

# X. ASTRONOMY: MOONS GALORE

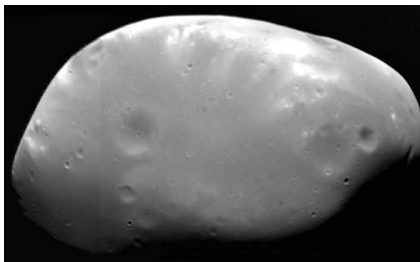
- A. The terrestrial planets in the Solar System have a total of 3 Moons. We have already discussed in great detail about the Earth's Moon. The remaining part of this section discusses the incredible variety of Moons found through the Solar System.
- B. Mars has two moons: Phobos and Deimos. Both have nearly black surfaces, darker than an Asphalt parking lot, that reflect only about 4-5%. In composition, they resemble the dark, carbonaceous asteroids, rich in carbon compounds and chemically bonded water. The fact carbonaceous bodies are native to the outer half of the asteroid belt suggests that they did not form around Mars, but were asteroids captured in a Martian orbit.

## 1. Phobos



- Phobos is 27 by 21 by 19 kilometers in diameter.
- Phobos is pocked and sculpted by craters.
- The largest crater, Stickney, stretches 8 kilometers across....one third the diameter.
- It's the result of an impact nearly large enough to have split Phobos in half.
- Grooves that stretch in a parallel pattern around the little moon, and radiate from Stickney, may be evidence of the fracturing that must have resulted from the impact. Strangely, the grooves are not uniform, but are pocked by little craters with raised rims. Some grooves are essentially chains of craters that look like minor eruptions.

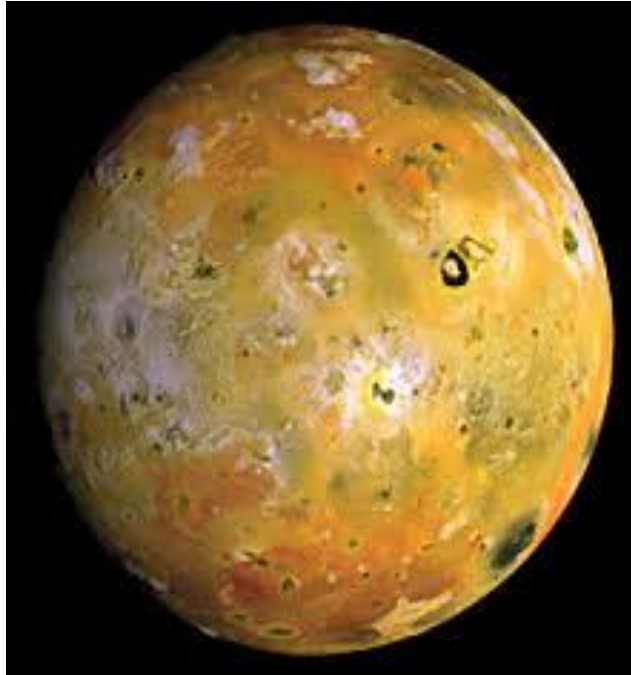
## 2. Deimos



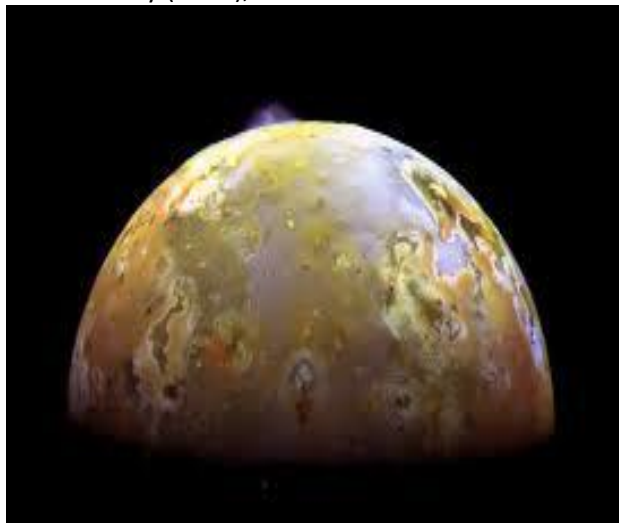
- a. Deimos is more muted, shaped somewhat like a potato, and its craters have lower rounded rims. It lacks crater chains.
- b. In the rolling tracts between its craters are scattered, house-sized boulders.
- c. If you pick up a rock, hold it at eye level, and let it fall on Deimos, it won't plummet to the surface as it would on Earth. Some thirty seconds after you let it fall, it will reach the ground---fifty times longer than it would take back home.

C. The Voyager and Galileo spacecraft obtained astonishing photographs of four large "Galilean moons" of Jupiter, of which are larger than our Earth Moon.

- 1. Io is the innermost moon, completing an orbit in only 1.8 days.
  - a. At least a half-dozen erupting volcanoes were found by Voyager.
  - b. Close-up pictures by Voyagers 1 & 2 in 1979 showed Io to be molten with orange, yellow, red, and white patches, and pocked with blackish spots.



