Department of Physics and Astronomy

Astronomy 1X

Session 2007-08

Solar System Physics I

Dr Martin Hendry

5 lectures, beginning Autumn 2007

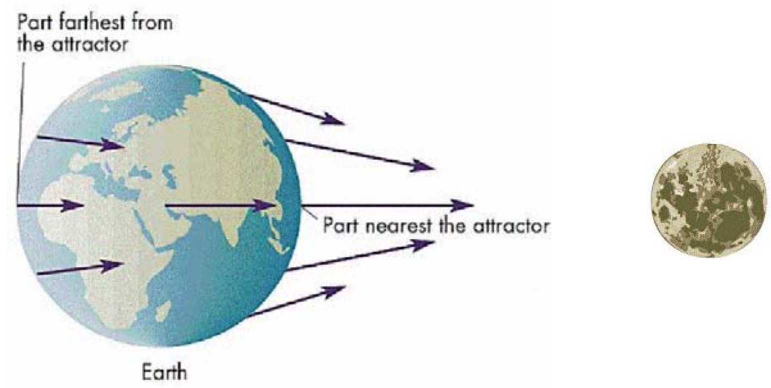
ASTRONOMY ASTROPHYSICS

UNIVERSITY of GLASGOW

Section 11: More on Tidal Forces

Tidal forces also have an effect (albeit less destructive) *outside* the Roche stability limit.

Consider the Moon's tide on the Earth (and vice versa).

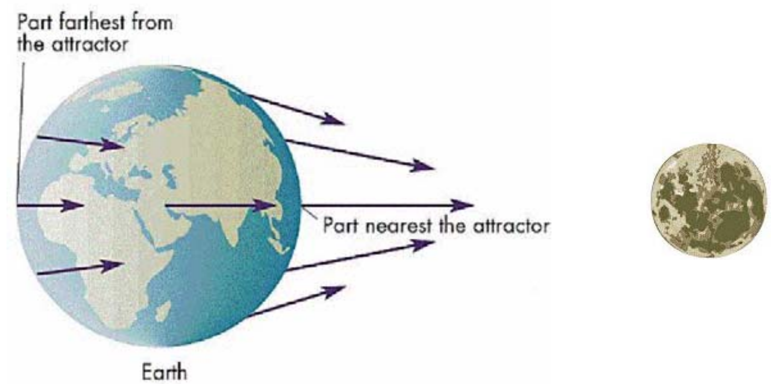


The tidal force produces an oval bulge in the shape of the Earth (and the Moon)

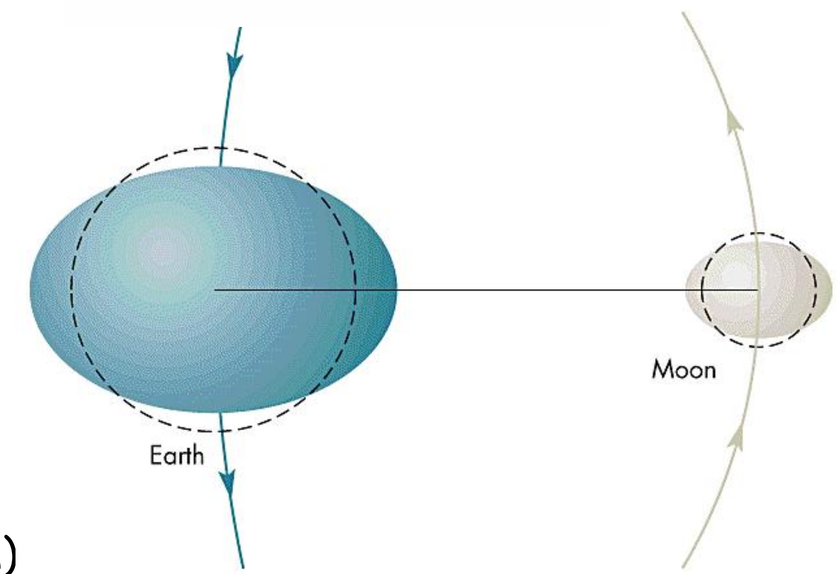
Section 11: More on Tidal Forces

Tidal forces also have an effect (albeit less destructive) *outside* the Roche stability limit.

Consider the Moon's tide on the Earth (and vice versa).



The tidal force produces an oval bulge in the shape of the Earth (and the Moon)



There are, therefore, **two** high and low tides every ~25 hours.

(Note: not every 24 hours, as the Moon has moved a little way along its orbit by the time the Earth has completed one rotation)

The Sun also exerts a tide on the Earth.

Now, $F_T \propto \dfrac{M_P}{r^3}$ so

$$\boxed{\frac{F_{T,\mathrm{Sun}}}{F_{T,\mathrm{Moon}}} = \frac{M_{\mathrm{Sun}}}{M_{\mathrm{Moon}}}\left(\frac{r_{\mathrm{Moon}}}{r_{\mathrm{Sun}}}\right)^3} \qquad (11.1)$$

and

$$M_{\mathrm{Sun}} = 1.989\times10^{30}\ \mathrm{kg} \qquad M_{\mathrm{Moon}} = 7.35\times10^{22}\ \mathrm{kg}$$

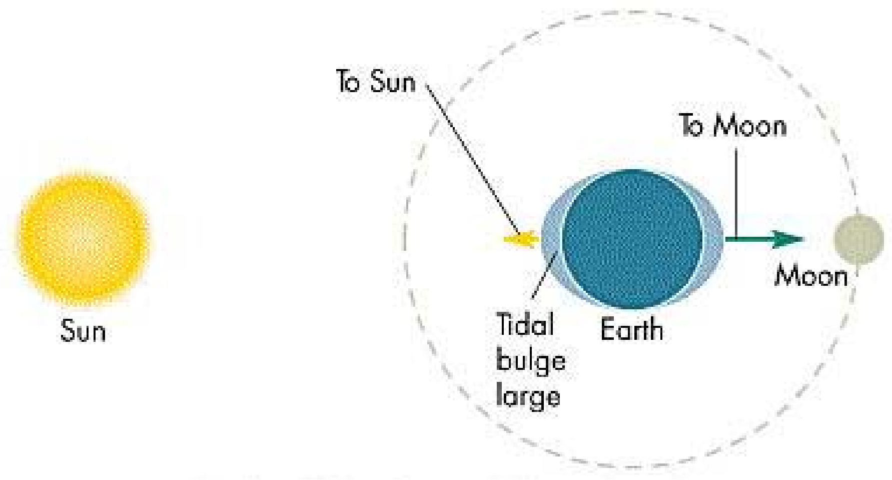
$$r_{\mathrm{Sun}} = 1.496\times10^{11}\ \mathrm{m} \qquad r_{\mathrm{Moon}} = 3.844\times10^{8}\ \mathrm{m}$$

so that

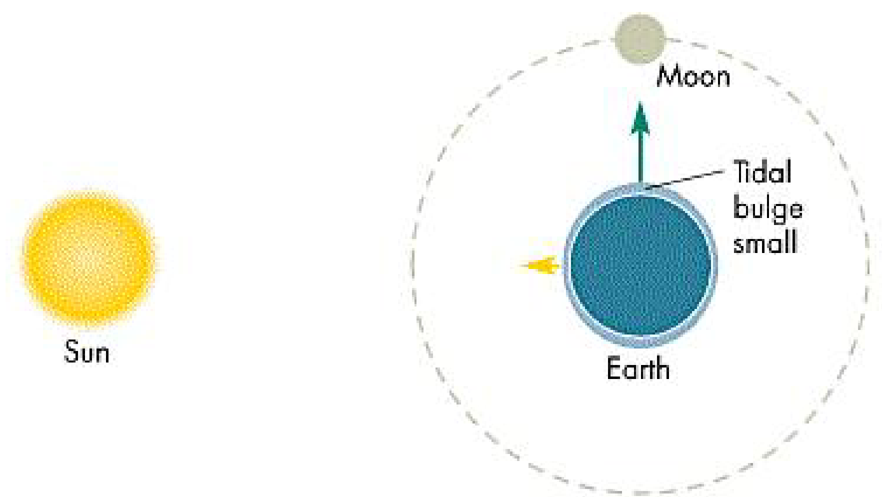
$$\boxed{\frac{F_{T,\mathrm{Sun}}}{F_{T,\mathrm{Moon}}} = \frac{M_{\mathrm{Sun}}}{M_{\mathrm{Moon}}}\left(\frac{r_{\mathrm{Moon}}}{r_{\mathrm{Sun}}}\right)^3 \approx 0.5} \qquad (11.2)$$

The Sun and Moon exert a tidal force similar in magnitude. The size of their combined tide on the Earth depends on their *alignment*.

