

Reading: Chap. 12, Sec. 12.1-12.4; next week: Chap. 13, Sec. 13.4, 13.1, 14.1-2  
 Homework #8: On website, due in recitation on Friday/Monday, Nov. 1/4  
 Exam 2 - Tuesday evening, November 12

**Last time: Tides and Rings**

- Captured moons vs. primordial moons: orbits and sizes
- Surface modification processes
- Jupiter’s moons - systematics (volcanic/rocky - cold and icy)
- Saturn’s Large Satellites, and Titan
- Moons of Uranus and Neptune
- PLUTO & Charon as KBOs

**Today: Icy Moons and Worlds of the Outer Solar System**

- Tidal forces as differential gravitational force (stretch)
  - deformation, spin synchronization, orbital changes
  - the Roche Distance: tidal breakup
- Planetary Rings: flatness, structure, and resonances
- Ring Systems
  - ways of seeing rings: reflection, transmission, occultation
  - Saturn vs. Uranus, Jupiter, Neptune

**Overview**

- volcanoes
- tectonics
- cratering
- ice geology



- atmosphere
- ice geology
- remelting

- tectonics
- cratering
- reassembly
- remelting

- nitrogen polar caps
- cratering
- geysers

**Moons!**

**REGULAR SATELLITES:**  
 large bodies formed w/parents

- 4 Galilean satellites of Jupiter
- 7 Larger moons of Saturn
- 5 large moons of Uranus

**COLLISION FRAGMENTS:**

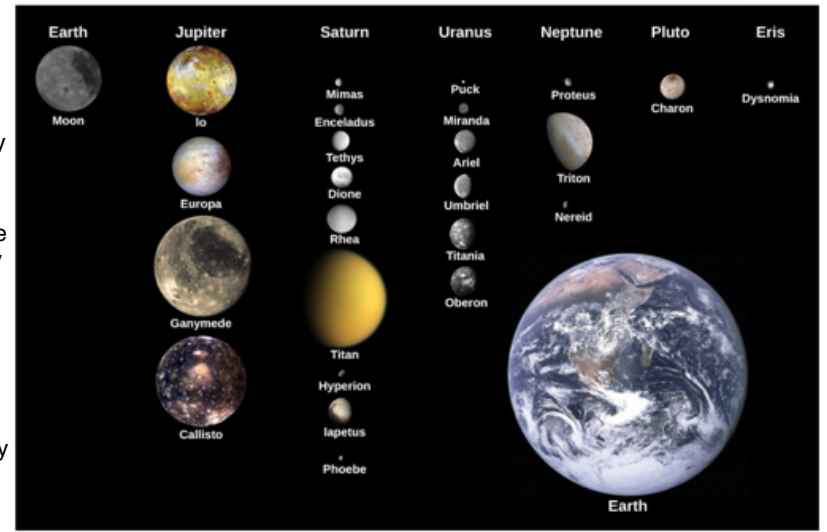
- small remnants of larger bodies (< 300 km in size)
- associated with ring systems

**CAPTURED ASTEROIDS:**

- small bodies orbiting (mostly) between Mars and Jupiter
- Mars (2), Jupiter (8), Saturn (1), Neptune (1)
- highly inclined, very elliptical