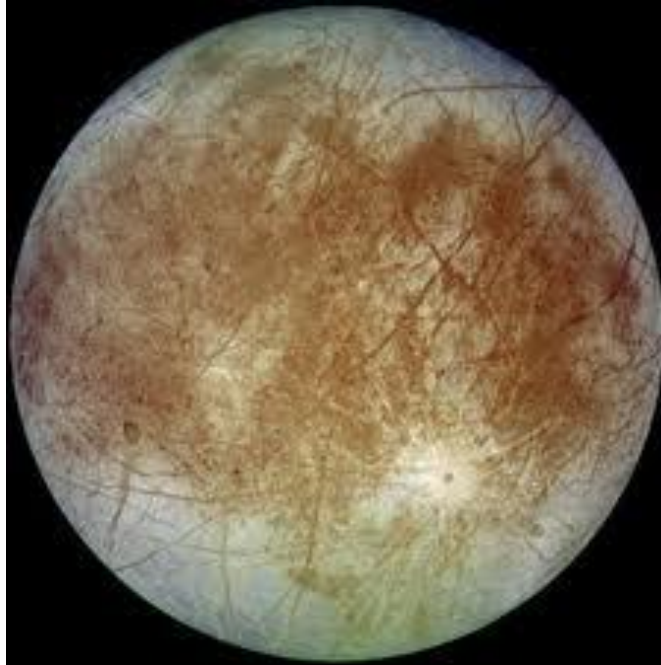
- c. More recently (1998), Galileo found several dozen volcanoes or vents.



- d. Although many of these have relatively low temperatures and eject molten sulfur (giving Io its orange hue), a few are hotter than any other known volcanoes.
- e. Io is the most volcanically active body in the Solar System.
- f. Io is kept partly melted by the varying tidal force of Jupiter, which release heat because of internal friction.
- g. The tidal force vary because gravitational interactions between Io and the other Galilean moons force its orbit to be eccentric (elliptical), rather than circular.
- h. Stanton J. Peale (Univ. of California) and his colleagues predicted this just before the Voyager spacecraft reached Jupiter in 1979.



- i. It has the geologically youngest surface in the Solar System.
  - j. Prior to the Voyager flyby, the interior of Jupiter was predicted to be molten because of friction associated with variable tidal forces: gravitational interactions with the other large moons force Io's orbit to be elliptical, so Jupiter's gravitational pull varies.
  - k. Given the presence of primitive organisms in oxygen-free, geothermally active regions of Earth, it is conceivable (but rather improbable, unless water is present) that similar life might exist on Io.
  - l. Io is 421,800 km from Jupiter. It has a diameter of 3,630 km. Slightly larger than our moon.
  - m. Io keeps the same face toward Jupiter as it orbits the planet (43 hours). Jupiter would seem to hang motionless in the sky, neither rising nor setting. As Io orbits, the giant planet goes through phases.
  - n. Because Jupiter covers a large part of Io's sky, the sun spends nearly 2.5 hours of each day in total eclipse behind Jupiter. Views of the Jupiter's auroral display are common.
2. Europa, the second moon, is one of the most fascinating bodies in the Solar System.
- a. Voyager images show a very smooth, icy (mostly water ice) surface.
  - b. Europa is 671,000 km from Jupiter and has a diameter of 3,130 km. It's revolves around Jupiter every 3 days & 14 hours.
  - c. The 1997 Voyager missions revealed that Europa is the most nearly featureless world known in the solar system.
  - d. From a distance, it looks like a mottled, cream-colored cue ball, with only faint markings and virtually no large impact craters.
  - e. The fractures, which may be tens of kilometers wide, and which can be traced from as little as tens of kilometers to as much as 3,000 km in length, separate individual iceberg-like plates



- f. The general paucity of craters suggests that the surface is young.
- g. Many narrow, dark stripes criss-cross the surface. These resemble fractures in an ice-covered pond.
- h. A reasonable conclusion is that a slushy region, or perhaps even an ocean of water, exists below the solid ice.
- i. Europa is kept partially melted for the same reason as Io.



- j. Subsequent studies by the Galileo spacecraft confirm that liquid water is probably present beneath the ice. Europa's conditions may therefore be quite suitable for the development of life. Future probes will be sent there to search for primitive life (bacteria, microbes, etc.)
- k. Tidal heating, more mild than in the case of Io, can keep Europa partially molten.
- l. The mean density of Europa, much higher than ice, is closer to that of silicate rocks, meaning that Europa must be mostly a rocky world. The layer of ice and water may

be only 100 km thick, which is to say the ocean could be 100 km deep under a 3 km thick icepack.

