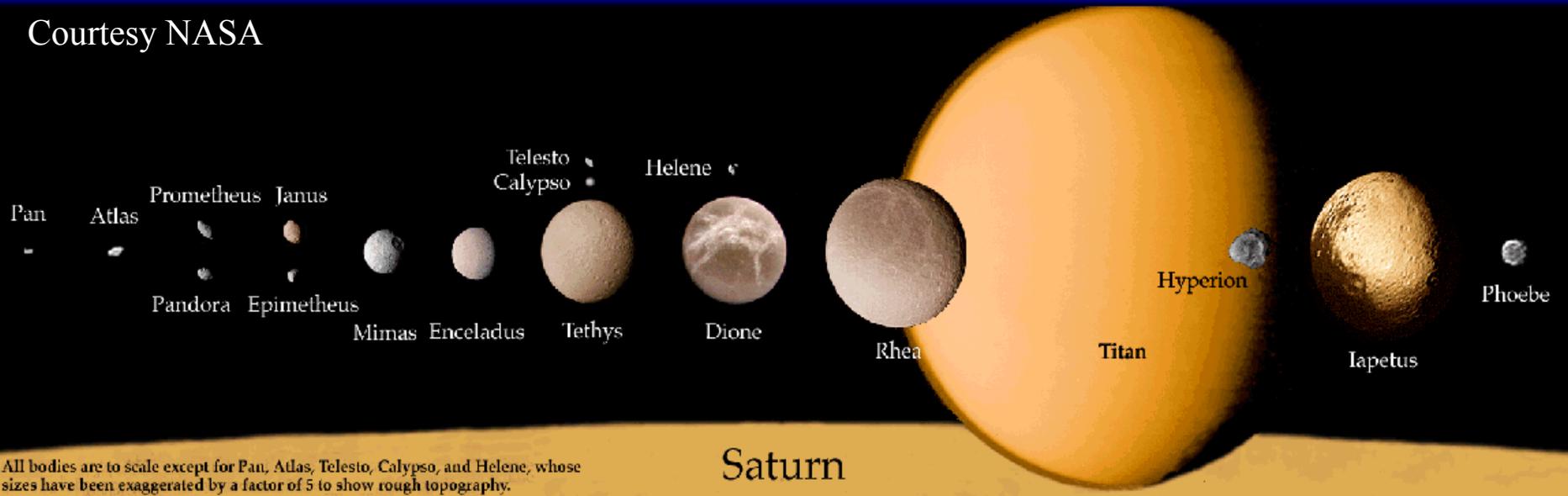
☀ the closer the moon is to the planet, the larger the gravitational component needed

☀ The *Roche limit* is the closest distance a moon can be to the planet and still hold together under its own gravity

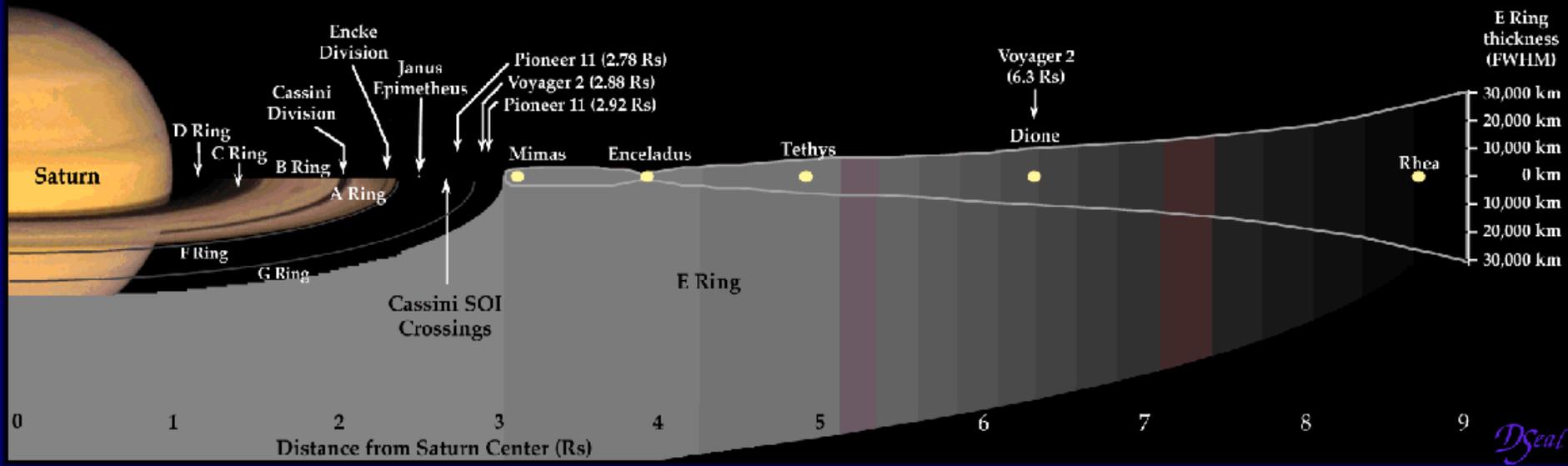


# Saturn's Satellites and Ring Structure

Courtesy NASA



Not shown:	
Pan	2.22 Rs
Atlas	2.28 Rs
Prometheus	2.31 Rs
Pandora	2.35 Rs
Titan	20.3 Rs
Hyperion	24.6 Rs
Iapetus	59.1 Rs
Phoebe	214.9 Rs



This graphic is available in color if required.