**Overview**

- volcanoes
- tectonics
- cratering
- ice geology



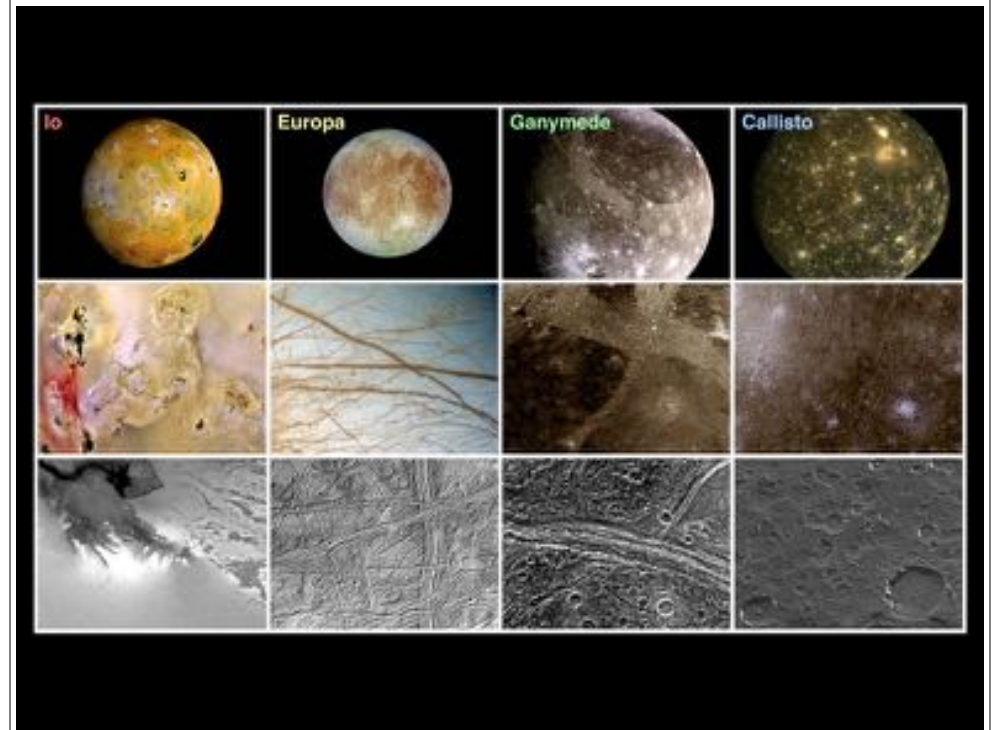
- atmosphere
- ice geology
- remelting

- tectonics
- cratering
- reassembly
- remelting

- nitrogen polar caps
- cratering
- geysers

## General Properties

- lower mass than planets, so...
  - modest compression
  - limited interior heat
- lower density than inner planets
  - nearly all < 2 x water
  - ice is a major constituent (25% to 75%)
- active surfaces when tidal heating present
  - moons close to planet can be heated by tides
  - heat flow → volcanoes, tectonic activity
  - Io, Europa; Enceladus; all Uranian satellites; Triton
- dormant surfaces on distant satellites
  - no tidal heating
  - frozen, inert interiors

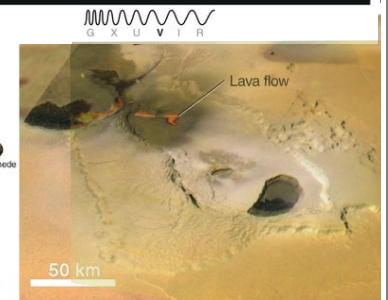
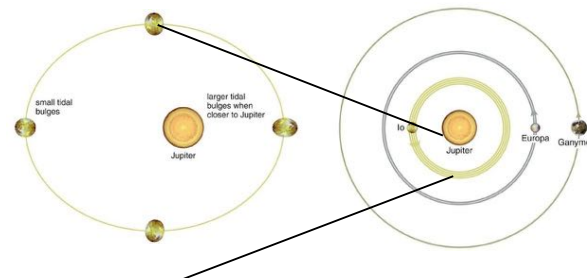
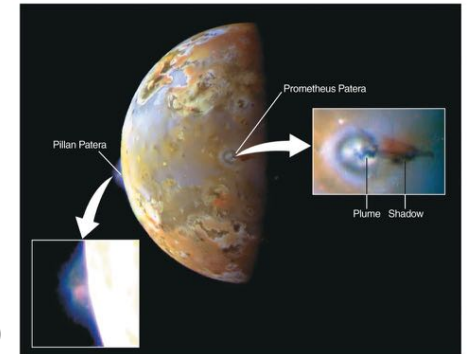


## Jupiter's Large Satellites

- **Io:**
  - closest to Jupiter → tidal heating
  - most volcanic activity in the Solar System
  - molten silicate interior (mean density of 3.7 g/cc)
  - red/yellow surface → sulfur compounds (i.e. SO<sub>2</sub>)
- **Europa:**
  - close to Jupiter → some tidal heating?
  - bright water-ice surface; ridges and grooves
  - mostly rocky interior (mean density = 3.0 g/cc)
  - subsurface H<sub>2</sub>O flows (tectonic activity, few craters)
- **Ganymede:**
  - some activity
  - grooves, craters (old surface), mostly ice interior
- **Callisto: ancient dark cratered surface, mostly ice**

## Io - the most active surface in our Solar System

- closest to Jupiter → tidal heating
- most volcanic activity in the Solar System
- molten silicate interior (mean density of 3.7 g/cc)
- red/yellow surface → sulfur compounds (i.e. SO<sub>2</sub>)