3. Ganymede is the third Galilean satellite from Jupiter.

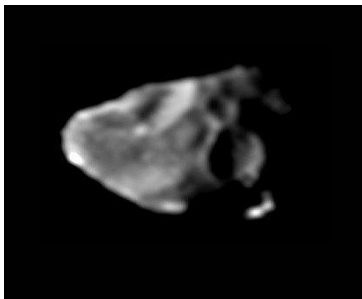


- a. It has a hard surface covered with many craters.
  - b. It is the largest moon of Jupiter, and also the largest moon in the entire solar system. It has a diameter of 5,280 km. It is 1,070,400 km from Jupiter. It takes 7 days & 3 hours to revolve around Jupiter.
  - c. Images from Voyager 2 in 1979, show contrasts between the old dark, heavily cratered terrain, and the light younger, fissured terrain, which appear to be regions of cleaner ice. Recent craters are also surrounded by halos of bright, fresh ice.
  - d. The number density of craters suggests that Ganymede may have solidified as recently as 1 billion years ago. Tidal interactions probably kept it molten for a long time.
  - e. In 2000, the Galileo probe passed only 809 km above the surface of Ganymede. It revealed that the icy crust may drift atop a more fluid layer---a buried ocean of liquid water, beginning at a depth estimated at 170 km below the icy surface. It also detected that the water is erupting to the surface as salty water, (magnesium sulfate).
  - f. Additionally, Galileo detected a magnetic field. This implies that Ganymede has a hot interior, with a metallic core and rocky mantle, overlain by the hundreds of kilometers of ice and the buried ocean.
4. Callisto, the outermost large moon, may be the most heavily cratered body in the Solar System.
- a. With a diameter of 5,000 km, Callisto is a slightly smaller sister of Ganymede.
  - b. Like Ganymede, it keeps on face toward Jupiter. It is 1,882,600 km from Jupiter and takes 16 days and 16 hours to revolve around Jupiter.
  - c. Callisto seems to have lacked the internal energy to drive complex geological processes to fracture the surface. Instead, it's surface is almost completely covered by old craters and has not been broken by eruptions of fresh ice, as has happened on Ganymede.
  - d. The surface has a concentration of dark soil, but wherever an asteroid has hit, it has

- blown away the dark soil and left a bright scar exposing the fresher ice underneath.
- e. Valhalla is a large crater surrounded by a spectacular series of ripples resembling a “bull’s eye”.

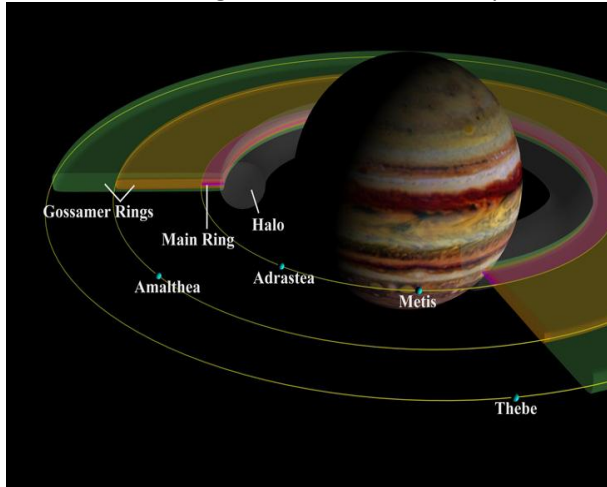


- f. Callisto’s hard, icy surface is probably very old.
- g. In 2001, a very close pass of the Galileo probe, only 138 km above Callisto, revealed interesting topographic features, including smooth plains dotted with “spires”, and conical, knoblike hills. These hills rise about 80-100 m and seem to be the last remnants of a resistant ice left behind as solar heating sublimed 100 m or so of the dirtier ice, leaving low, “spire” ---dotted plains.
5. Amalthea is a small moon, much closer to Jupiter than are any of the larger Galilean satellites.

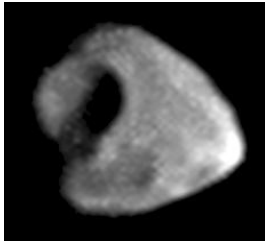


- a. Three images snapped by Voyager 1 as it went past Jupiter show Amalthea to be very elongated in shape and reddish in color.
- b. The color may be due to a coating of sulfur compounds transferred off the neighboring moon, Io.

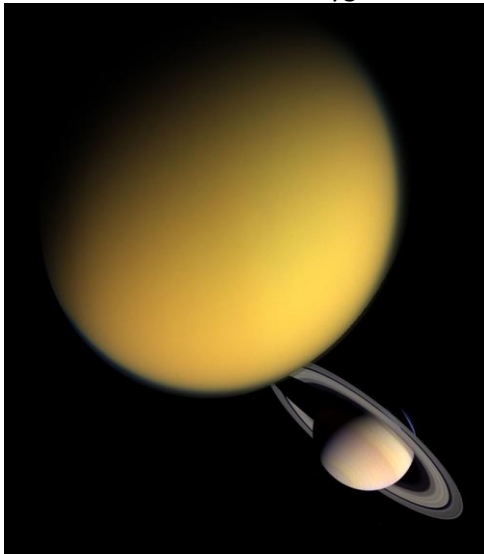
6. There is a thin ring at a distance of 1.8 Jupiter radii from Jupiter's center.



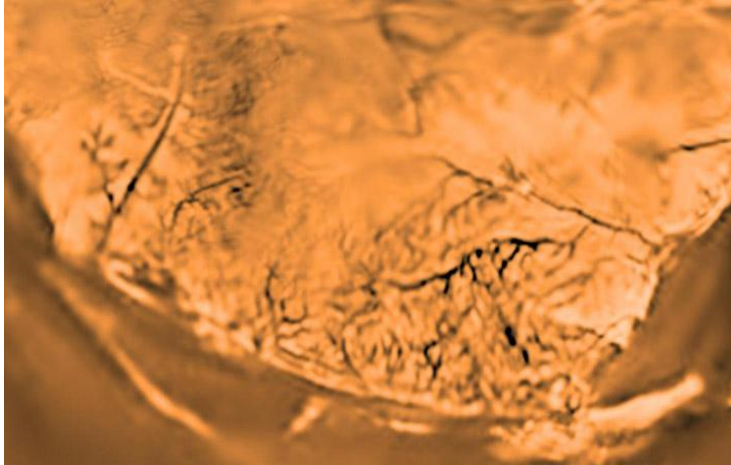
7. Thebe, about 100 km across, and is located farther out from Jupiter, between the orbits of Amaltheo and Io. This should make it red in color with great views of the Io volcanoes.