*DSeal*



# Saturn's Moons

☀ Saturn has at least 20 moons with dimensions larger than 20 km. Many have surfaces of ice

☀ **Titan** is the second largest moon in the solar system; the largest almost unexplored 'world'

☀ Surface temp  $-180^{\circ}\text{C}$ , atmosphere 99%  $\text{N}_2$ , 1%  $\text{CH}_4$  (methane)

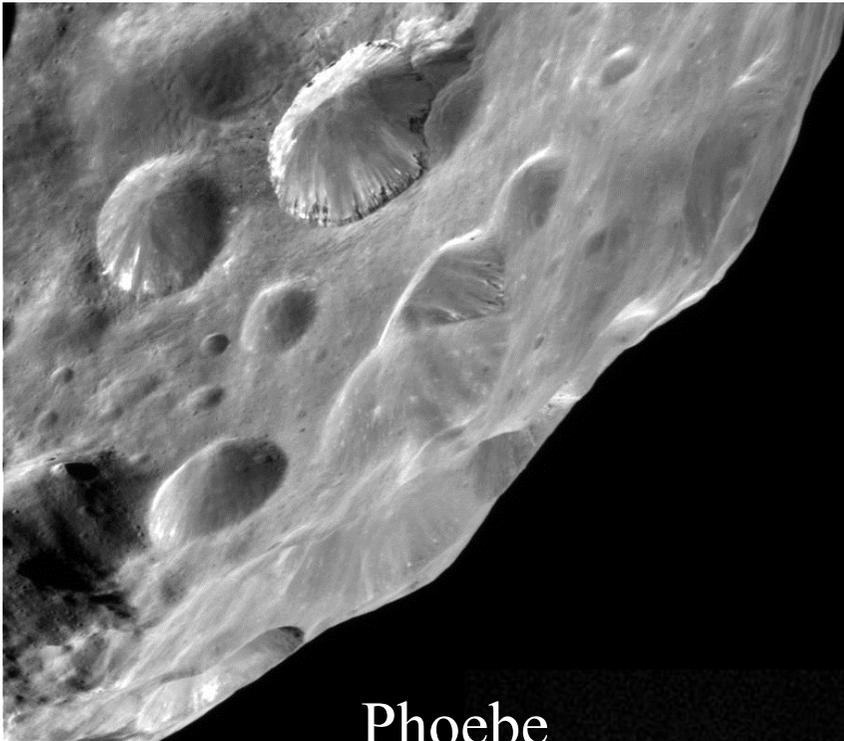
☀ Hazy atmosphere. Some evidence that methane is converted into an organic soup by sunlight. Is there life on Titan? Huygens probe landed in 2005