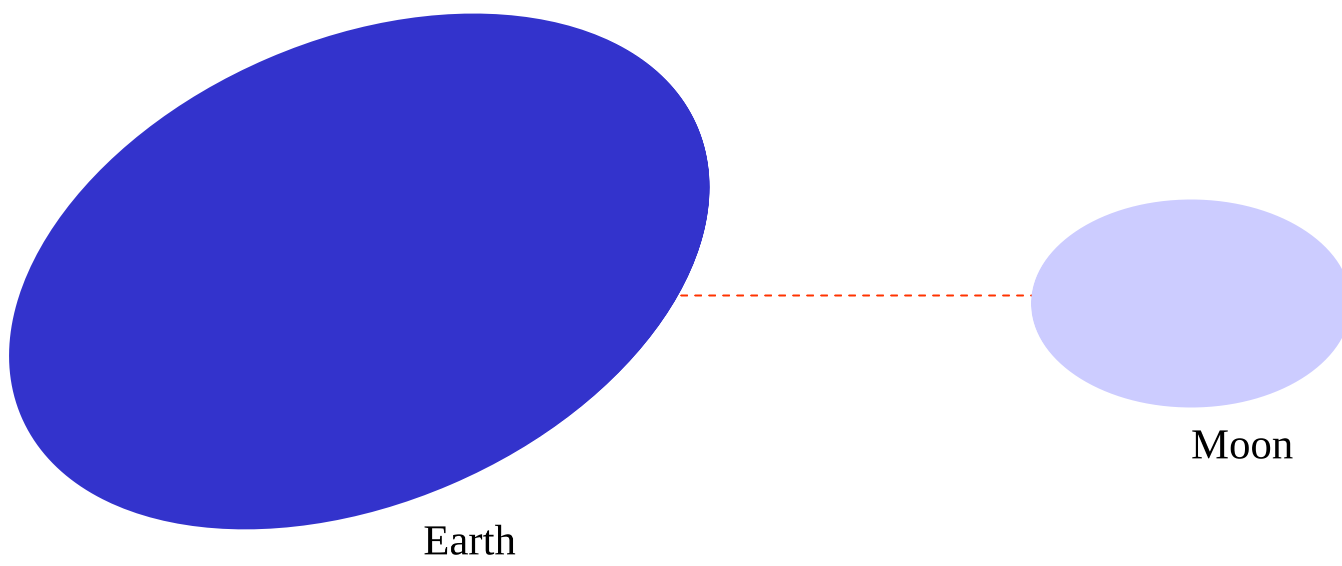
Spring tides occur when the Sun, Moon and Earth are aligned (at Full Moon and New Moon). High tides are much higher at these times.



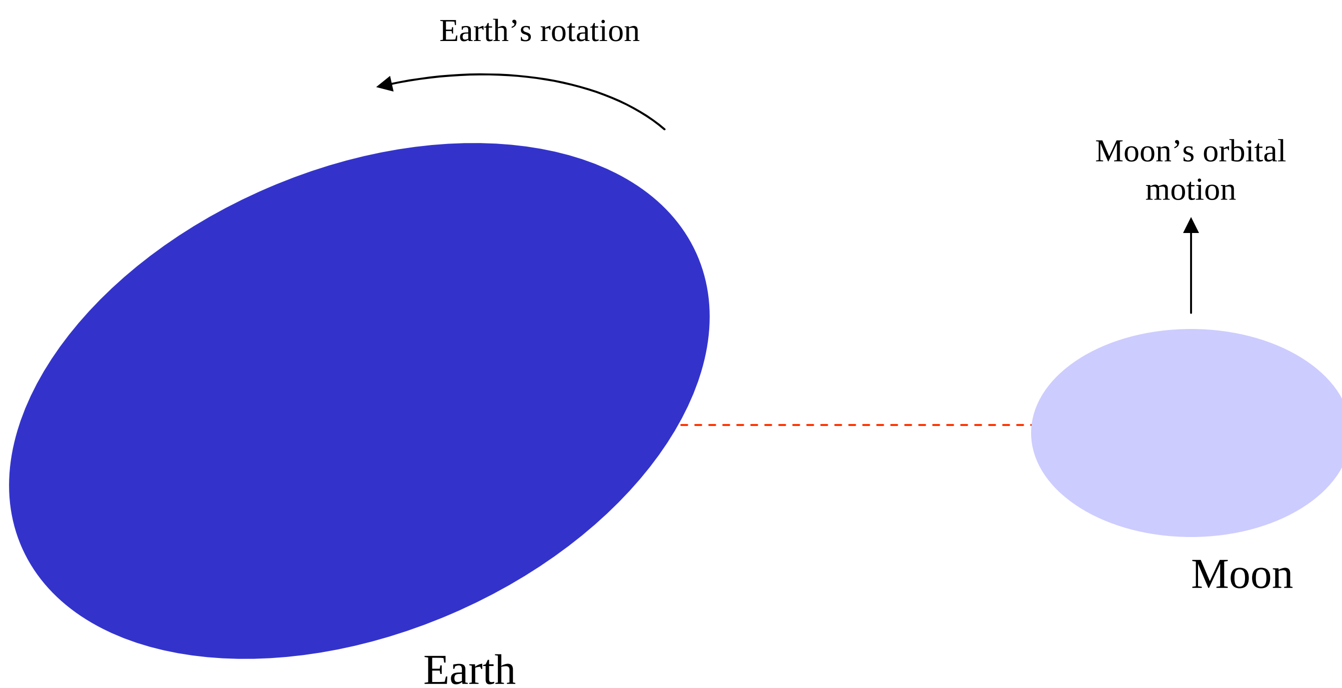
Neap tides occur when the Sun, Moon and Earth are at right angles (at First Quarter and Third Quarter). Low tides are much lower at these times.



Even if there were no tidal force on the Earth from the Sun, the Earth's tidal bulge would **not** lie along the Earth-Moon axis. This is because of the Earth's rotation.

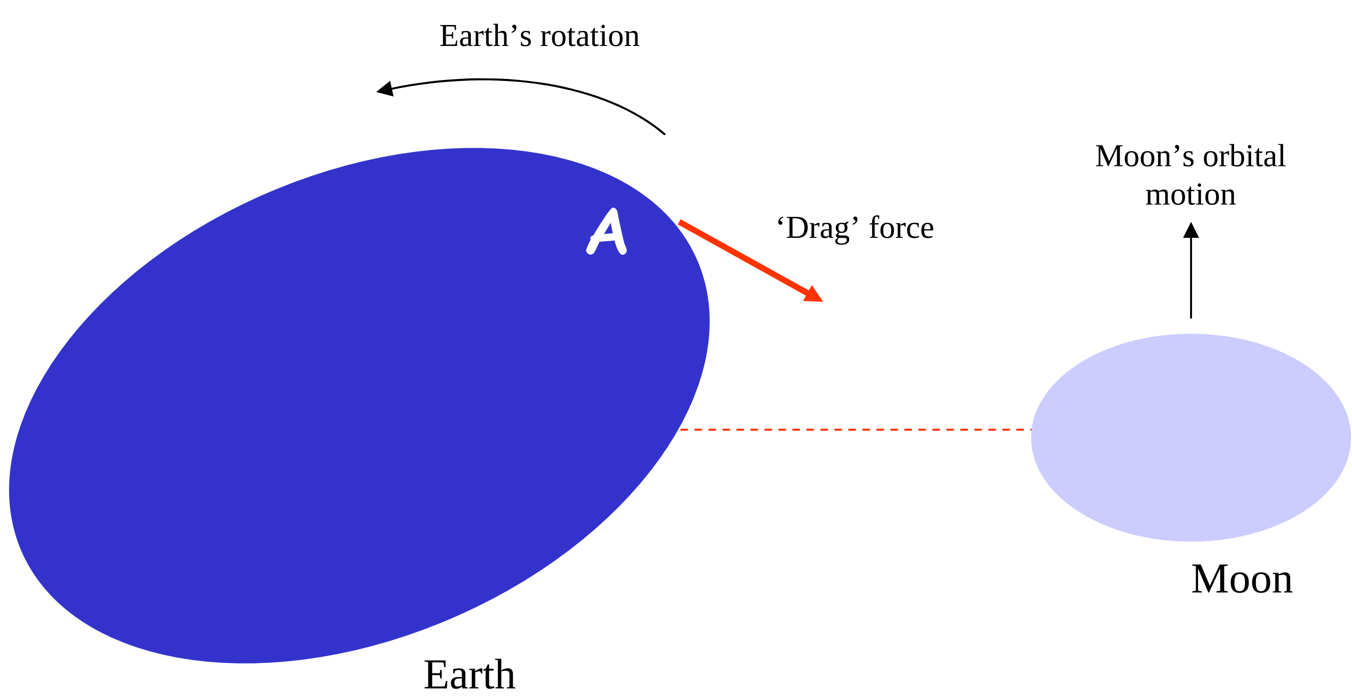


The Earth’s rotation carries the tidal bulge ahead of the Earth-Moon axis. (The Earth’s crust and oceans cannot instantaneously redstribute themselves along the axis due to friction)



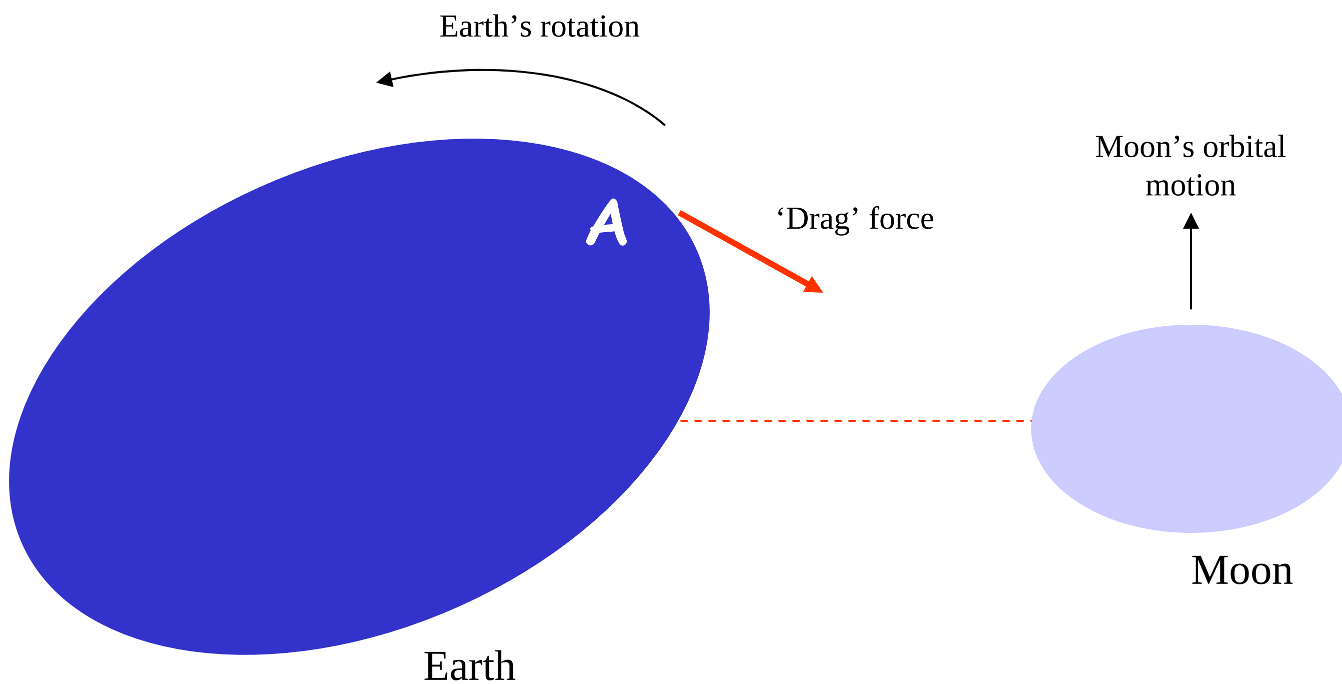
The Moon exerts a drag force on the tidal bulge at *A*, which slows down the Earth's rotation.