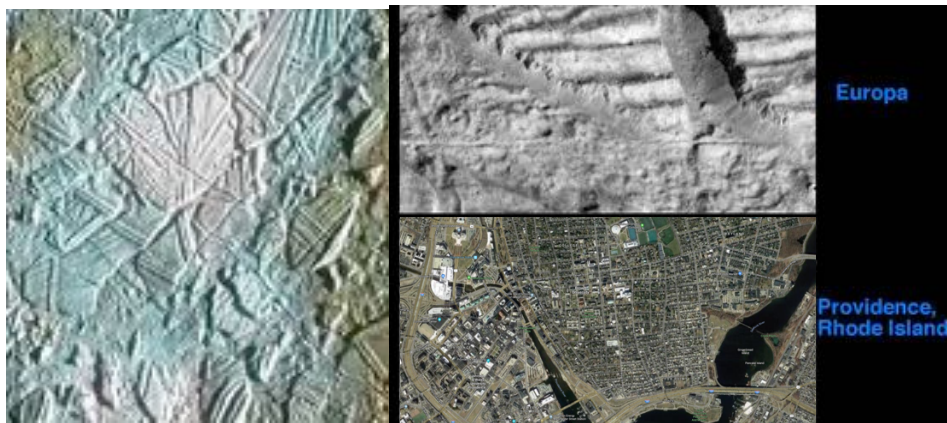




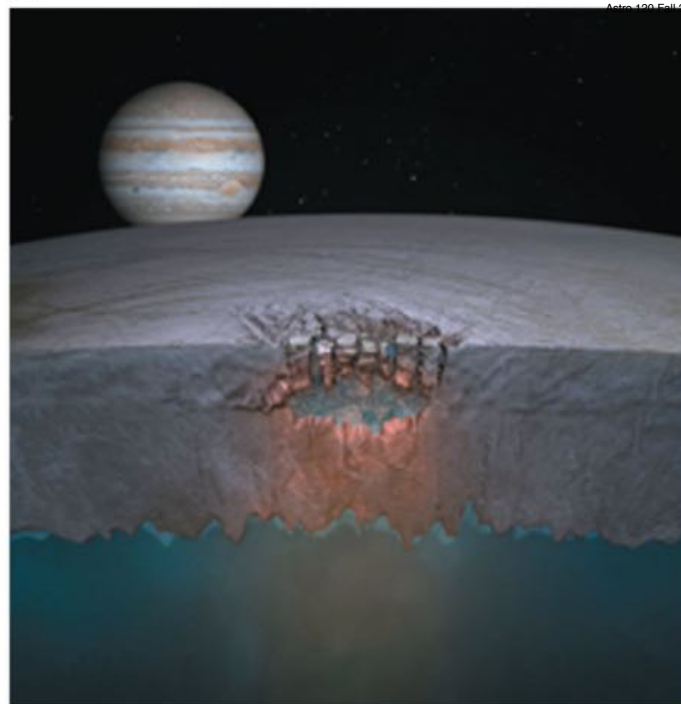
## Europa

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- close to Jupiter + some resonant tidal heating?
- bright water-ice surface; ridges and grooves
- mostly rocky interior (mean density = 3.0 g/cc)
- subsurface H<sub>2</sub>O flows (tectonic activity, few craters)
- magnetic field - subsurface liquid salt water ocean



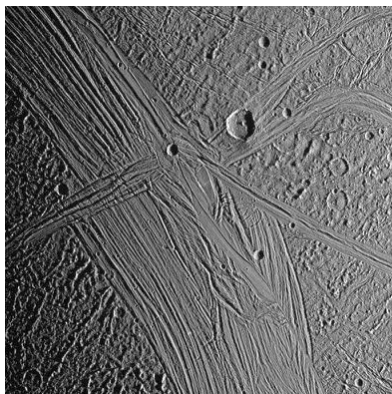
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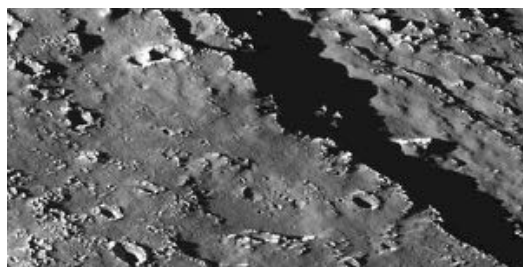
## Ganymede and Callisto

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- some activity (Ganymede)
- grooves and 'fresh' terrain (Ganymede)
- saturated, dark cratered surfaces (both)



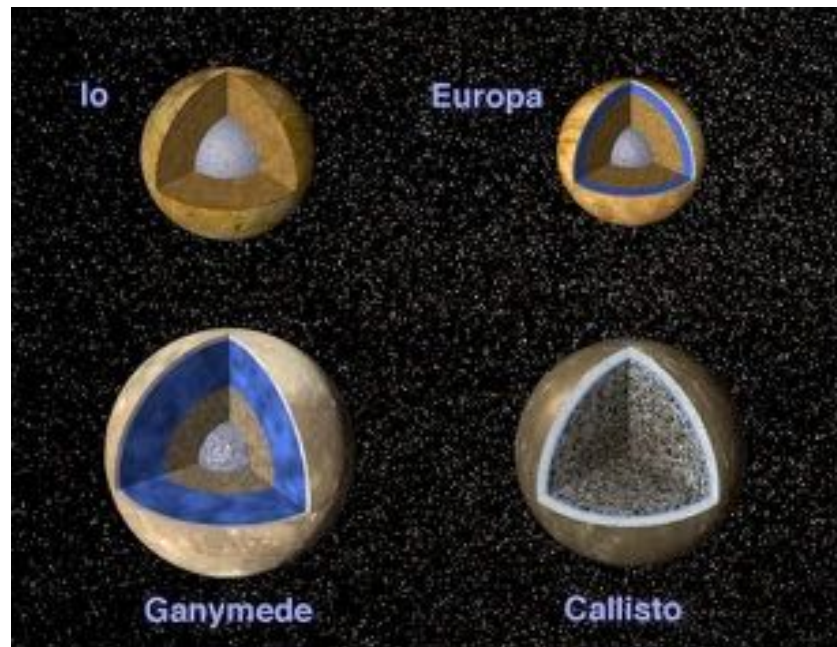
Groovy Ganymede



Callisto Scarp

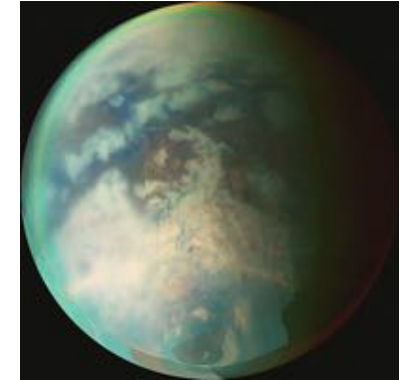
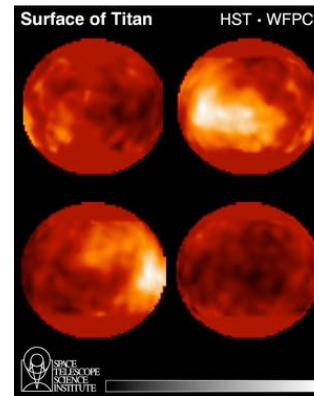
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## Jovian Satellite Interiors