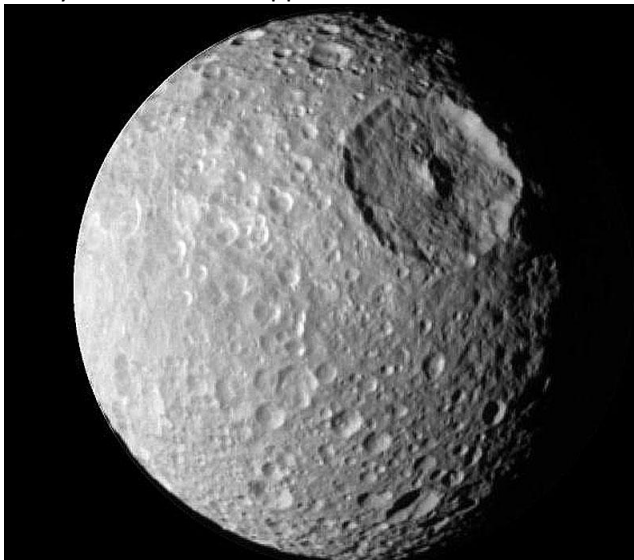
8. Astronomers have found a total of at least 58 probable moons of Jupiter, and the number is growing rapidly. There may be hundreds of moons orbiting Jupiter, some of which are likely to be captured asteroids.
- As progressively smaller bodies are found, the question of whether to call them "moons" arises. Do the small particles in Jupiter's ring count as moons, for example?
- D. Saturn currently has 30 known moons (12 were found in the year 2000), many of which are very small and are probably captured asteroids.
- The largest, Titan, has a thick atmosphere consisting primarily of nitrogen molecules ( $N_2$ ), like the Earth but without oxygen. It is the only known moon with a thick atmosphere.



- a. There are also some hydrocarbons such as methane ( $\text{CH}_4$ ); the atmosphere is smoggy.
- b. The surface of Titan is relatively warm due to the atmosphere and some greenhouse heating.
- b. Titan's atmospheric composition somewhat resembles Earth's probable primitive Atmosphere, and it is possible that amino acids may have formed, (but there is little Oxygen).
- c. Methane ( $\text{CH}_4$ ) lakes might exist on Titan's surface! If so, it is conceivable that life may have arisen, although this would be difficult without water.
- d. Titan is 1,222,000 km from Saturn and has a diameter of 5,140 km. It takes 16 days to revolve around Saturn.
- e. In 2004, the American/European Cassini Saturn orbiter studied Titan at close range. Cassini release the European-built Huygens probe, which parachuted through the Clouds and took pictures on the way down to the surface. The aerial images showed clear examples of streambeds or drainage channels with branching Tributaries, confirming fluids on the surface and a large lake.



- f. Huygens found the surface to be covered with a thin icy crust. The "rocks" are pebble sized chunks of ice.
2. Mimas, dramatically illustrates that major collisions have occurred in the Solar System history: It has a crater approx.  $\frac{1}{4}$  as wide as the moon itself.

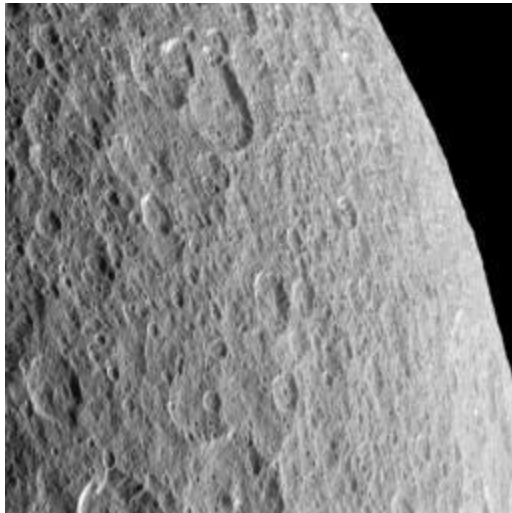




- a. Mimas is the innermost of Saturn's large moons, an icy globe 390 kilometers wide.
  - b. Seen from Earth, it is very faint in the glare of nearby Saturn, and yet it was discovered as early as 1789 by Sir William Herschel.
  - c. It's largest impact crater, named Herschel, is about 130 km across and 9 km deep. It has a broad central peak 4 km high. One of the largest in the Solar System.
  - d. Mimas suffers concentrated bombardment, because it is close to giant Saturn, whose strong gravity attracts impactors.
  - e. Mimas is of further interest because of its gravitational influence on particles in Saturn's rings---the effect called resonance. Mimas goes around Saturn in 22.6 hours. Particles in the central part of the rings go around Saturn twice in this time.
3. Rhea is a little less than half the size of our own moon ---only 1,530 km in diameter.