The length of the Earth's day is increasing by 0.0016 sec per century.



At the same time, bulge A is pulling the Moon forward, speeding it up and causing the Moon to spiral outwards. **This follows from the conservation of angular momentum**.

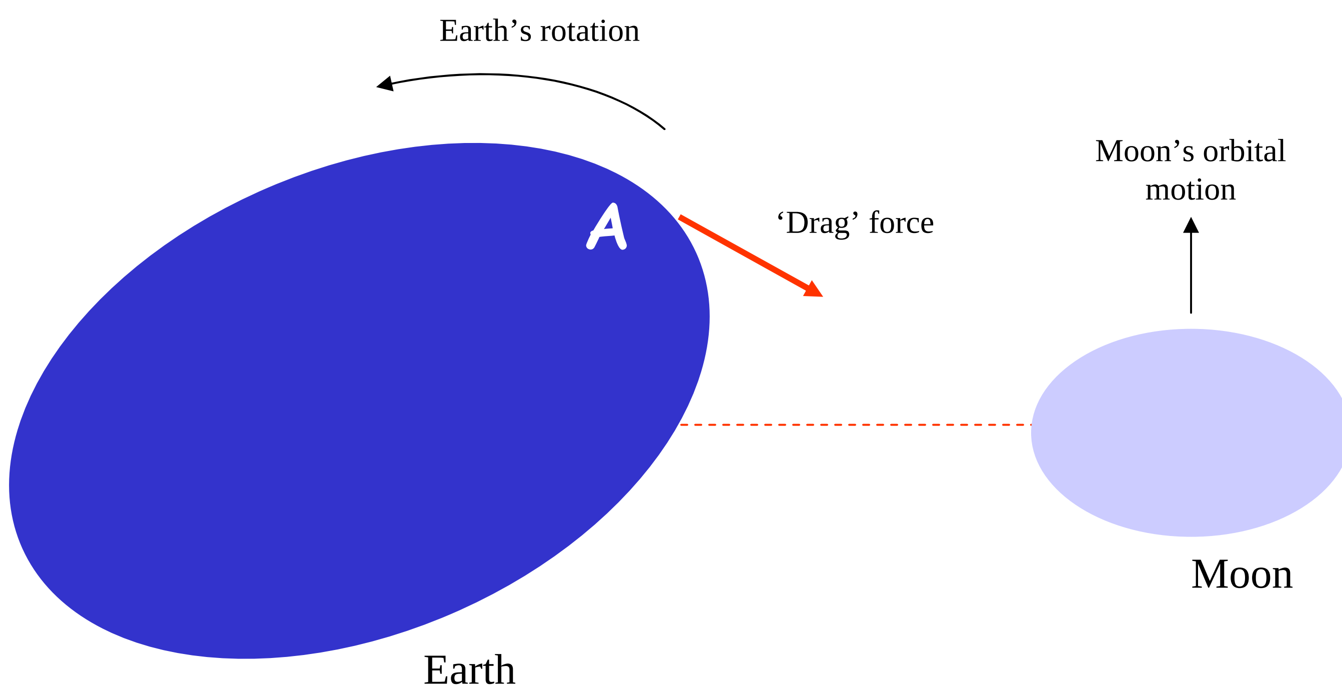
The Moon's semi-major axis is increasing by about 3cm per year.



- Given sufficient time, the Earth's rotation period would slow down until it equals the Moon's orbital period – so that the same face of the Earth would face the Moon at all times.

(This will happen when the Earth's "day" is 47 days long)

In the case of the Moon, this has *already happened !!!*



- Given sufficient time, the Earth's rotation period would slow down until it equals the Moon's orbital period – so that the same face of the Earth would face the Moon at all times.

  (This will happen when the Earth's "day" is 47 days long)

  In the case of the Moon, this has *already happened !!!*

- Tidal locking has occurred much more rapidly for the Moon than for the Earth because the Moon is much smaller, and the Earth produces larger tidal deformations on the Moon than vice versa.

- Given sufficient time, the Earth's rotation period would slow down until it equals the Moon's orbital period – so that the same face of the Earth would face the Moon at all times.

  (This will happen when the Earth's "day" is 47 days long)

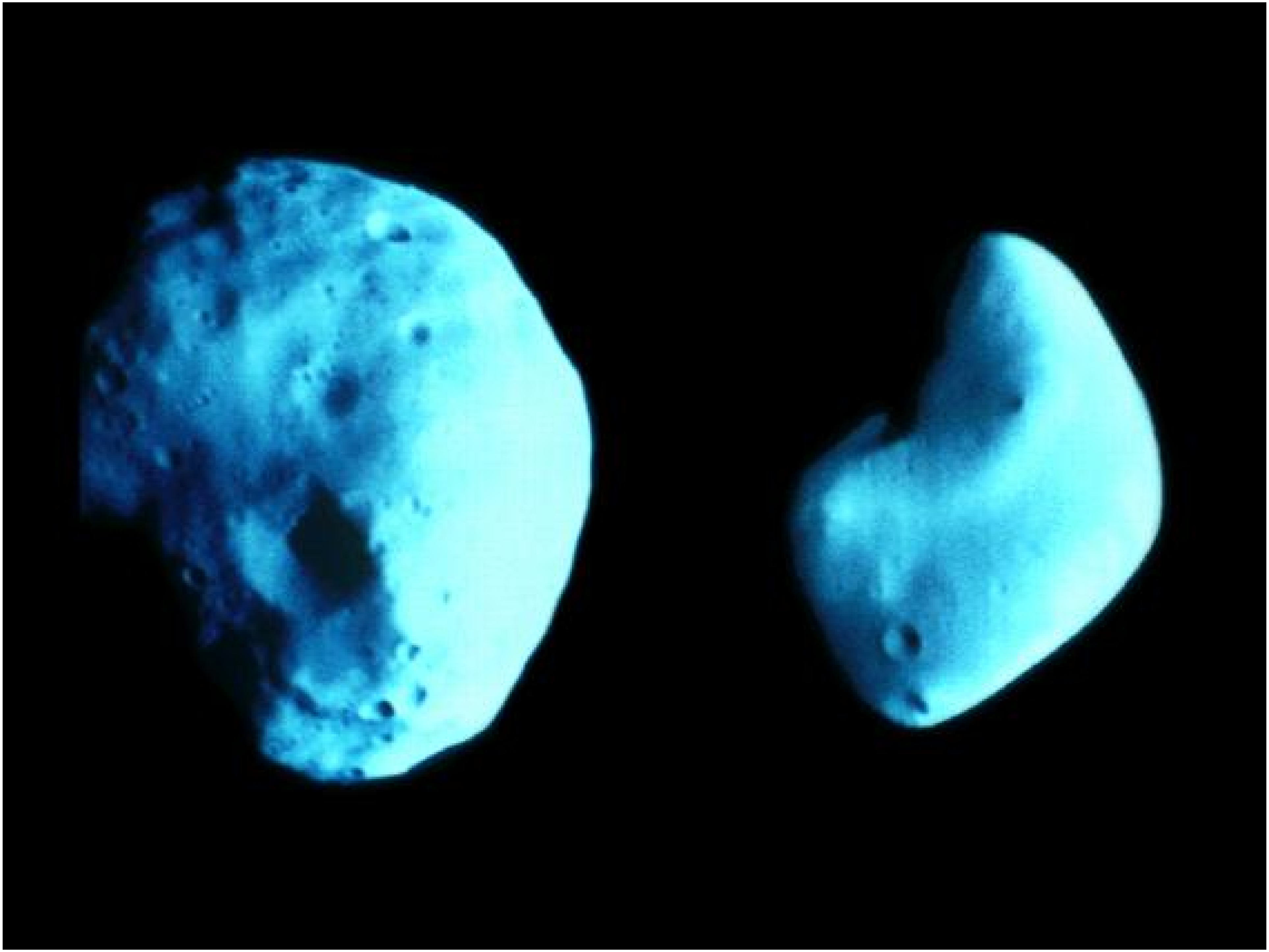
  In the case of the Moon, this has *already happened !!!*

- Tidal locking has occurred much more rapidly for the Moon than for the Earth because the Moon is much smaller, and the Earth produces larger tidal deformations on the Moon than vice versa.