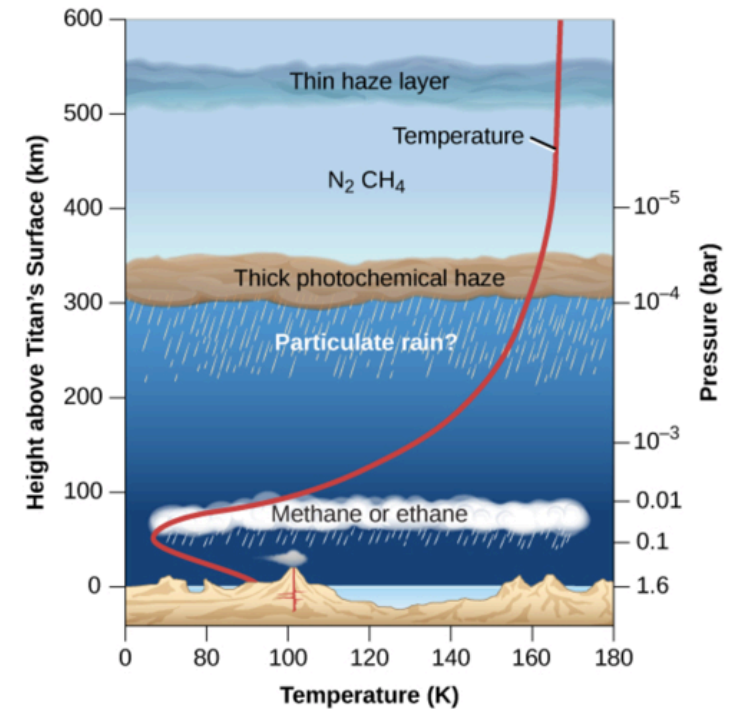
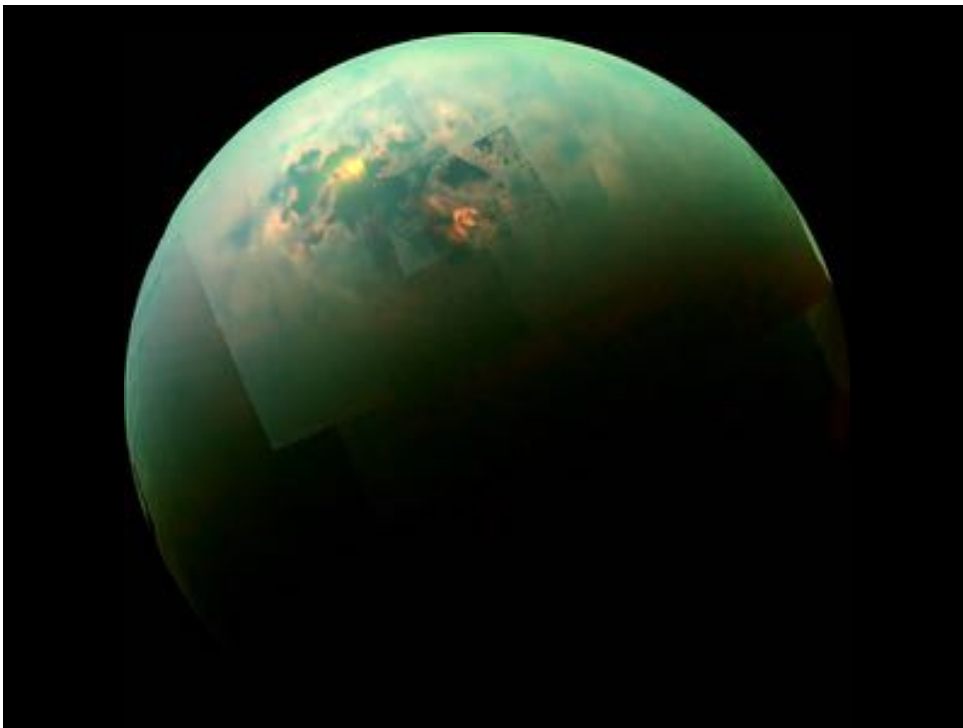
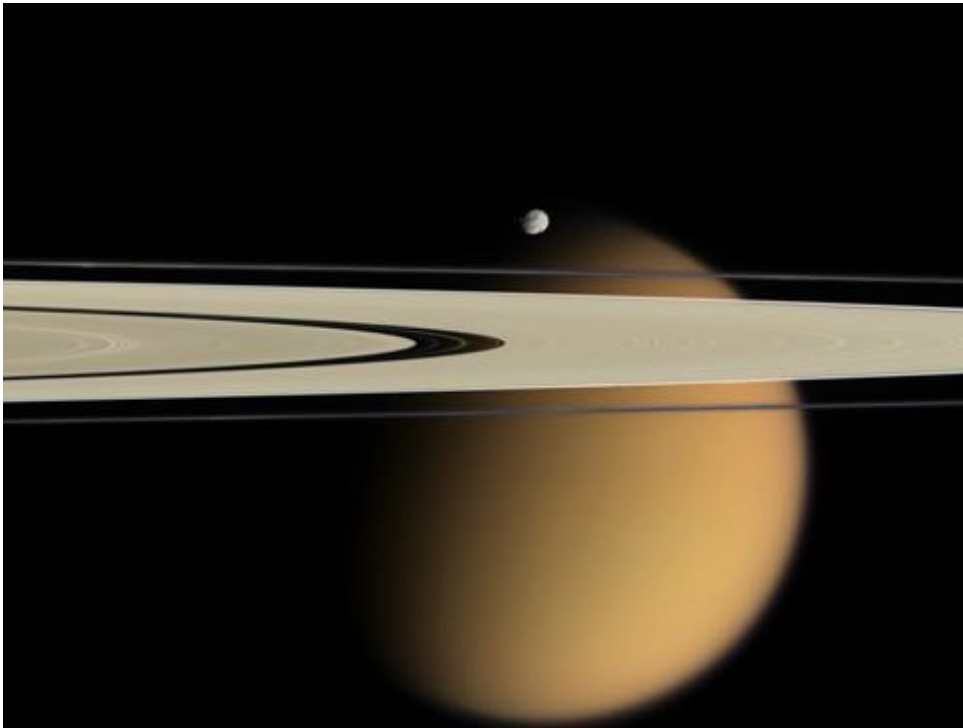