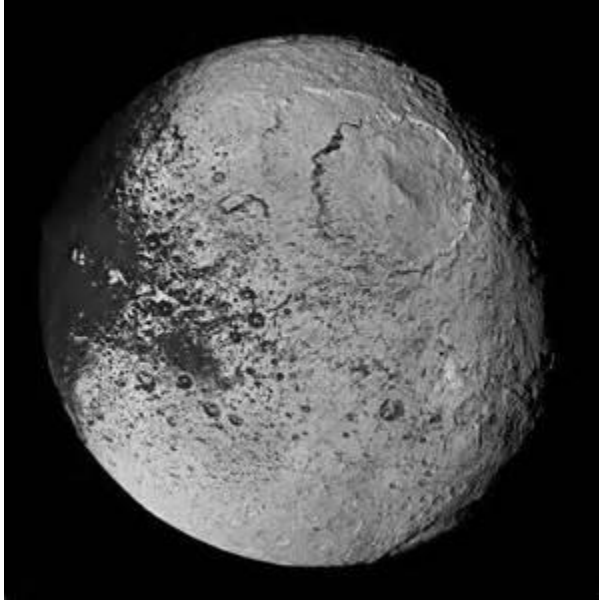


- a. It is in the middle of Saturn's satellite system, one in from Titan.
- b. Spectroscopic observations show that it has now atmosphere at all and that its surface is a bright material reflecting 60% of the sunlight falling on it---mostly frozen water and a small amount of darker soil.

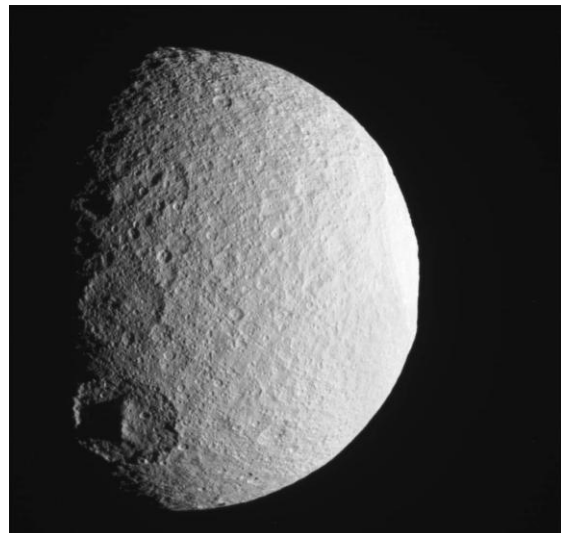
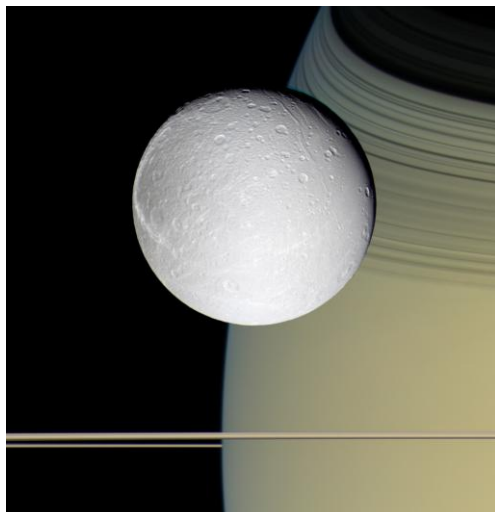


- c. Close-up photos taken by Voyager1 reveal a wilderness of craters; Rhea is one of the most crater-crowded worlds in the solar system.
- d. The surface appears as if it has been hardly disrupted by internally generated geologic activity or tidal heating.

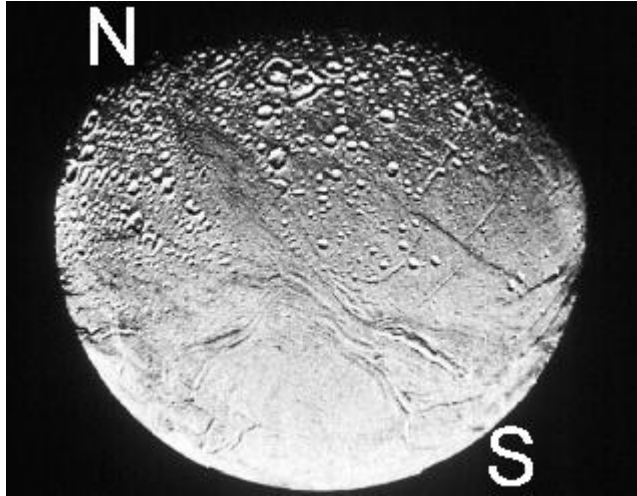
- e. The density of Rhea is low, only  $1.3 \text{ g/cm}^3$ . This implies that Rhea is a giant snowball!
- 4. Iapetus, an outer satellite of Saturn, has been a puzzle since its discovery in the 1600s.