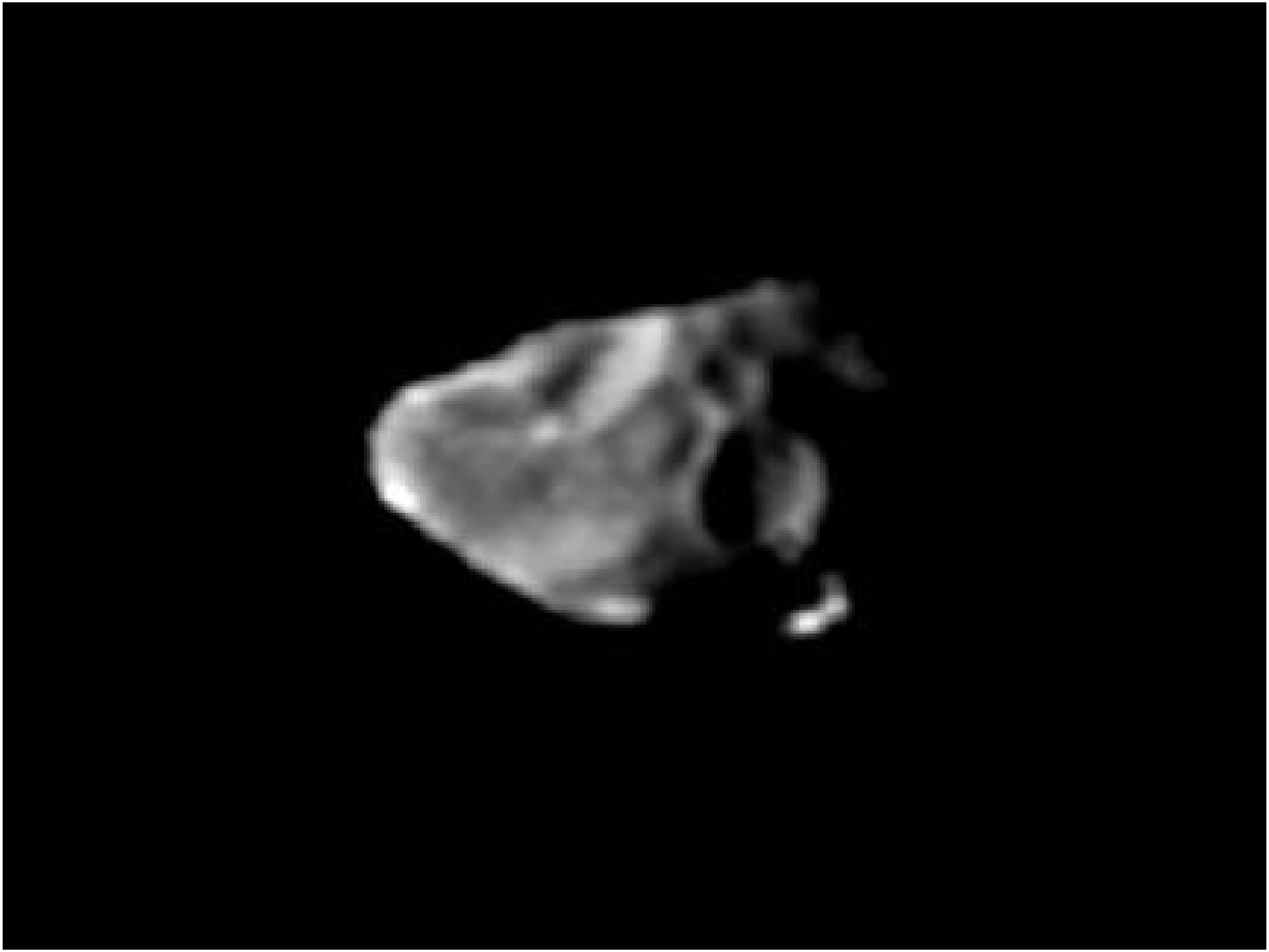
- The Moon isn't exactly tidally locked. It 'wobbles' due to the perturbing effect of the Sun and other planets, and because its orbit is **elliptical**. Over about 30 years, we see 59% of the Moon's surface.

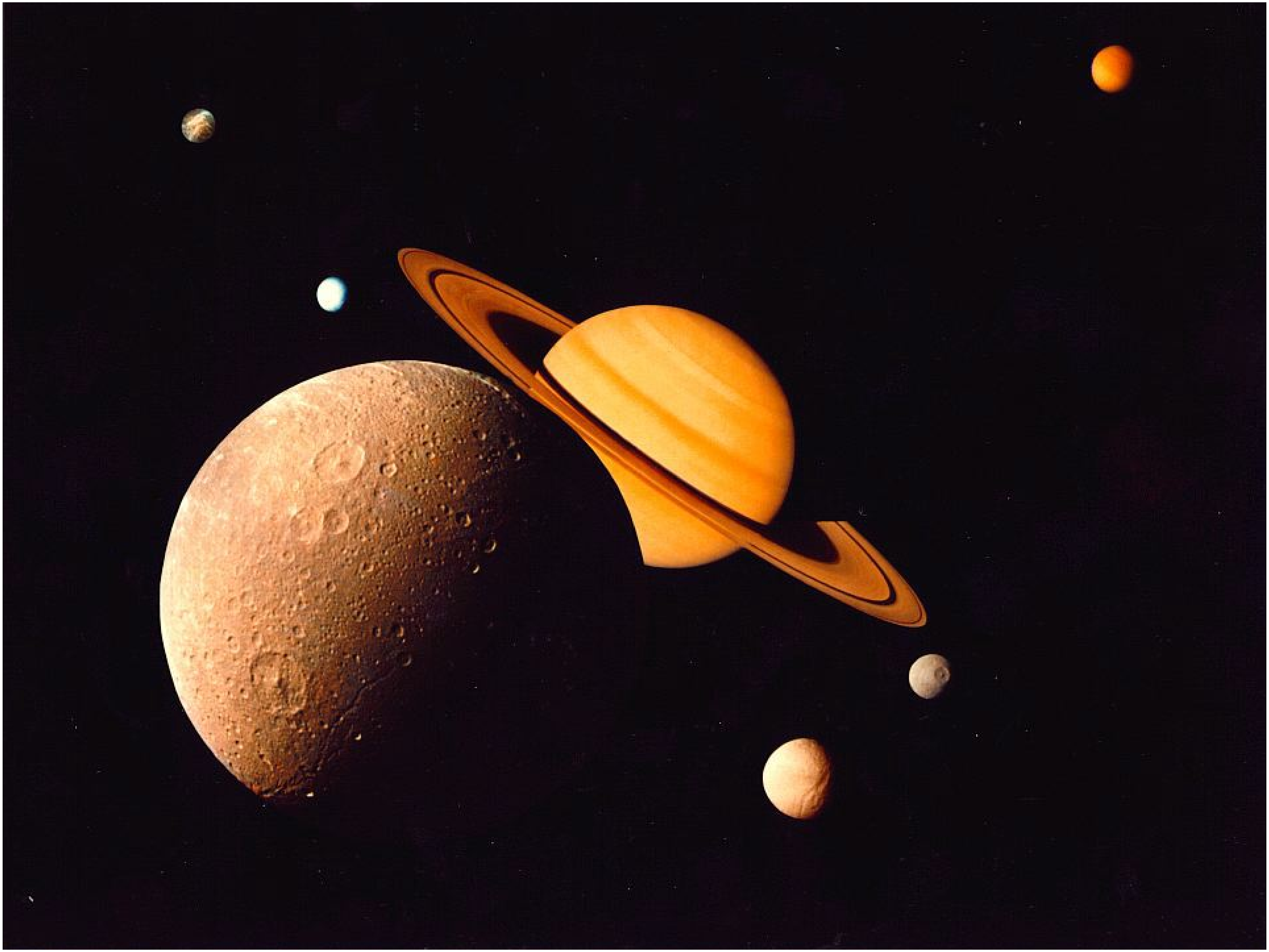
- Many of the satellites in Solar System are in synchronous rotation, e.g.

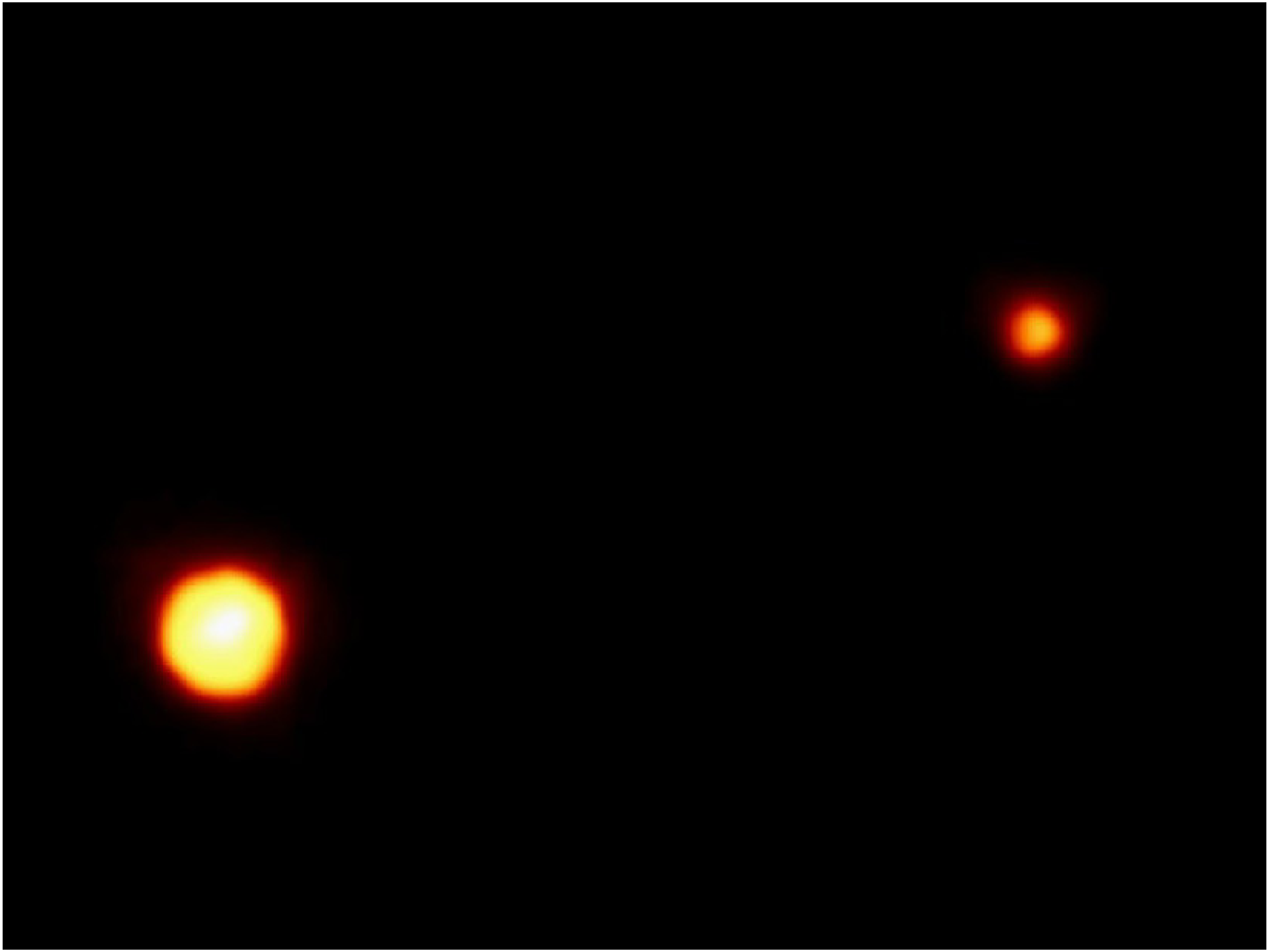
Mars:	Phobos and Deimos
Jupiter:	Galilean moons + Amalthea
Saturn:	All major moons, except Phoebe + Hyperion
Neptune:	Triton
Pluto:	Charon