## Titan: (the largest of Saturn's moons)

- thick nitrogen (+aerosol) atmosphere
- atmosphere origin ?
- opaque in optical; surface visible in infrared
- ethane rain / lakes?



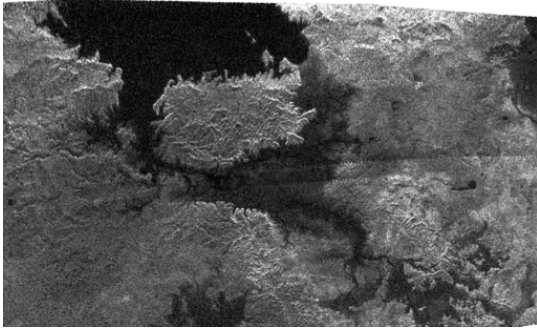
Cassini Image





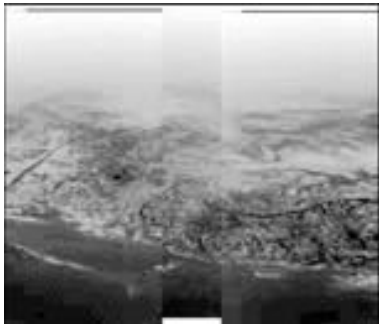
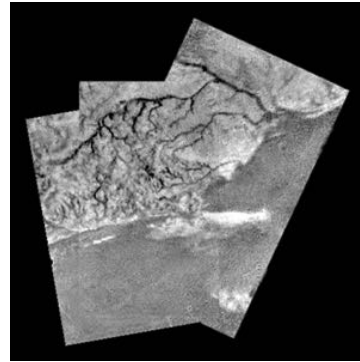
## Towards Titan's Surface - the view from Huygens

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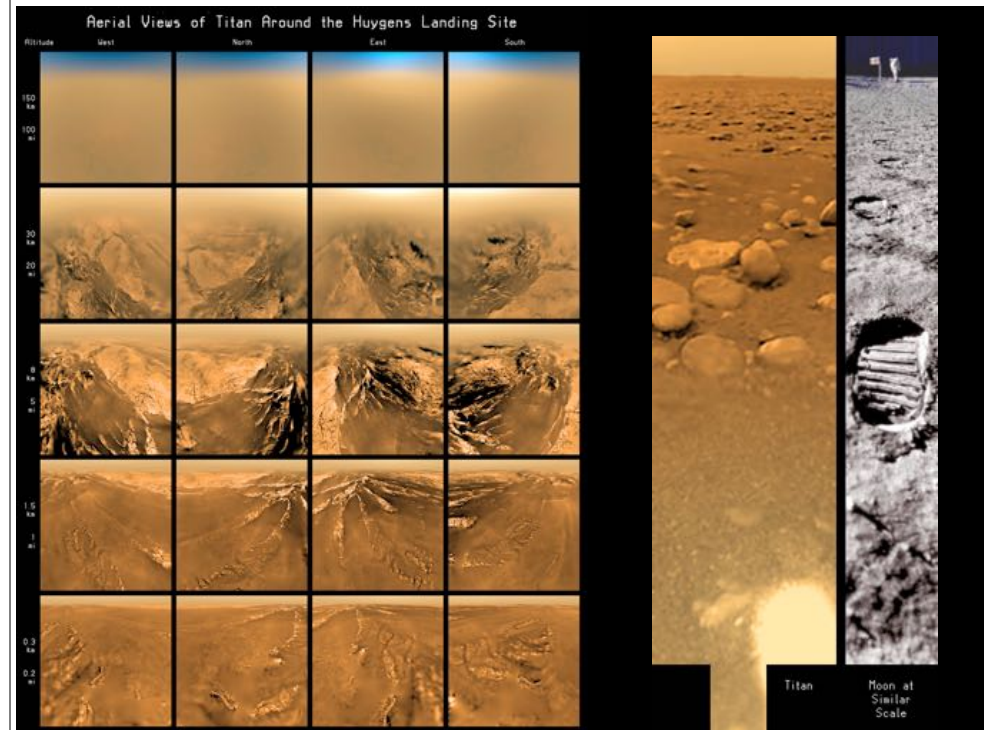


Lakes

Rivers



Shores...