# Moons

Rhea



Phoebe



Courtesy  
ESA

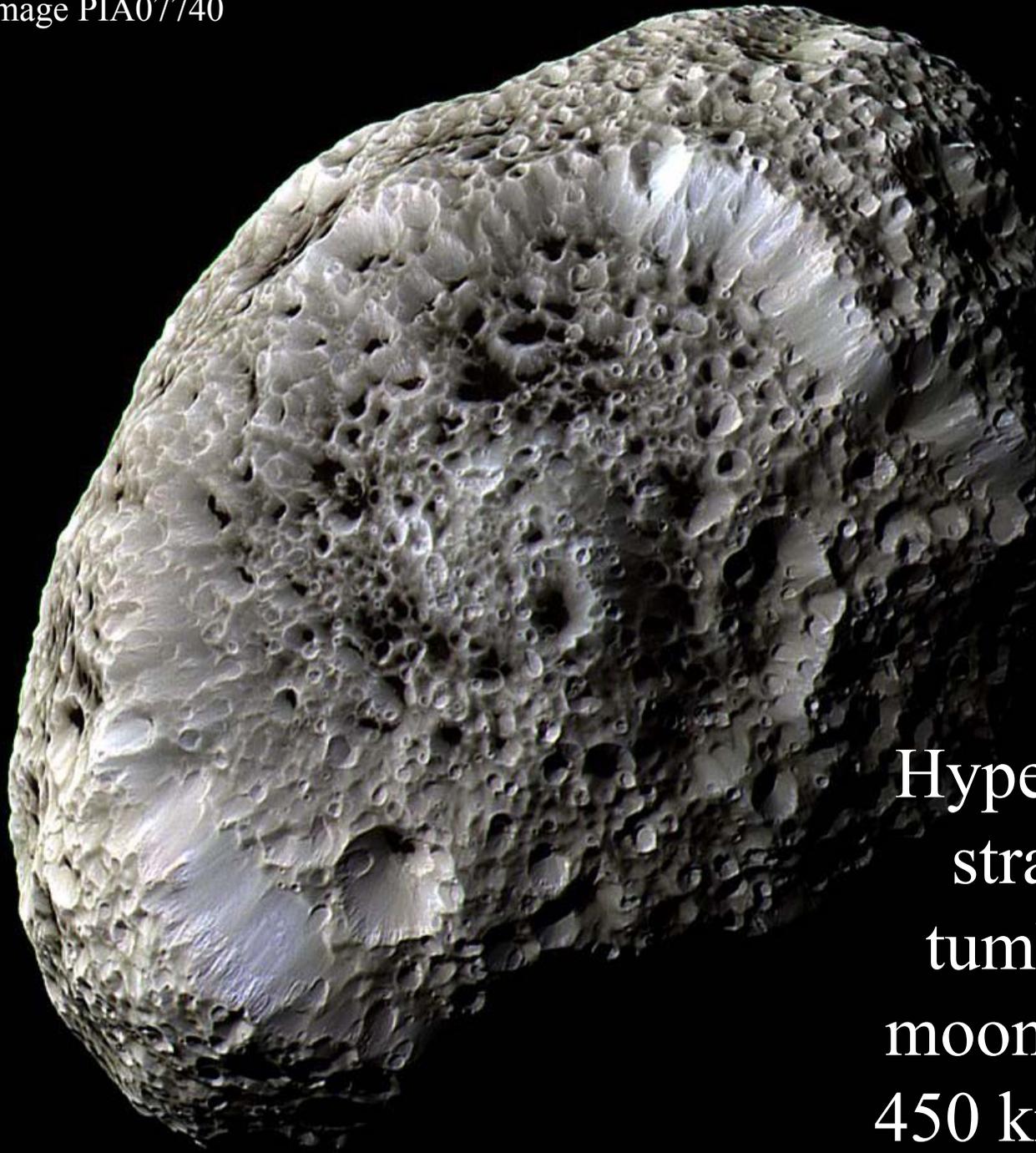
Mimas



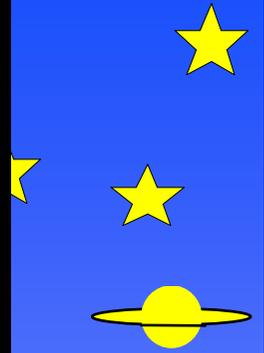
Tethys



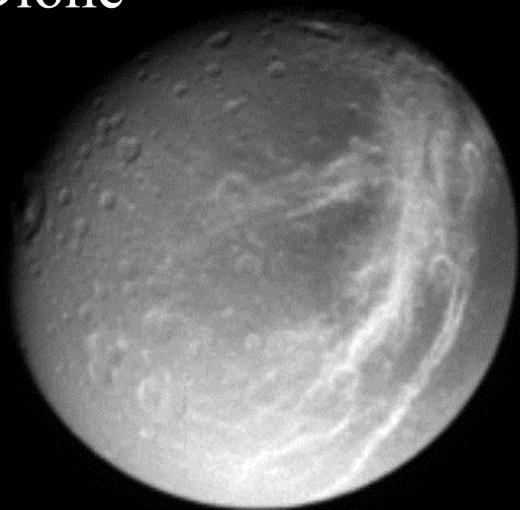
NASA image PIA07740



Hyperion a  
strange  
tumbling  
moon about  
450 km long



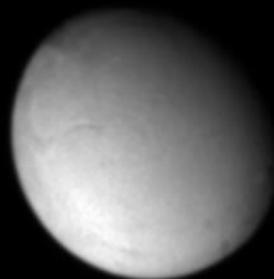
Dione



Cassini/Huygens Moons

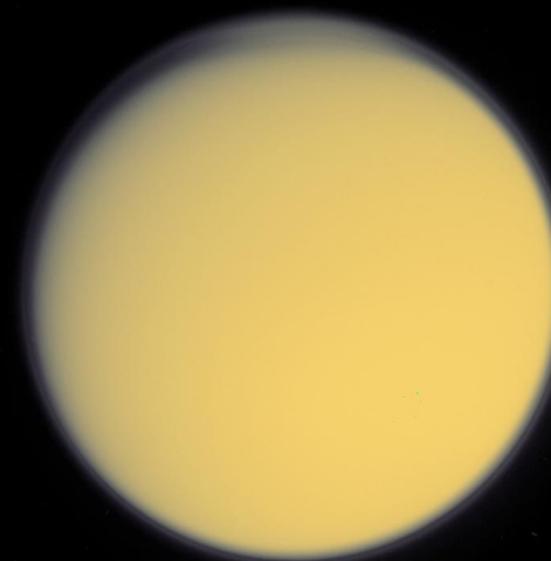


Enceladus



Courtesy ESA

Titan



Enceladus —  
a moon  
with life?



NASA image PIA06254



[http://photojournal.jpl.nasa.gov/jpegMod/PIA08384\\_modest.jpg](http://photojournal.jpl.nasa.gov/jpegMod/PIA08384_modest.jpg)

↑ The black and white moon

A blue rectangular panel with yellow stars, a white comet, and a yellow planet with rings.

Iapetus

Equatorial bulge,  
courtesy: NASA N00091828





# Titan on one page

 Second largest moon in solar system

-  atmosphere: 98% N<sub>2</sub>; 2% CH<sub>4</sub> (methane); press 1.5 bar
-  many derivative chemicals:
  -  acetylene (C<sub>2</sub>H<sub>2</sub>), hydrogen cyanide (HCN), benzene (C<sub>6</sub>H<sub>6</sub>), etc.
-  visibility obscured by an orange organic chemical haze
-  multi-layered layered atmosphere ~ 300 km thick
-  methane clouds and rain
-  rotation period 15.9 days; atmosphere circulates faster
-  surface temp 95 K
-  surface features seen in IR or by radar, hard to interpret