The moons of Jupiter



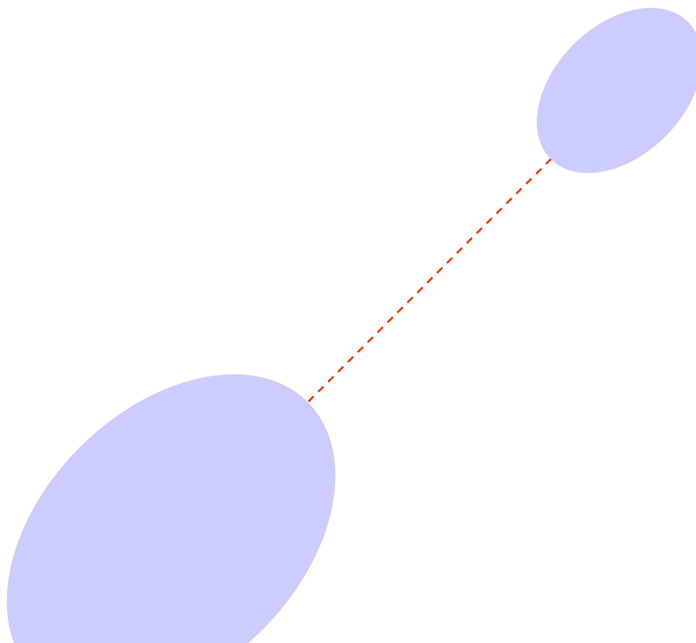


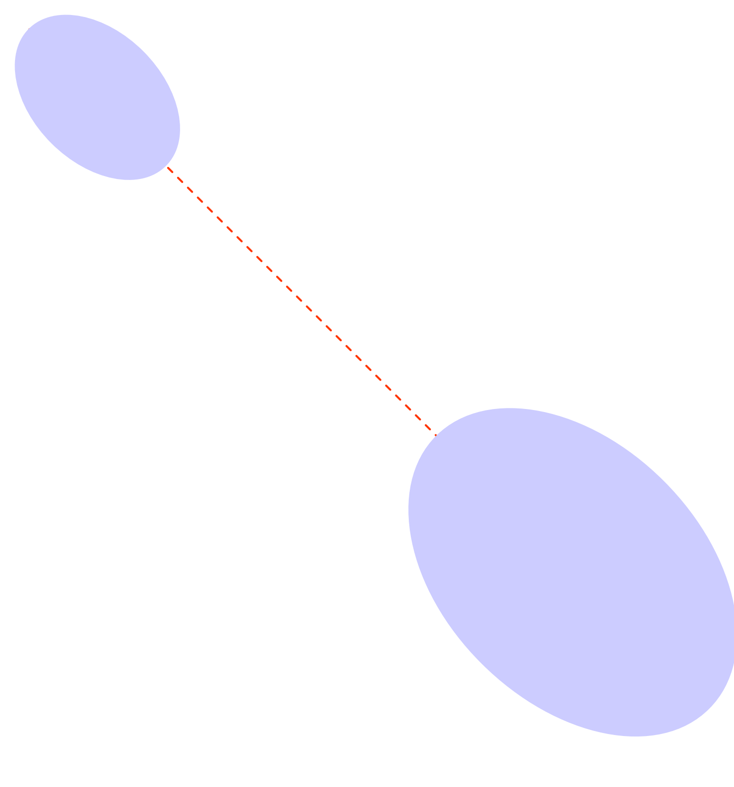


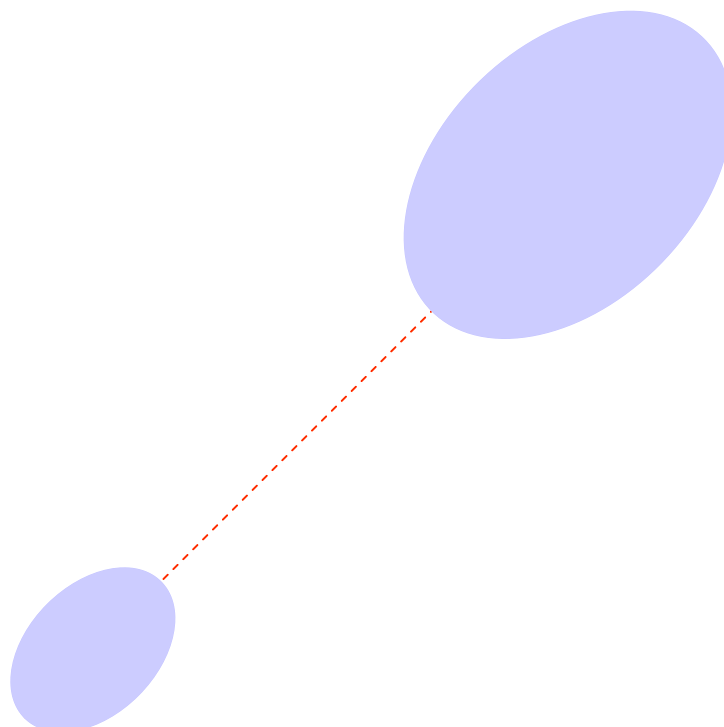
- Many of the satellites in Solar System are in synchronous rotation, e.g.

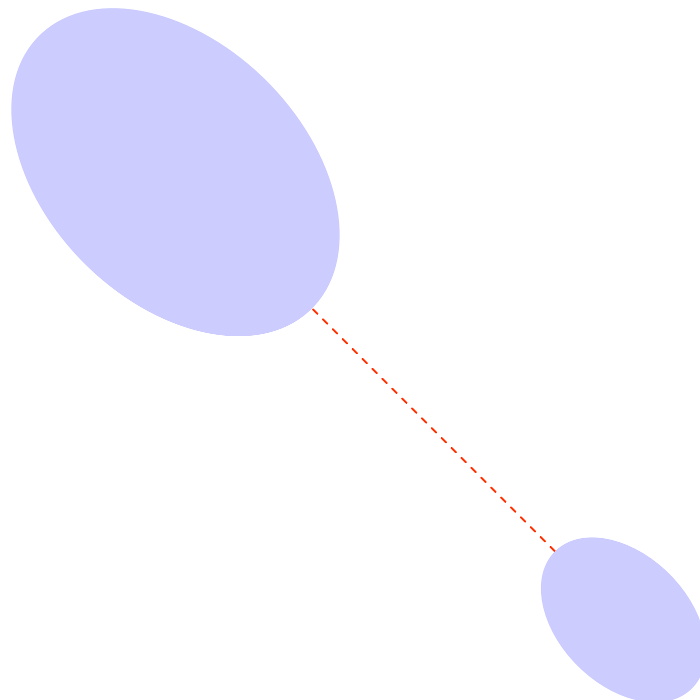
Mars:	Phobos and Deimos
Jupiter:	Galilean moons + Amalthea
Saturn:	All major moons, except Phoebe + Hyperion
Neptune:	Triton
Pluto:	Charon

- Pluto and Charon are in mutual synchronous rotation: i.e. the same face of Charon is always turned towards the same face of Pluto, and vice versa.







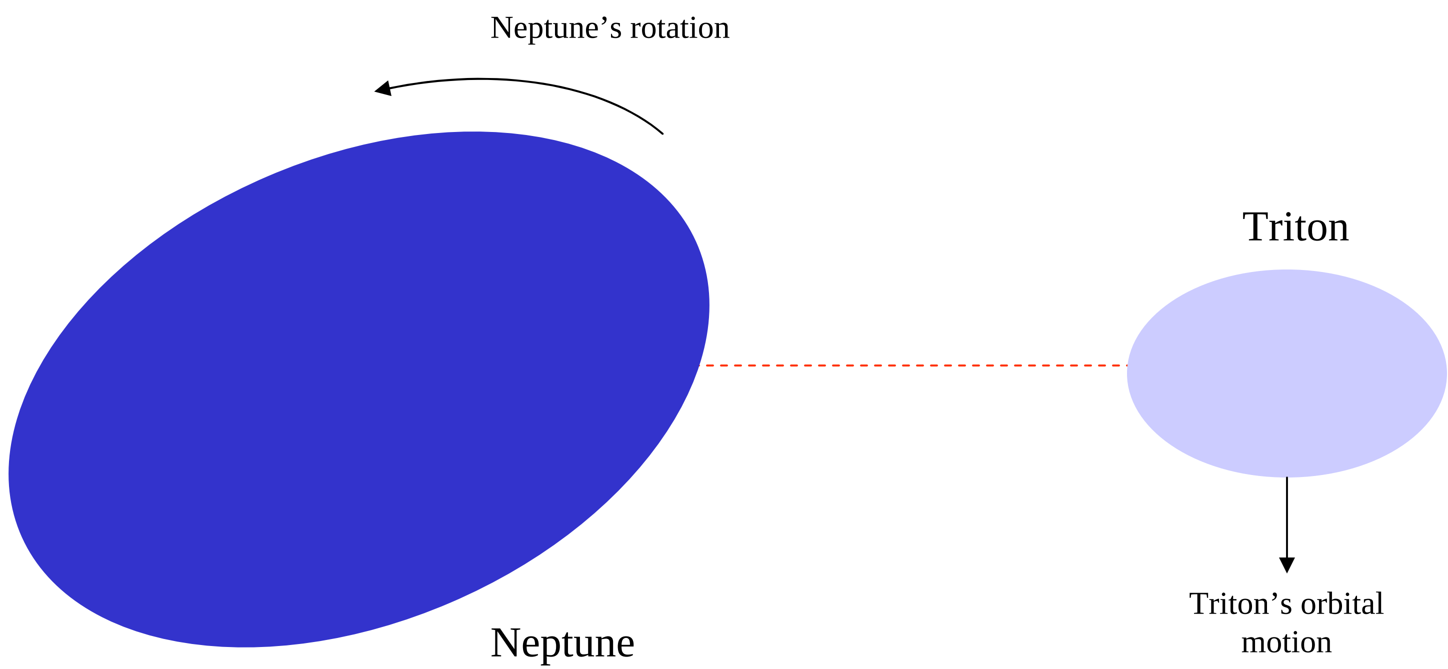


- Many of the satellites in Solar System are in synchronous rotation, e.g.