- a. Iapetus is a world divided. One side is surfaced with frozen water, the other with blackish, rocky material.
- b. The boundary between the two is ragged but sharply defined, as seen in the photo.
- c. Iapetus's orbit is tipped almost  $15^\circ$ , so that it passes well above and below the plane of the rings.
- d. A possible explanation for the 2-faced moon involves dust blown off Phoebe, the next and farthest moon out. Phoebe is dark gray and alone among Saturn's moons, moves in a retrograde orbit.
- e. This means that any debris knocked off Phoebe, by meteorites circles Saturn in the same clockwise direction. Dust from Phoebe tends to spiral inward and eventually encounter Iapetus, which moves in a prograde, or counterclockwise direction.
- 5. Dione and Tethys, along with their larger sister, Rhea, are perhaps the most "typical" moons Saturn.

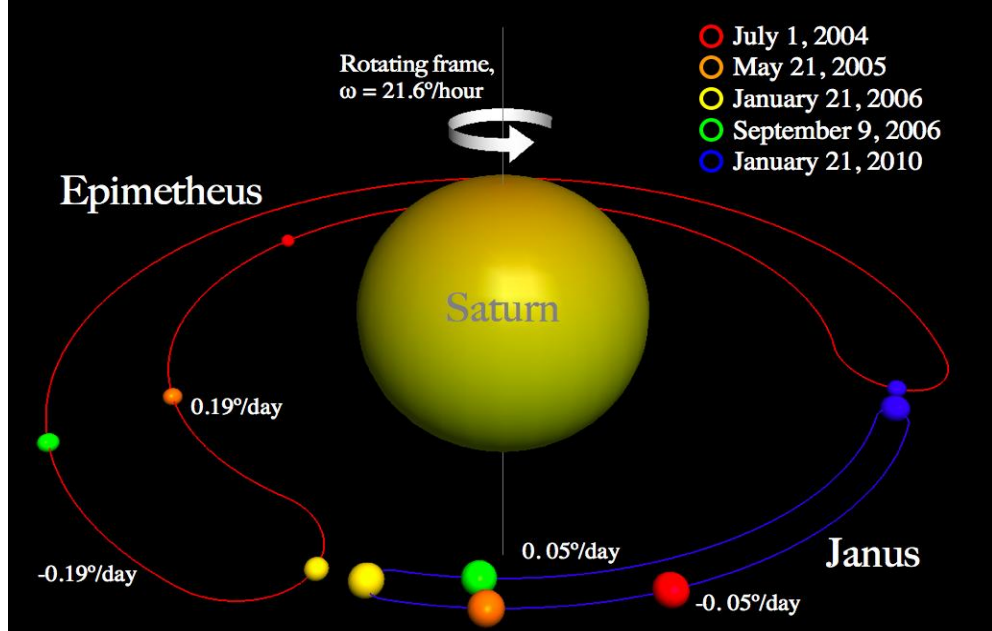


- a. Their diameters are 1,120 and 1048 km, close to the 1,000 km cutoff below which most worlds become too small to develop much distinctive, internally generated geologic activity.
  - b. They are bright, covered with water-ice, and heavily cratered.
  - c. Their only remarkable features are patchy areas of darker tone and some swaths of bright material that seem draped across the craters, like a thin, lacy veil.
  - d. The enormous trench, Ithaca Chasma, stretches three-fourths of the way around Tethys. Over 100 km wide in places, it reaches depth of sever kilometers.
6. Saturn's modest-sized moon Enceladus surprised scientists with it's geological complexity.



- a. At only 500 km in diameter, Voyager shows not only ancient, cratered regions, but also much younger, uncratered plains, cut by fractures, grooves, and strange swaths of contorted ridged terrain.
  - b. Long, straight fracture lines cross the plains, as if they were scribed at random with a giant's pen. Such flowing and fracturing must have required a heat source in recent times.
  - c. The source of the heat is uncertain. Calculations of these forces in the Saturn system have indicated that they are barely able to do the job because of the particulars of the satellite. So Enceladus's resurfaced plains pose a mystery.
  - d. Another odd aspect is that the icy surface is extraordinarily bright, reflecting more than 90 % of the sunlight that hits it. This is the most reflective ice in the solar system. The implication is that fresh, white frost is continually condensing on the surface, which in turn suggest s water vapor is escaping from the interior.
7. One of the most curious relationships exists between 2 of the small, innermost moons of Saturn, named Janus and Epimetheus. They move in circular orbits around Saturn, at Almost exactly the same distance from the planet. They are called co-orbital satellites. However, there is not much chance of their collision because they do a fantastic dance around each other and end up exchanging paths.
- a. Imagine that Hanus is closer to Saturn and is catching up to Epimetheus. It comes up from below and behind. As they approach each other, their gravities attract. Janus is pulled upward toward Epimetheus, and Epimetheus is pulled downward toward Janus. Following Kepler's laws, Janus thus slows down (because it is now in a higher orbit), and Epimetheus speeds up. Janus, now rising to a higher orbit, moves into a slightly higher orbit than Epimethheus, as Epimetheus drops to a slightly lower orbit.