# Huygens ahoy

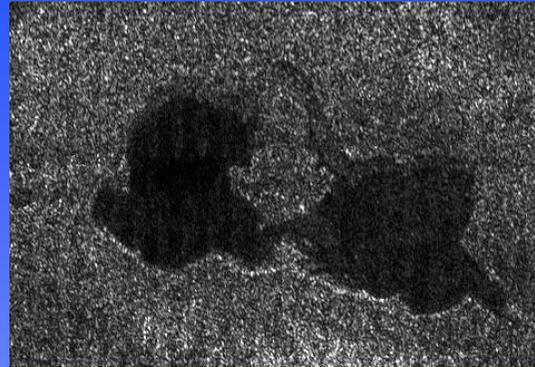


NASA/ESA image PIA07800

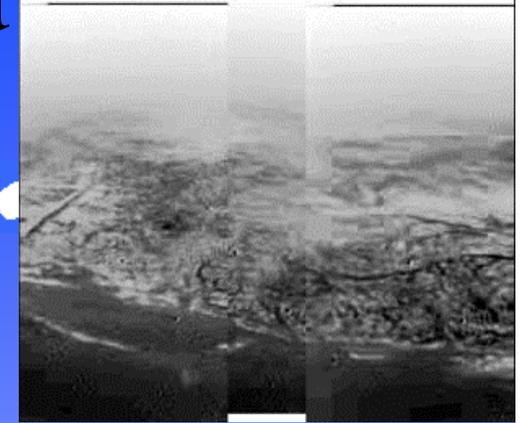


On the ground

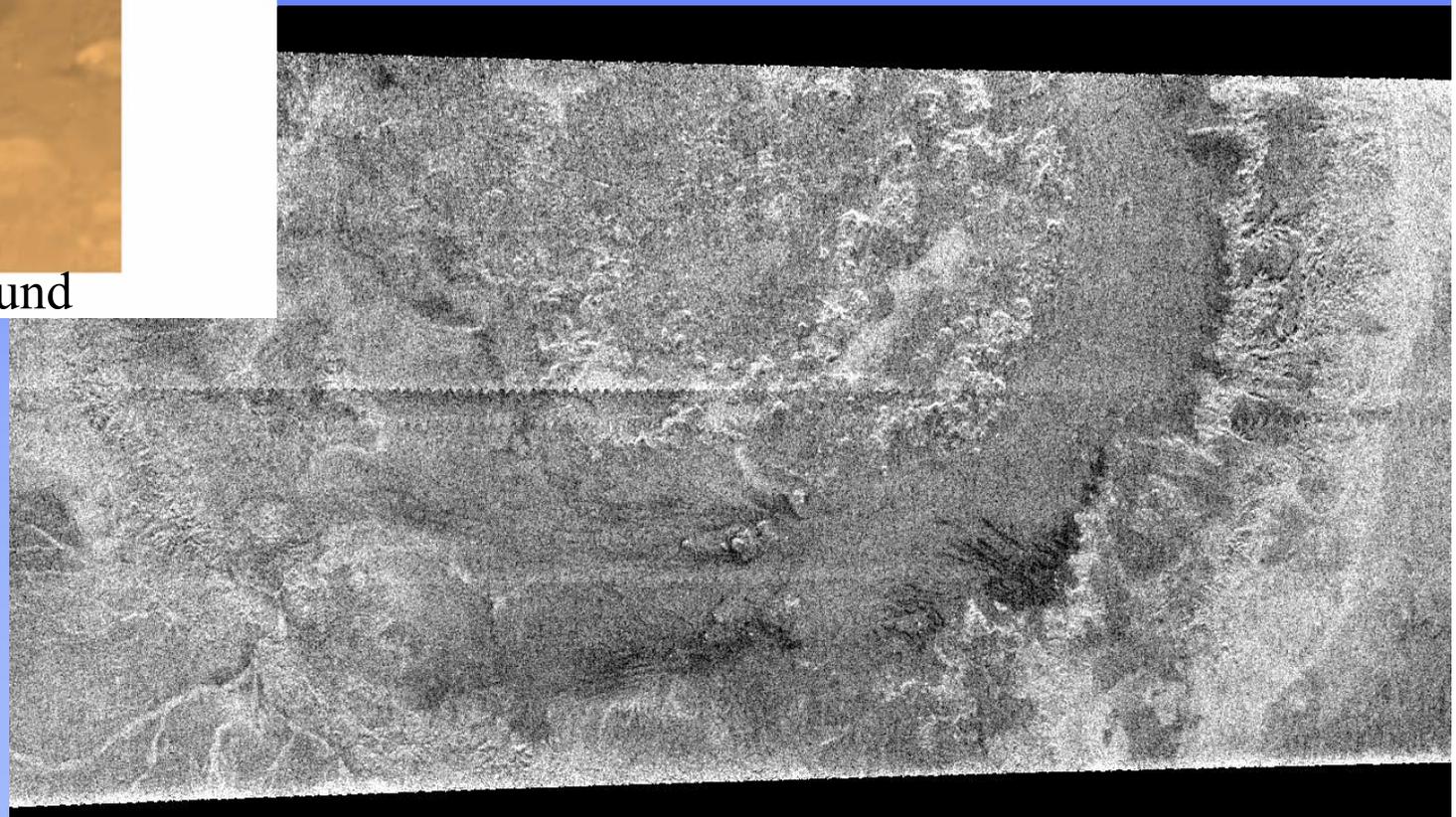
# Titan revealed



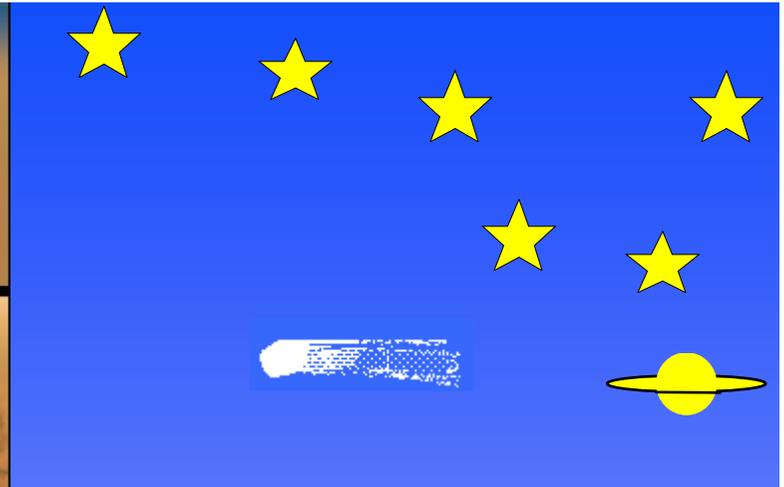
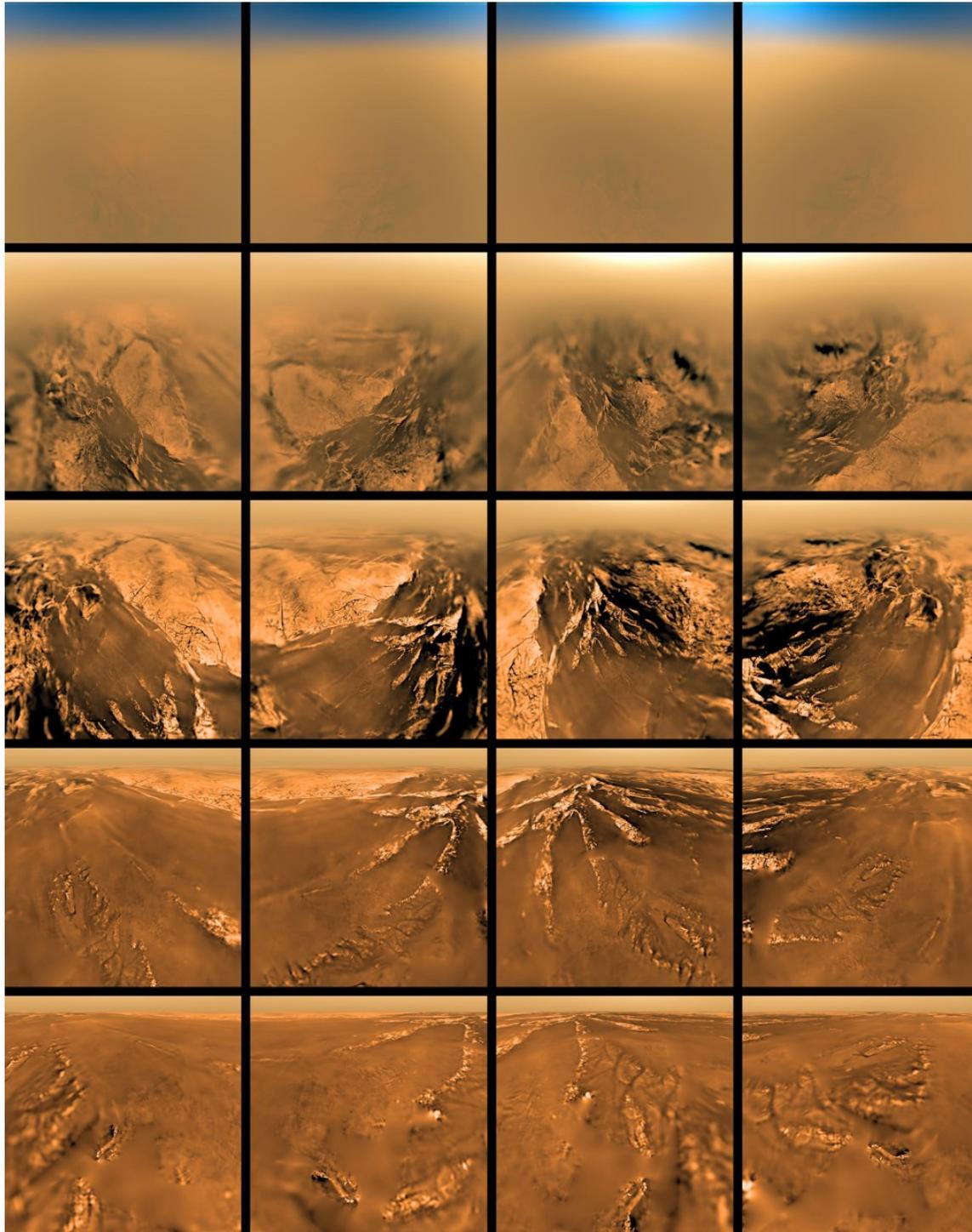
Radar image of twin lakes