Mars:	Phobos and Deimos
Jupiter:	Galilean moons + Amalthea
Saturn:	All major moons, except Phoebe + Hyperion
Neptune:	Triton
Pluto:	Charon

- Pluto and Charon are in mutual synchronous rotation: i.e. the same face of Charon is always turned towards the same face of Pluto, and vice versa.

- Triton orbits Neptune in a **retrograde** orbit (i.e. opposite direction to Neptune's rotation).

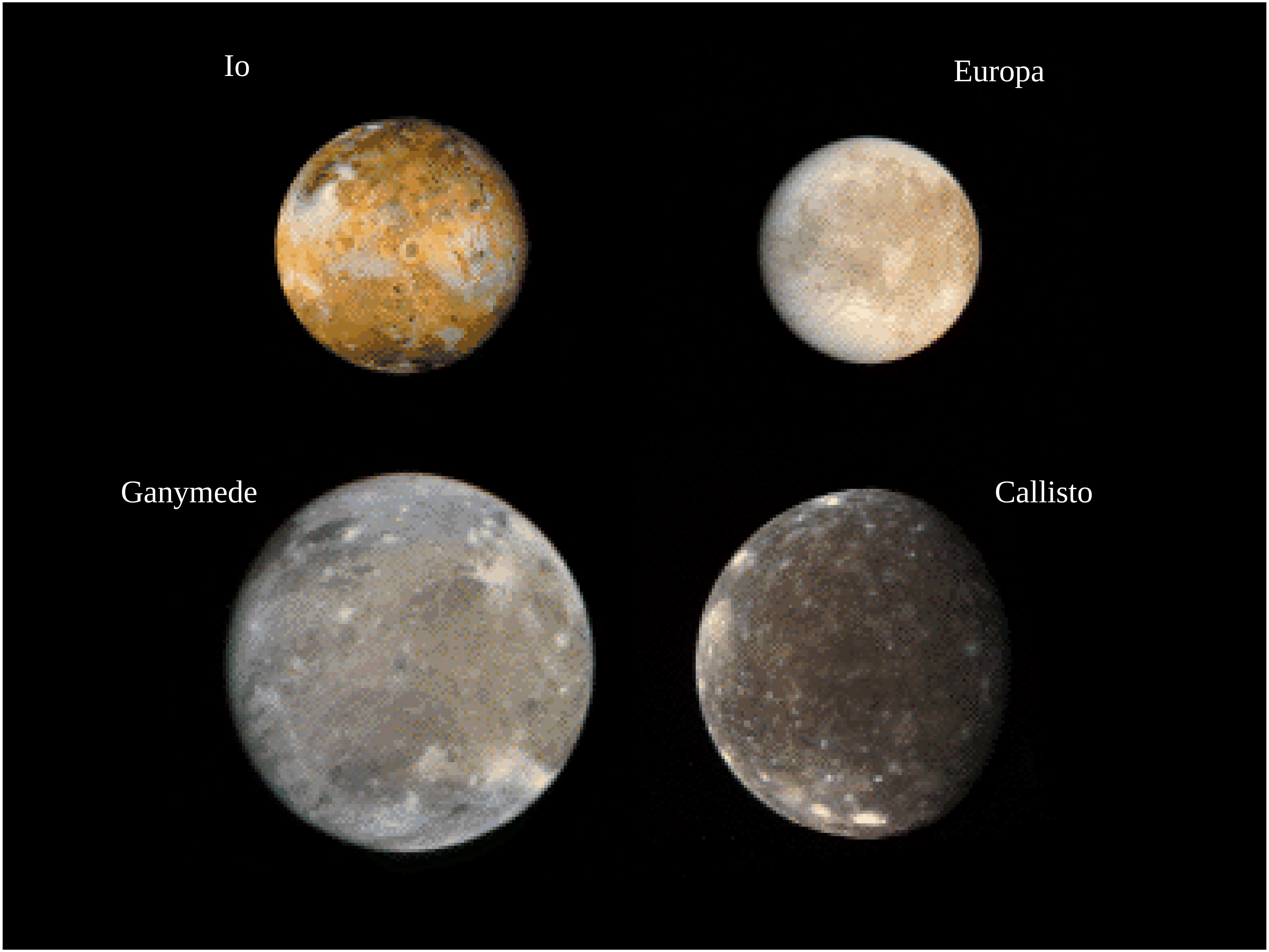


In this case Neptune's tidal bulge acts to *slow down* Triton. The moon is spiralling toward Neptune (although it will take billions of years before it reaches the Roche stability limit)

Section 12: The Galilean Moons of Jupiter

Tidal forces have a major influence on the Galilean Moons of Jupiter

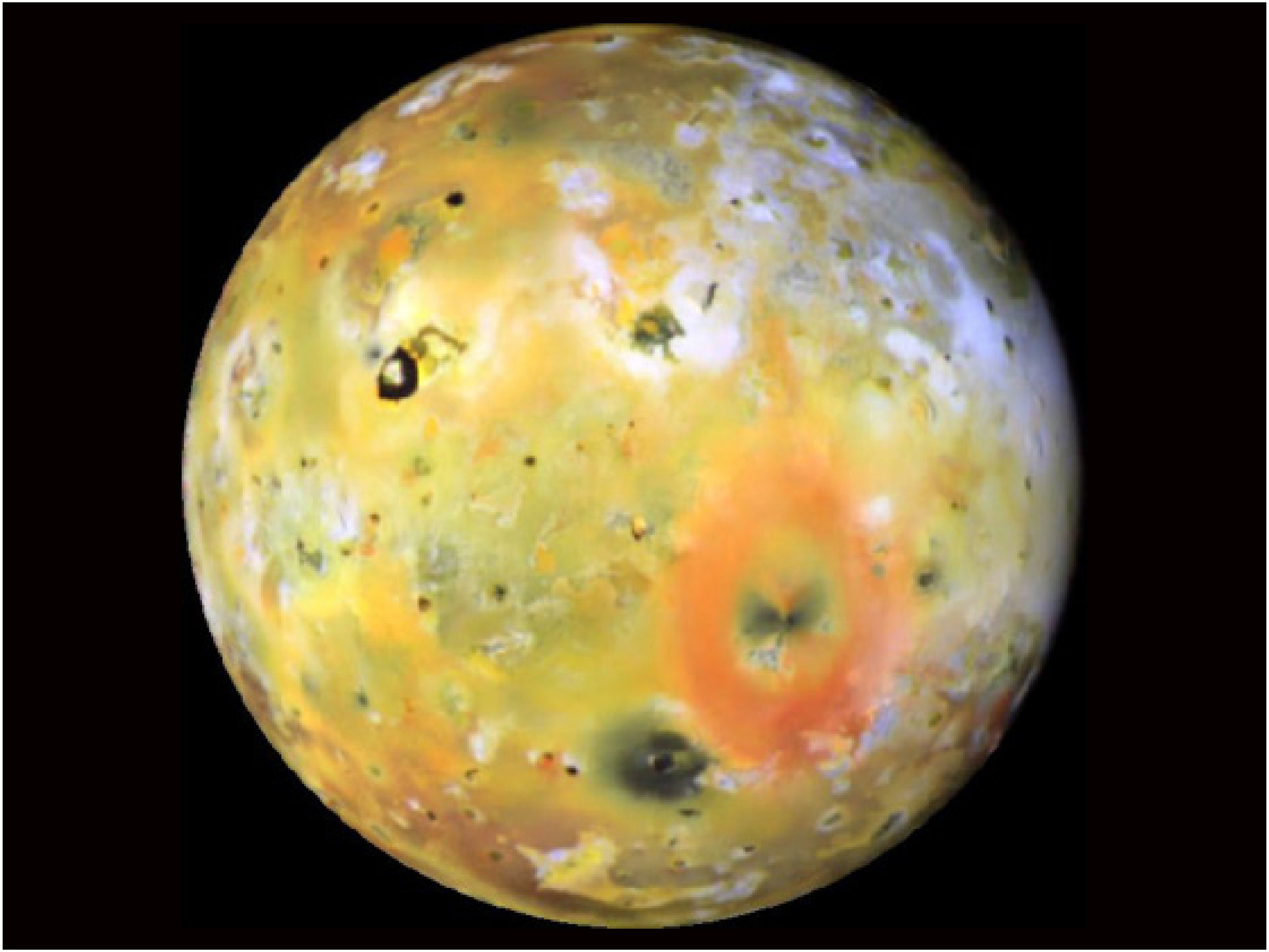
Name	Diameter (m)	Semi-major axis (m)	Orbital Period (days)	Mass (kg)
Io	3.642×10^{6}	4.216×10^{8}	1.769	8.932×10^{22}
Europa	3.120×10^{6}	6.709×10^{8}	3.551	4.791×10^{22}
Ganymede	5.268×10^{6}	1.070×10^{9}	7.155	1.482×10^{23}
Callisto	4.800×10^{6}	1.883×10^{9}	16.689	1.077×10^{23}
The Moon	3.476×10^{6}	3.844×10^{8}	27.322	7.349×10^{22}
Mercury	4.880×10^{6}	—	—	3.302×10^{23}