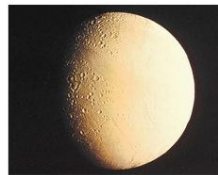


## Saturn's Other Large Satellites

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### • Dione, Tethys, Enceladus:

- close to Saturn → some tidal heating?
- evidence of resurfacing: water flows, tectonics?
- Enceladus: relatively recent flows



### • Rhea, Mimas

- heavily cratered, ancient surfaces
- bright surface → water ice
- low density → little rock



### • Iapetus:

- half of surface is bright, half is dark
- dark side = forward-facing surface. why??'



## Enceladus - "warm" geysers of organic stuff?

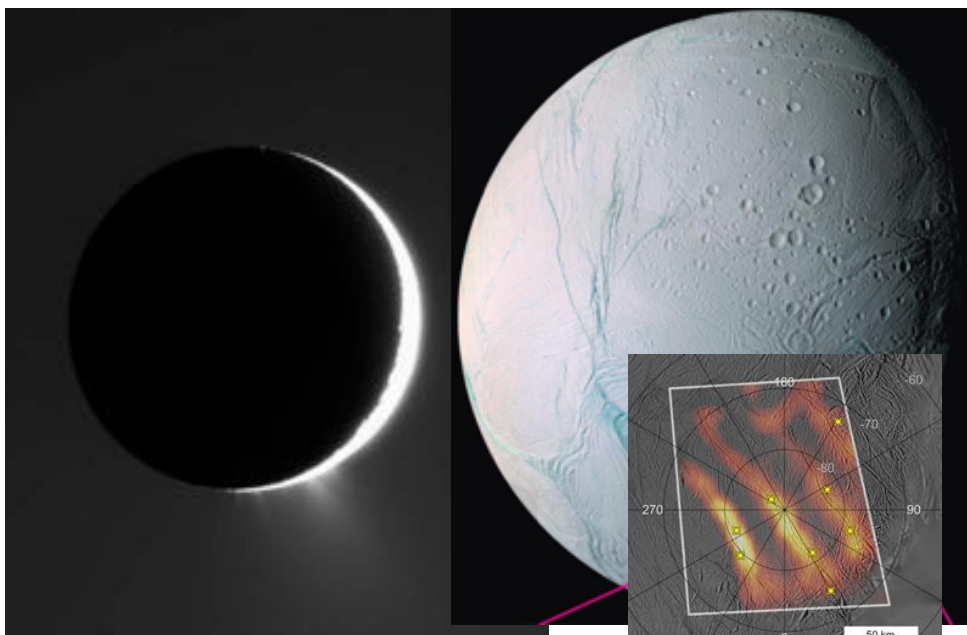
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- thermal mapping shows warmer material below polar cracks
- plumes of organic-rich material flowing up from the cracks

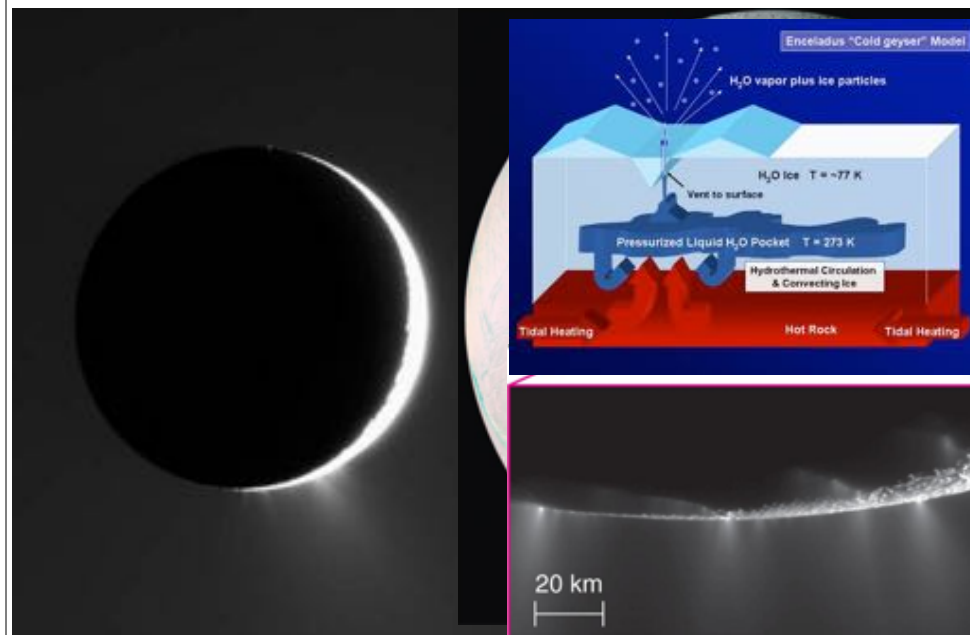
## Enceladus - "warm" geysers of organic stuff?