Descending probe image



Giant crater seen  
by radar (Circus  
Maximus, 440 km  
diameter) →



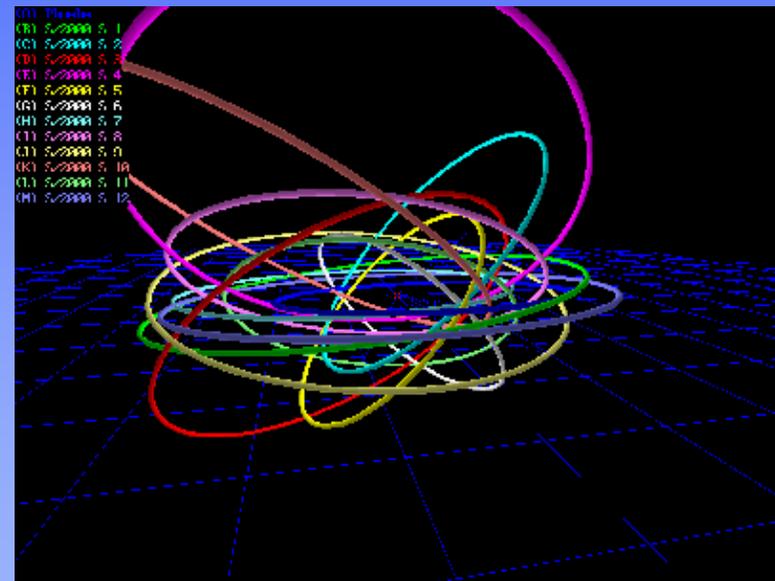
# Tumbling through Titan's atmosphere

NASA/ESA image PIA08119

# Saturn's Irregular Moons

☀ Another 12 moons were announced in 2001

- 🌟 typically a few km in diam
- 🌟 some in retrograde orbits, like Phoebe the most distant of the previously known moons
- 🌟 some orbits highly eccentric
- 🌟 residue from the formation of the solar system



Courtesy: [www.obs-nice.fr/gladman/saturn.html](http://www.obs-nice.fr/gladman/saturn.html)

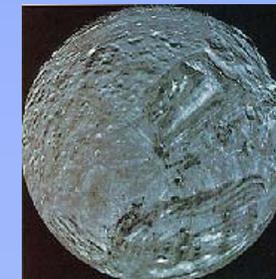
# Uranus

☀ A cold, blue world only seen by naked eye under most favourable conditions. Discovered telescopically by Wm. Herschel in 1781. Blue colour due to  $\text{CH}_4$  absorption. Overall composition like Jupiter

☀ Rotation axis at  $98^\circ$  to ecliptic

☀ Magnetic field odd:- inclined at  $55^\circ$  to poles and well off-centre of planet

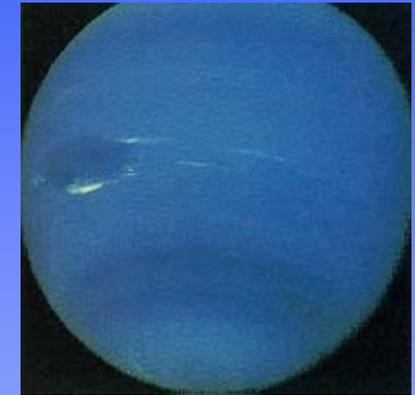
☀ Well developed ring system. Moons *Miranda*, *Ariel*, *Umbriel*, *Titania* and *Oberon* all over 100 km in diameter