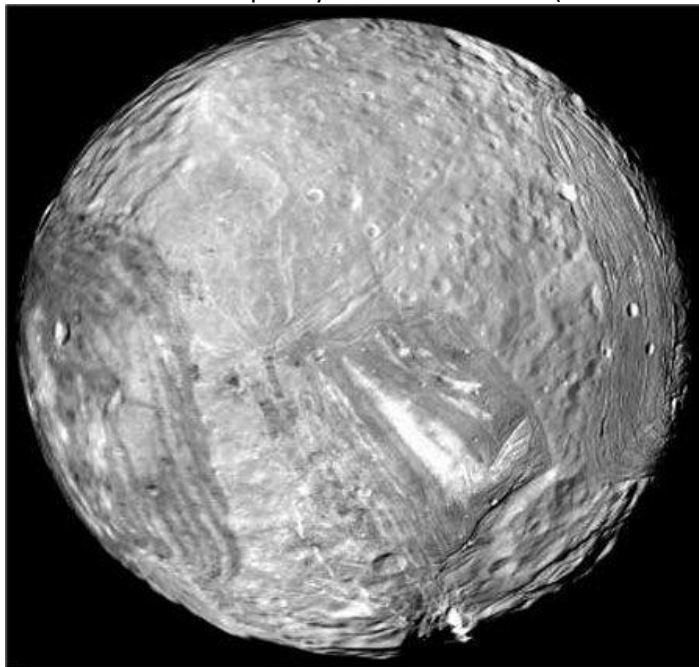
In fact, they have essentially exchanged orbits! Janus, now moving slower, drops back out of sight.



- b. Later, Epimetheus, now in the lower orbit, would move up to Janus from behind, and the roles would be exactly reversed. The two would exchange orbits a second time, bringing us back to the starting configuration.

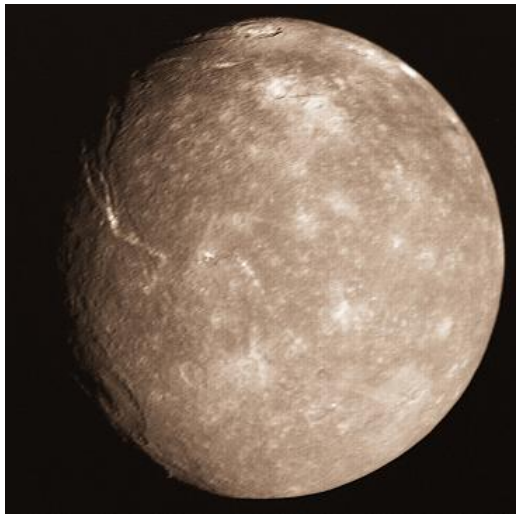
E. Uranus has 21 moons. The true totals are probably considerably larger. The Voyager 2 flyby in 1986 provided our first detailed views of Uranus. Good views were obtained of several the Moons.

1. Miranda is a most remarkable moon: it is relatively small, yet shows evidence of complex features such as deep canyons and striations. (470 km in diameter)

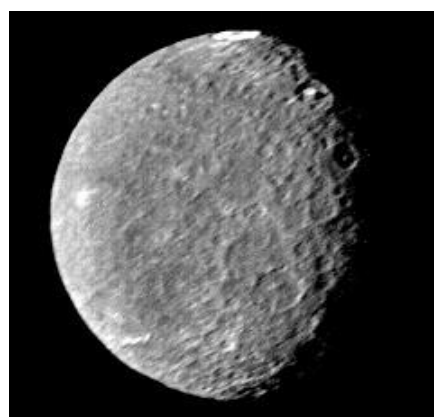
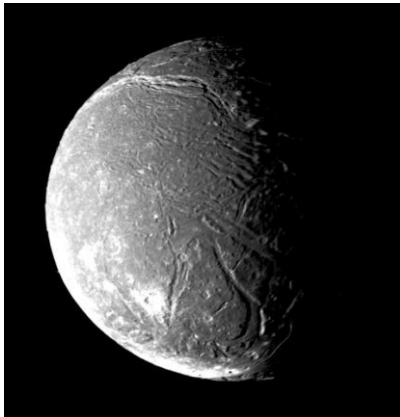


- a. Swaths are discolored, either darker or lighter than the background.

- b. Parts of the surface have been described as “jumbled” or “chaotic”. The most outstanding feature is the most dramatic cliff discovered so far in the solar system. A fractured segment has dropped as the crust split along two fractures. The drop created a beautiful scarp, running dozens of kilometers across the planet and rising as much as 5 km above the valley floor!
  - c. Voyager 2 scientists found that Miranda receives an estimated fourteen times as many asteroid hits per square kilometer as the outer moon, Oberon. Amazingly, the calculations revealed that, based on the number of larger craters on Oberon, Miranda has probably been hit by objects large enough to smash it to smithereens!
  - d. The pieces would go into orbit around Uranus and eventually reassemble. This may have happened several times.
2. Titania and Oberon are the largest of Uranus’s many moons and the outermost 2 of the 5 large moons discovered from Earth.



- a. The diameters of Titania and Oberon are respectively 1580 and 1520 km, compared to a range of 470-1170 km for the next biggest 3 moons and a mere 50-150 for the 10 small moons found by Voyager 2.
  - b. The surfaces of these 2 moons are moderately bright and heavily cratered. Spectroscopic studies indicate that they are composed of a mixture of water ice and darker soil, probably carbonaceous in character. The geology are not distinctive.
3. Ariel and Umbriel are the two mid-sized moons of the 5 Uranian satellites that were discovered from Earth.