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## Enceladus - "warm" geysers of organic stuff?

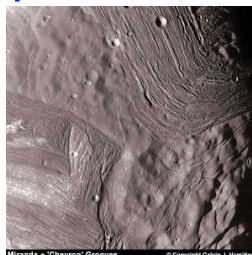
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## Moons of Uranus and Neptune

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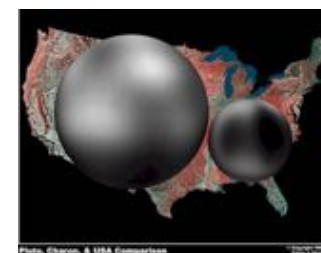
- **Uranus: Miranda**
  - innermost satellite-lots of tectonic activity
  - very varied terrain features
  - broken up and reassembled?
- **Uranus: outer satellites**
  - all larger than Miranda
  - all show evidence of resurfacing: tectonics
  - all show heavy cratering
- **Neptune: Triton**
  - retrograde orbit, inward spiral - a captured body?
  - modest density (2 g/cc)
  - thin nitrogen atmosphere
  - lots of resurfacing
  - wind-blown plumes and geysers



## Pluto - and beyond

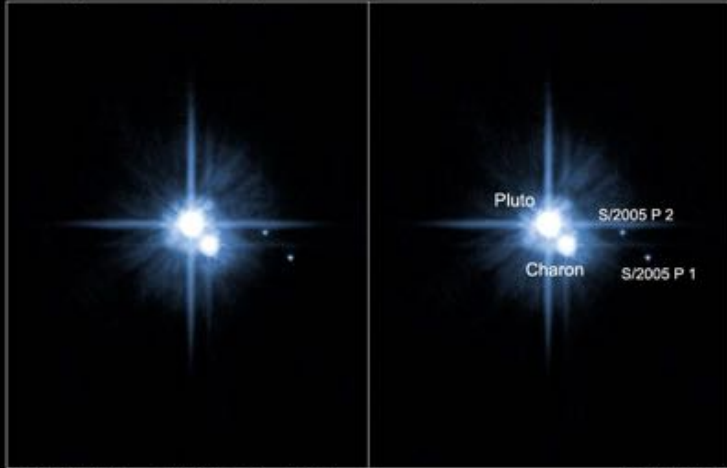
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- Discovered in 1930 in search for trans-Neptunian planet
- **Extremely small**
  - $M = 0.002 M_{\text{Earth}}$  (1/6  $M_{\text{moon}}$ )
- **Extremely remote**
  - orbital period = 248 years
  - eccentric orbit - was closer than Neptune from 1979 through 1999!
- Has a large moon (and several smaller ones)
  - Charon discovered in 1978
  - observed by HST



Pluto System ■ February 15, 2006

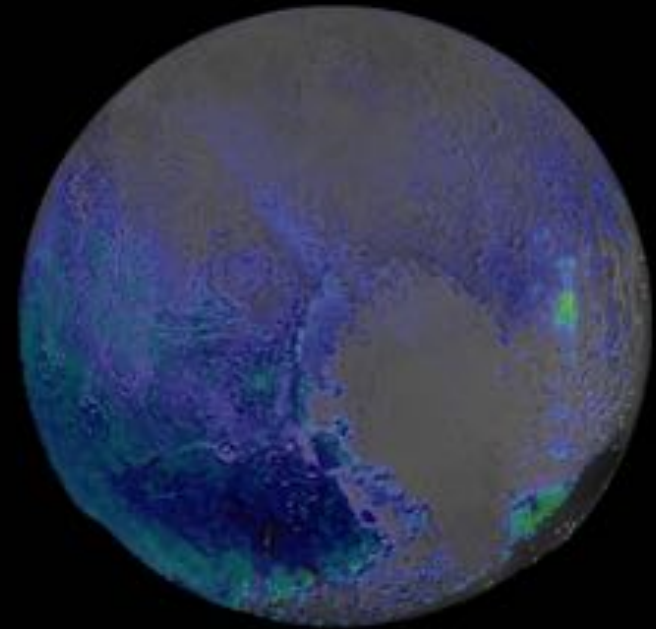
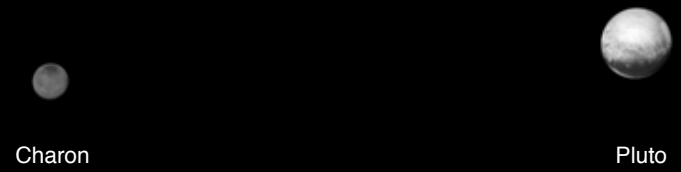
Hubble Space Telescope ■ ACS/HRC



NASA, ESA, H. Weaver (JHU/APL), A. Stern (SwRI),  
and the HST Pluto Companion Search Team