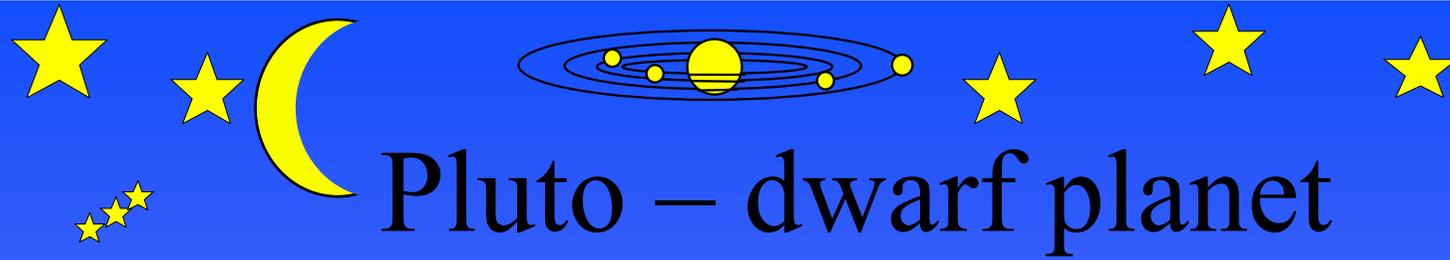


Miranda

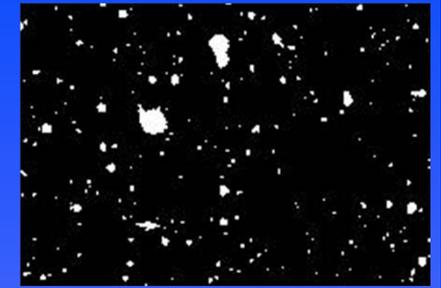
# Neptune

- ☀ Indistinct from Earth ( $a = 30 \text{ AU}$ )
- ☀ Much of what we know comes from *Voyager* fly-past in 1989 and more recent Hubble Space Telescope pictures
- ☀ Another cold, blue world. Yet another planet with a great spot, presumed a storm system
- ☀ Radiates more internal heat than Uranus, driving high level clouds at over  $500 \text{ km hr}^{-1}$





# Pluto – dwarf planet



## What's visible

☀ Discovered by Clyde Tombaugh in 1930

☀ Apparent magnitude  $\sim 14$ ; apparent diameter  $\sim 0.08''$  arc; not even visible as a disk with HST; looks like a star from the ground

☀ Orbit “a” = 39.4 AU; period 248 years; eccentricity 0.244; inclination to ecliptic  $17.2^\circ$ ; 3:2 resonance in period with Neptune, sometimes coming closer to the Sun than Neptune



# Pluto

## What's there

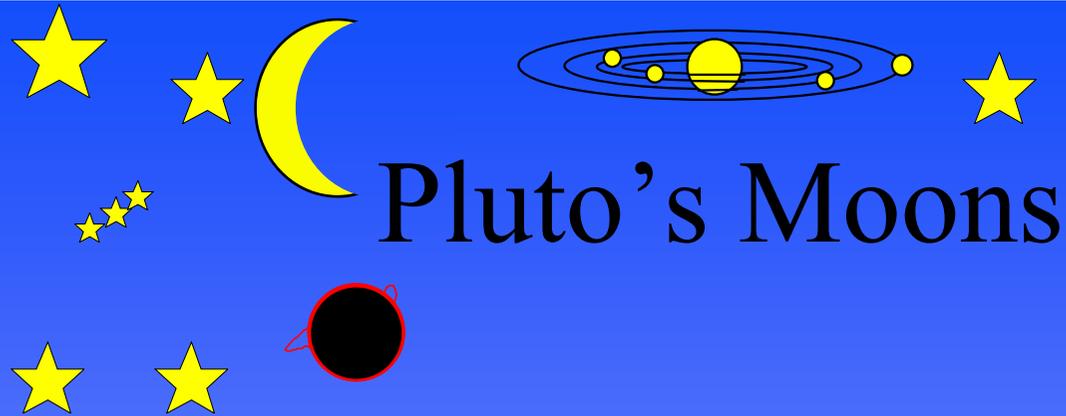
NASA:  
'New  
Horizons'  
image  
13/07/2015

☀ Diameter 2372 km;  
density 1870 kg m<sup>-3</sup>

- ★ surface ices of H<sub>2</sub>O, N<sub>2</sub>, CH<sub>4</sub>, CO
- ★ temp ~40 K; more atmosphere as Pluto nears Sun
- ★ a 'typical', large, Kuiper Belt object?

Pluto: courtesy NASA New Horizons probe 2015





Pluto and Charon  
always face each other



Charon orbits  
in 6.4 days

☀ Little planet with the big moon: Charon

- ★ diameter: 1206 km
- ★ density:  $1650 \text{ kg m}^{-3}$
- ★ surface:  $\text{H}_2\text{O}$  ice +....

☀ Four other small moons

- ★ Nix & Hydra (2005)
- ★ Kerberos (2011)
- ★ Styx (2012)

Charon: New Horizons image courtesy NASA



# Varuna — 2000 WR106

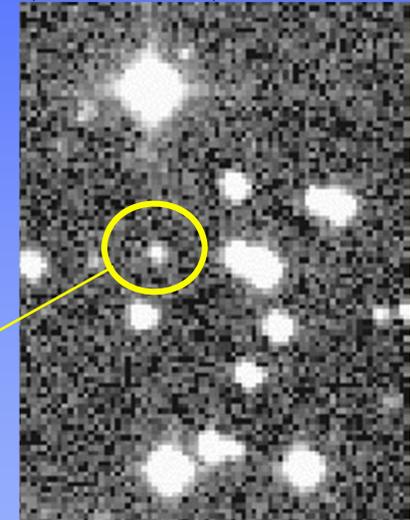
☀ The first large trans-Neptunian object (TNO) discovered, besides Pluto and Charon

★ 20,000<sup>th</sup> ‘minor planet’ in the solar system to be individually identified

★ named in March 2001 after Hindu lord of the cosmos

★ ~900 km in diameter; 43.274 AU orbital major axis; inclination  $17.1^\circ$ ; eccentricity 0.056; apparent magnitude ~20 but variable as it rotates on its axis; dark surface (little surface frost)