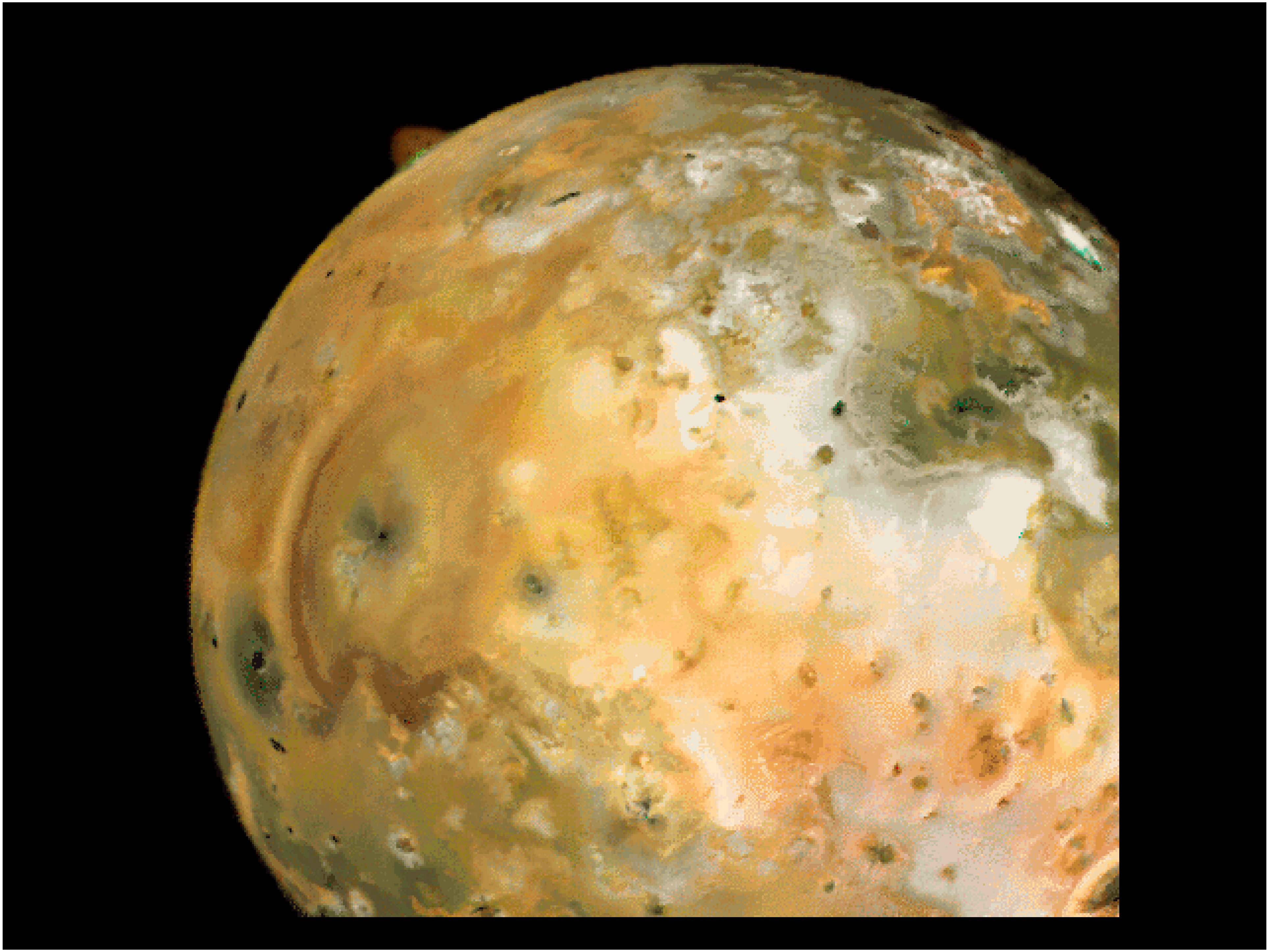

Io
Europa
Ganymede
Callisto

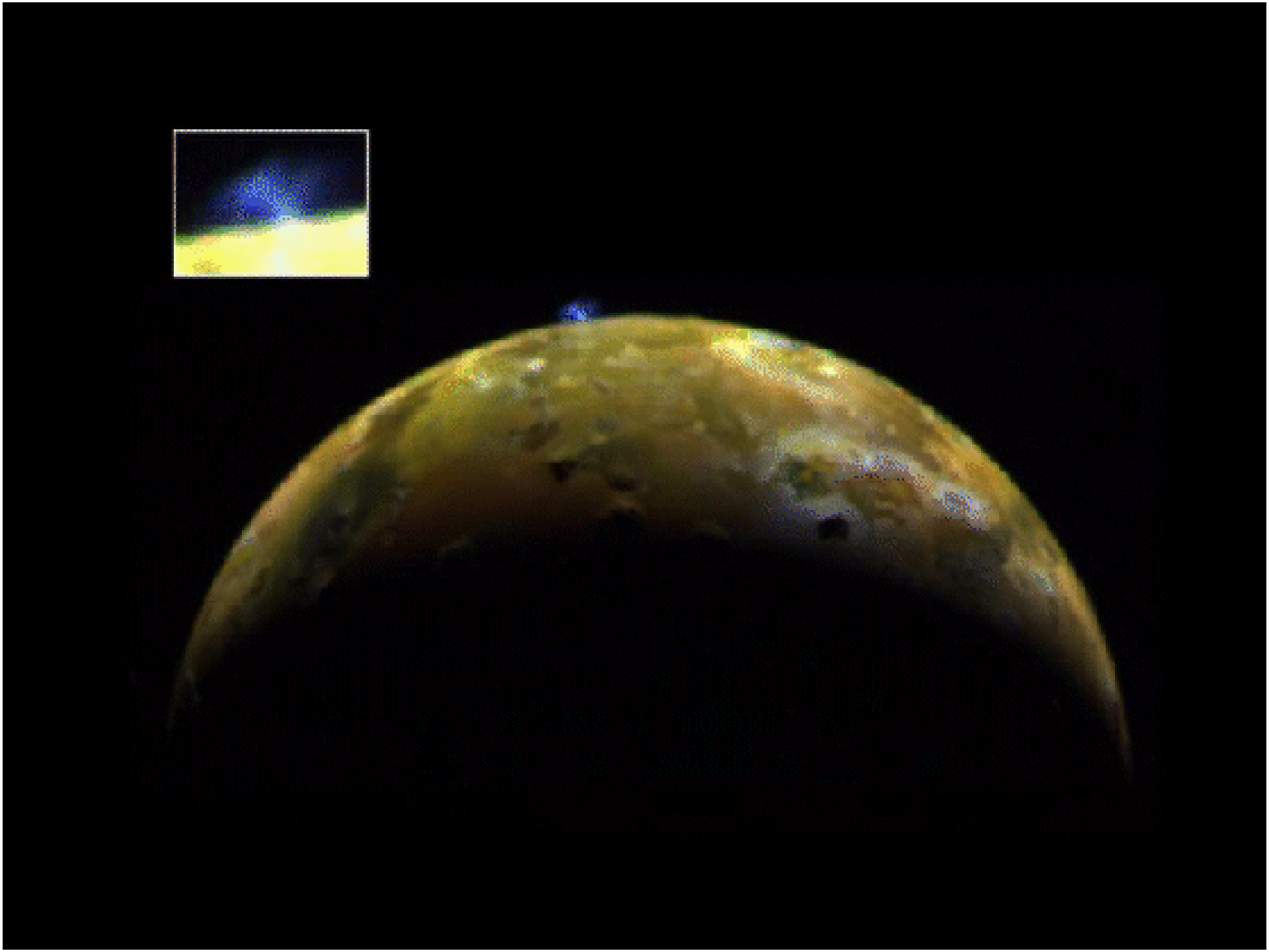
The orbital periods of Io, Europa and Ganymede are almost exactly in the ratio **1:2:4**. This leads to **resonant effects** :

- The orbit of Io is perturbed by Europa and Callisto, because the moons regularly line up on one side of Jupiter. The gravitational pull of the outer moons is enough to produce a small eccentricity in the orbit of Io. This causes the tidal bulges of Io to 'wobble' (same as the Moon) which produces large amount of **frictional heating**.

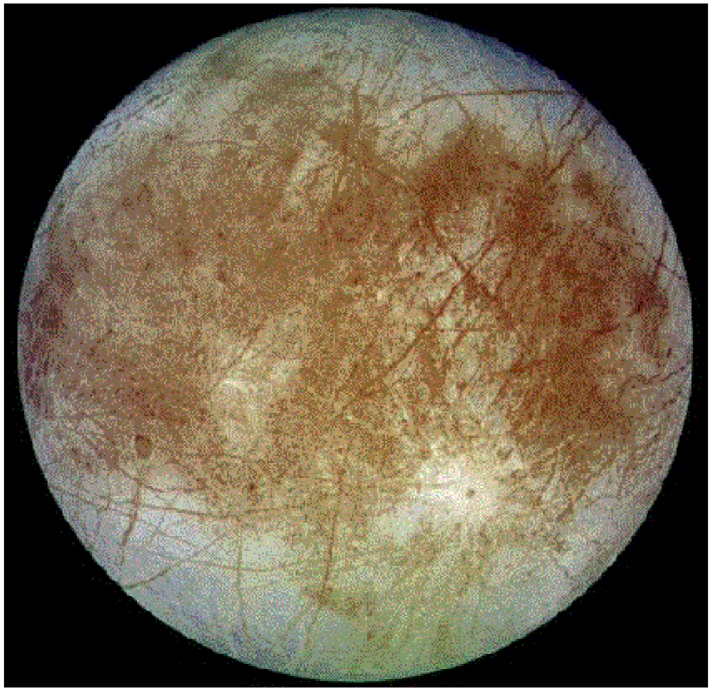
- The surface of Io is almost totally **molten**, yellowish-orange in colour due to sulphur from its continually erupting **volcanoes**.