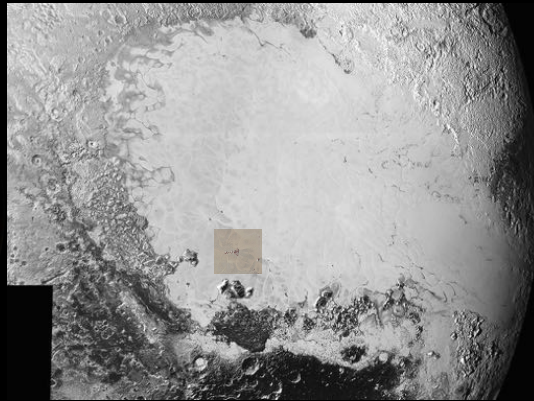
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## New Horizons - July, 2015

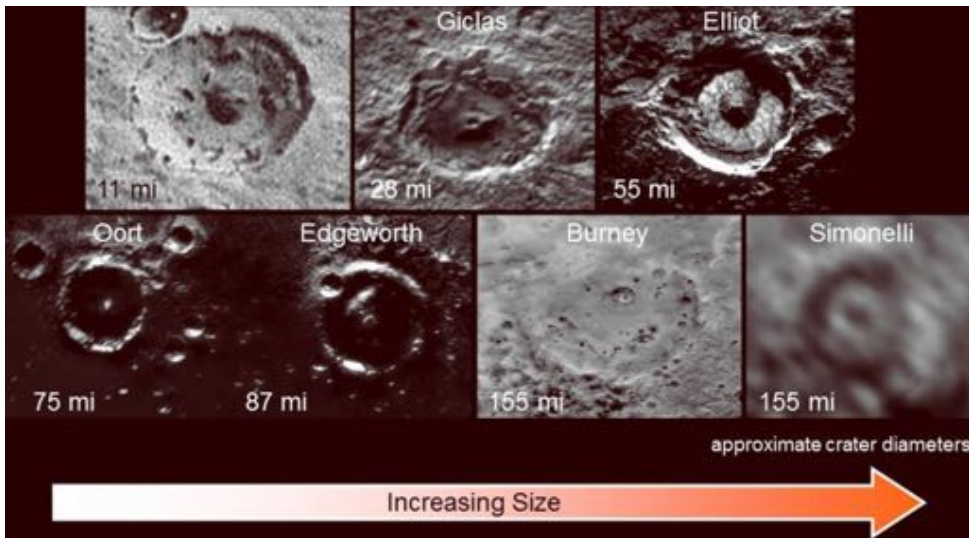
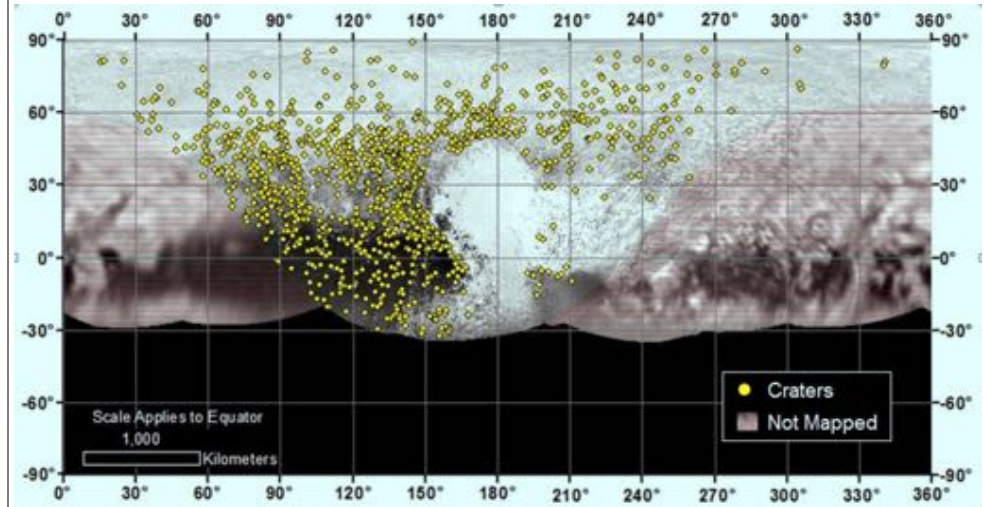




# Pluto



Water ice mountains  
floating in a sea of soft  
nitrogen ice





## New Horizons - July, 2015



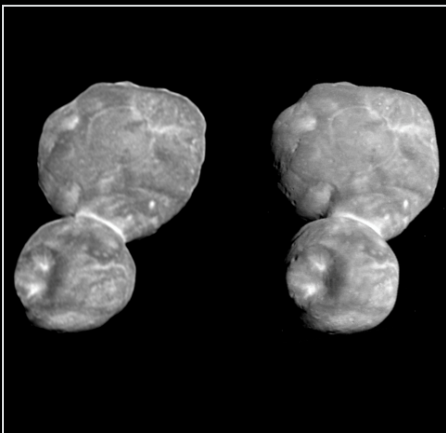
## Charon and the Small Moons of Pluto



10 miles  
10 km

Charon

## Ultima Thule - flyby: January 1, 2019 35 km long; 6.5 billion km from Earth



## Pluto is not alone out there

- Pluto is one of many “trans-neptunian objects” (TNOs)
- a.k.a. the Kuiper Belt objects (KBOs)
- 1st KBO found in 1992, Quaoar found in 2002
- ERIS - found in 2005 is 25% bigger than Pluto