Varuna



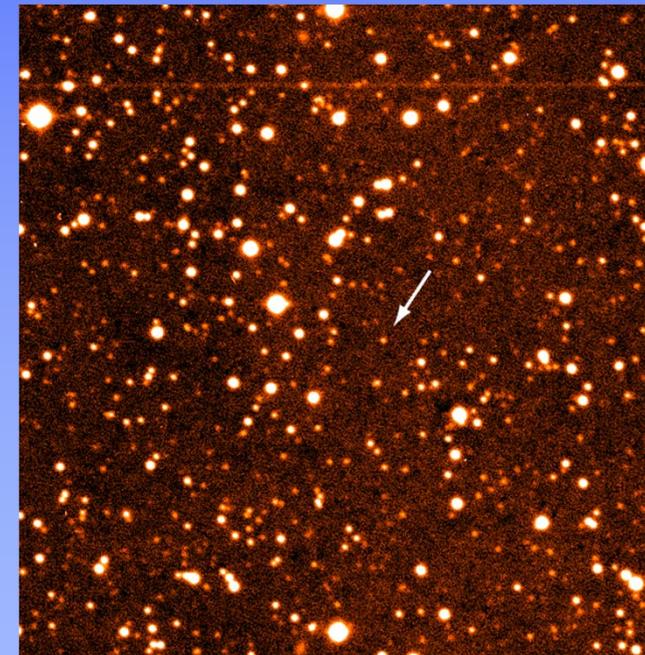
# Quaoar – 2002LM60

☀ ('Kwa-whar') in 2002, the largest solar system object found since Pluto

- 🌟 1250 km diameter
- 🌟  $e = 0.037$ , inclined at  $\sim 8^\circ$
- 🌟  $a = 43.37$  AU



Courtesy:Nasa

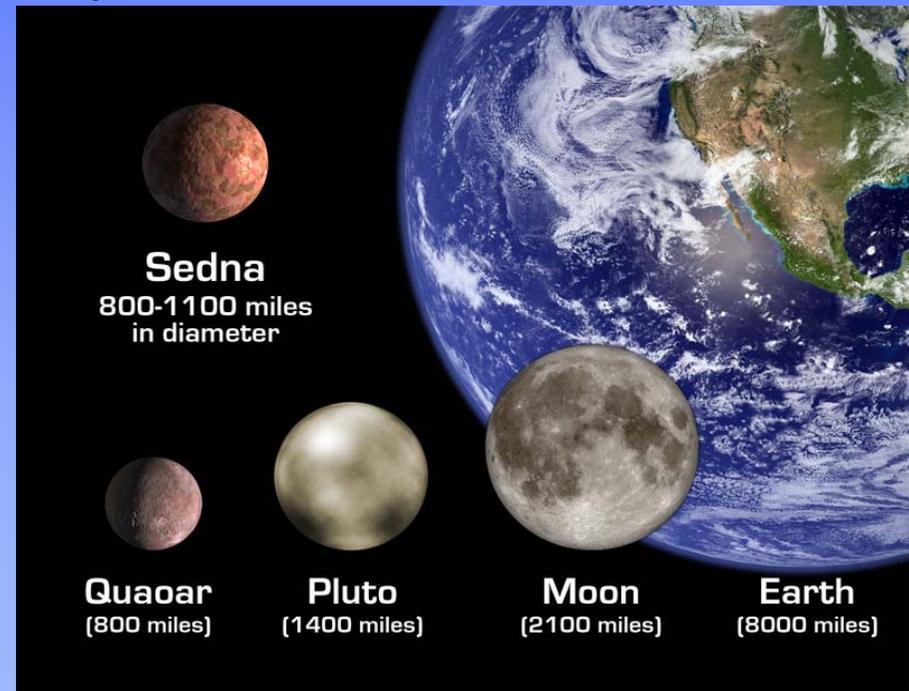
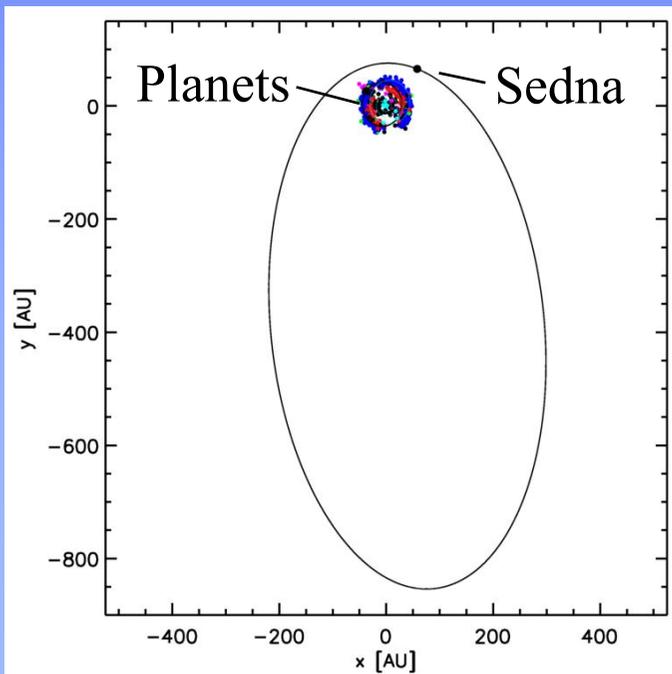


Courtesy: (with animation of the original)  
<http://www.gps.caltech.edu/~chad/quaoar/>

# Sedna - 2003 VB12

☀ At the time of discovery, thought to be the largest solar system body found since Pluto

★ well beyond Pluto



Illustrations courtesy: <http://www.gps.caltech.edu/~mbrown/sedna/>

# Orcus

☀ Discovered and ratified in 2004

♄ named after Greek god Hades

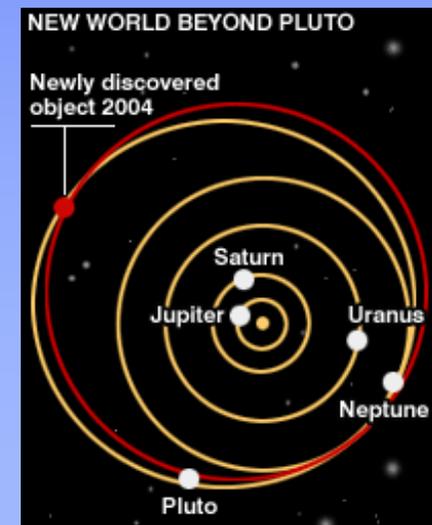
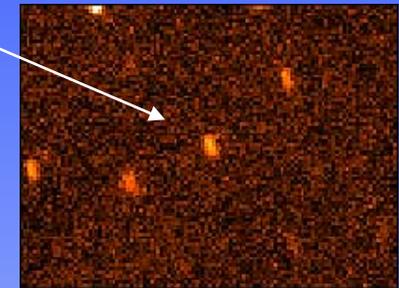
☀ ~1600 km diameter,  $a = 46.16$  AU