- a. The diameters are measured at about 1170 and 1160 km respectively.

- b. They are heavily cratered and covered with dusty water-ice.
  - c. Umbriel's claim to fame lies in the fact that it is much darker than the other 4 large moons. Because its surface structures, mainly craters, show no other peculiarities, it remains a puzzle that one moon should be darker than its neighbors.
  - d. On Ariel, tidal heating seems to have caused expansion and crustal fracturing. This is manifested in large, fractured canyons, curving across the globe among the craters.
- F. In January 2003, 3 additional moons of Neptune were found, for a total of 11.
1. Neptune's largest moon, Triton, is only a bit smaller than our moon and Jupiter's Europa, but it is as different from each as smooth, icy Europa is from our rock-stewn, cratered moon.
    - a. Triton is the only large satellite with retrograde orbital motion, (clockwise as seen from the north side of the solar system).
    - b. Its orbit also has an uncommonly high  $23^\circ$  tilt off the plane of the planet's equator.
    - c. All this suggests that Triton's origin is different from that of most other major satellites.

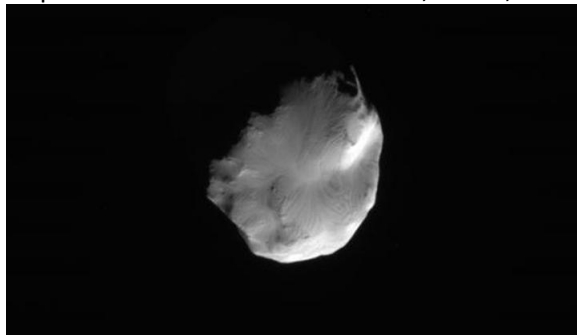


- d. Another unusual property of Triton is that through spectroscopic observations indicates a faint thin atmosphere of nitrogen.
- e. In 1989, Voyager 2 imaged unexpected erupting geyserlike vents, emitting columns of dark smoke that rises vertically as much as 8 km, and shear off in high-altitude winds, making long, horizontal streamers.
- f. Instead of an ancient, cratered surface, the Voyager pictures revealed a peculiar surface of winding fissures, flat-floored frozen "ice-lakes", and knobby-surfaced plains called "cantaloupe terrain", since the texture looked strikingly like the skin of that fruit.
- g. The surface seems composed mainly of methane and nitrogen ices, with a seasonal bright winter polar cap of nitrogen frost. In places, the geyser vents are accompanied by black streaks, all running the same direction across the surface; these probably mark deposits of dark dust erupted from the geyser and then blown in a fixed direction by prevailing winds.

- h. Voyager 2 also showed that Triton's surface has a daytime temperature of  $-235^{\circ}\text{C}$ , the coldest daytime temperature of any world.
  - i. The absence of impact craters meant that the surface is relatively young, perhaps only a few hundred million years.
  - j. What energy source could have provided heat to resurface a cold ice world so far from the sun?
2. Nereid, the outermost large moon of Neptune, was discovered in 1949 by the Dutch-American astronomer Gerard Kuiper.



- a. Nereid---with a diameter of 340 km---may be a captured interplanetary body. The evidence comes from the extreme elliptical shape of the orbit, and its great distance from Neptune, where a capture would be relatively easy. The elliptical orbit takes Nereid from nearly 10 million kilometers to only 1.4 million kilometers from Neptune.
3. Neptune's innermost known moon, Naiad, takes only 7.2 hours to go around Neptune.



- a. Naiad has an orbit inclined about  $4.5^{\circ}$  to the ring plane, so that it rises "above" the rings on one side of Neptune, then crosses the ring plane to orbit "below" the rings on the other side. Given time, such a moon could be expected to move into the ring plane; thus, a recent impact may have bumped it into its present inclined orbit.

G. Questions:

1. How do studies of other planets and moons in the Solar System potentially help us understand various aspects of Earth better, such as its climate, surface features, interior, and history?
2. Explain why Jupiter's innermost large moon, Io, has so much active volcanism.
3. Discuss evidence that Jupiter's second large moon, Europa, has an ocean (or slush) of water below its icy surface.
4. State in what way Saturn's largest moon, Titan, is unique among moons in the Solar System.
5. Discuss how Jupiter's and Saturn's moons greatly enrich the range of "planetary" surface phenomena to which we have access in the Solar System.
6. How can we determine the approximate age of a moon's surface from the number of



visible craters per unit area? (Assume the cratering rate as a function of time was similar to that on Earth's Moon.)

7. What is the difference between Prograde and Retrograde of a moon's orbit?
  
8. Name the two moons of Mars?
9. Name the 4 main moons of Uranus?
10. Name the 3 main moons of Neptune?
11. What is the most striking characteristic of Triton?
12. What is the most striking characteristic of Miranda? How do you think it occurred?
  
13. What is the most striking characteristic of Callisto?
14. What is the most striking characteristic of Titan?
  
15. Which moon do you think is the most likely to harbor life? Why?
  
  
16. Which moon in the Solar System would you like to spend billions of \$\$\$ to explore? Why?
  
  
17. Explain the strange relationship of the moons Janus and Epimetheus? Why and How?