🌟 apparent mag ~ 19

☀ Orbit Pluto like, hence a 'plutino'

☀ A Kuiper belt object

☀ May be second largest TNO after Pluto



# “Haumea, Make-make, Eris”

☀ 2003EL61; 2005FY9; 2003UB313

★ Make-make (formerly 2005 FY9)

∩ a dwarf planet, diam ~ 1500 km; temp ~ 30 K

∩ a = 45.791 AU; orbital inclination 29°; e = 0.159

★ Haumea (formerly 2003EL61)  
with moons Hi’aka and Namaka

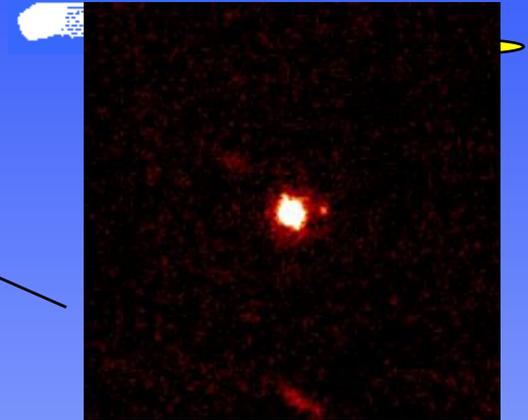
∩ dwarf planet, a = 43.337 AU; orbital inclination 28.3°; e = 0.189

∩ rotating every 4 hours; elliptical

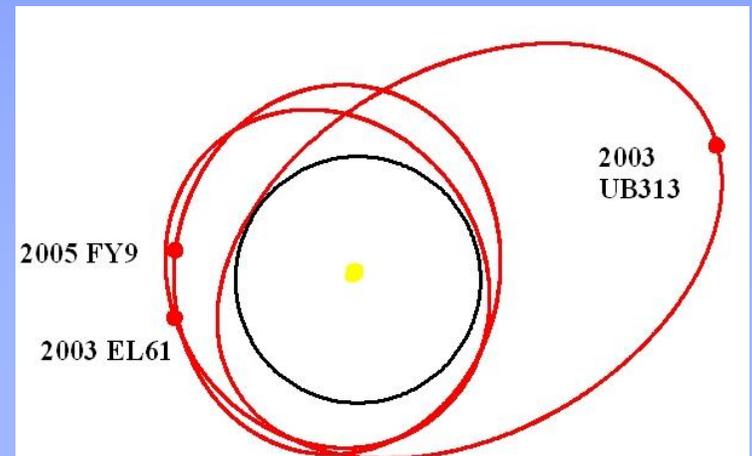
★ Eris (formerly 2003UB313)

∩ a = 67.89 AU; inclination 44°; e = 0.438

∩ a dwarf planet bigger than Pluto  
diam ~ 3000 km; period 560 years;  
furthest from Sun at 97 AU



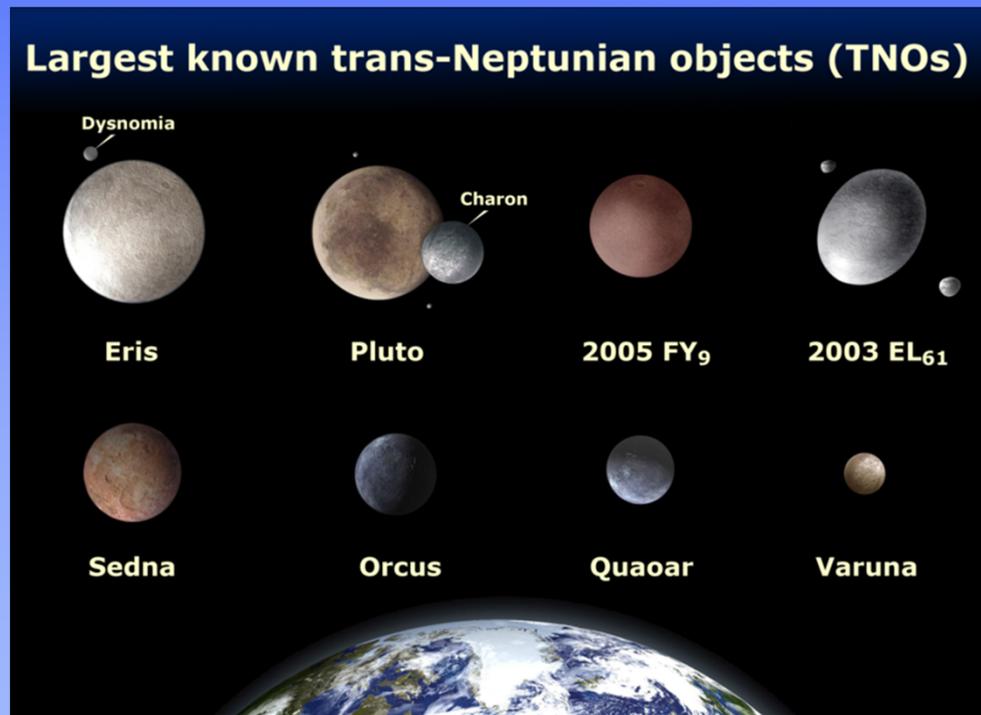
*Eris and moon Dysnomia*



<http://www.gps.caltech.edu/~mbrown/planetlila/>

# TNOs in summary

- ☀ Several objects comparable to Pluto in size
- ☀ Some have moons
- ☀ Many more will be discovered



Courtesy: NASA, ESA, and A. Feild (STScI)