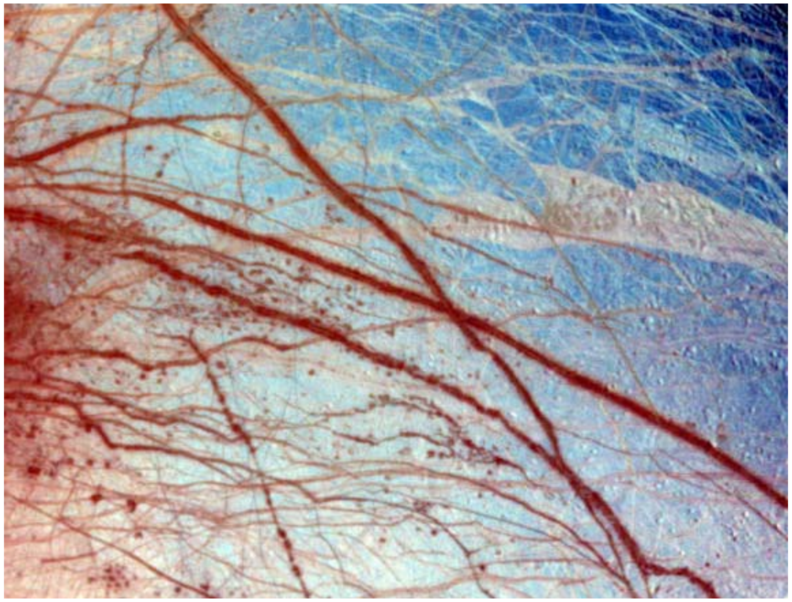


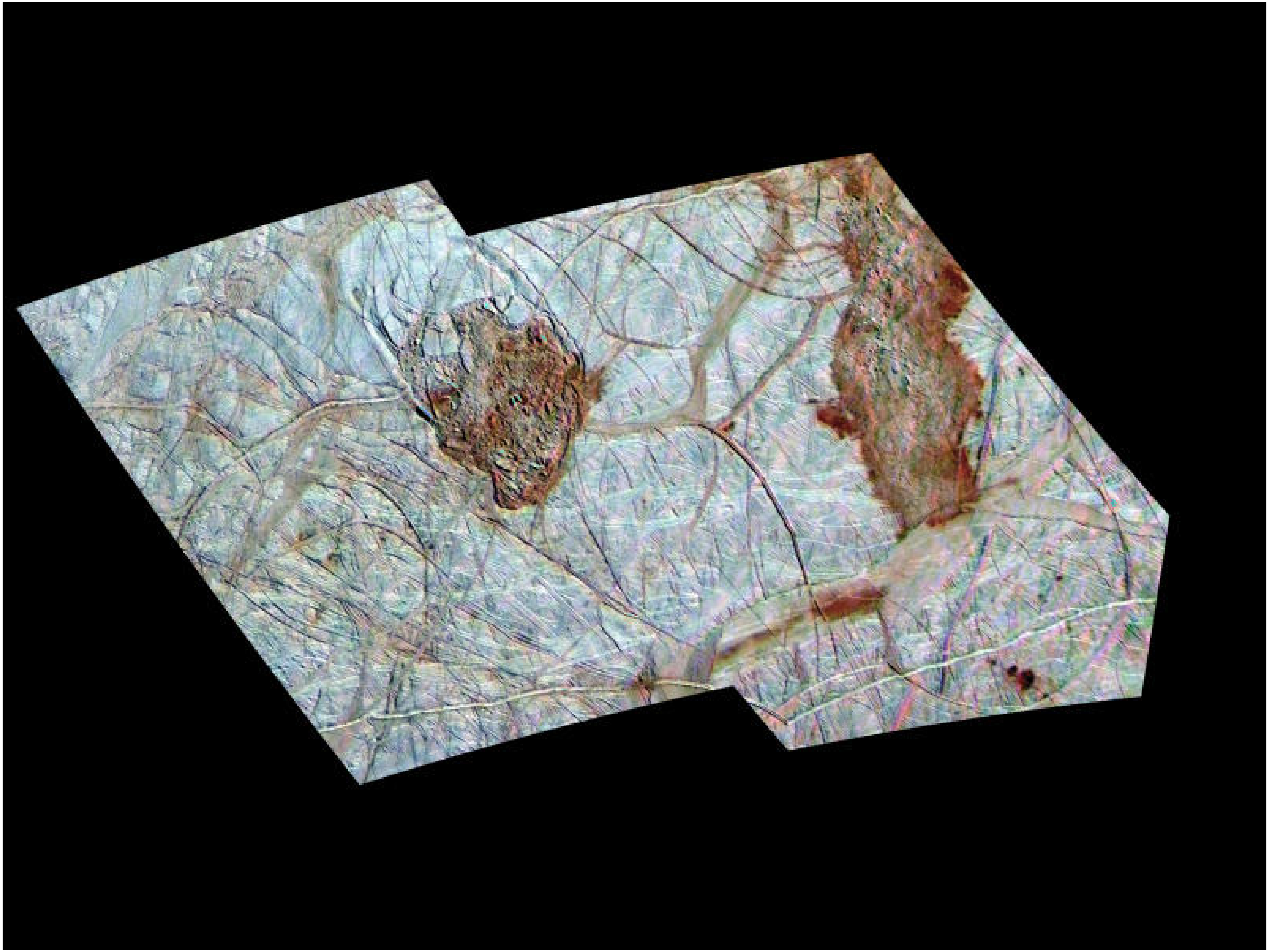




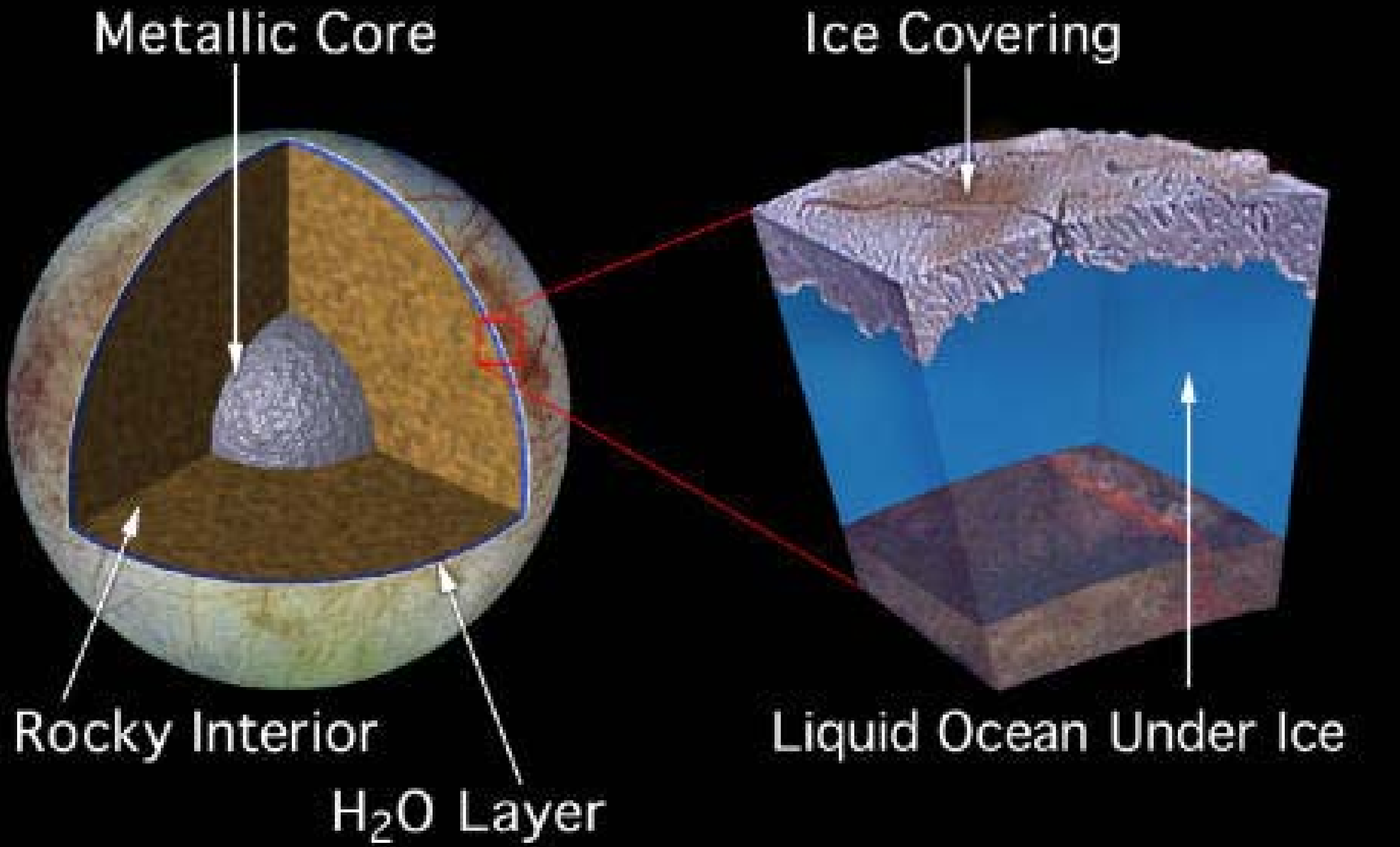
- Tidal friction effects on Europa are weaker than on Io, but still produce striking results. The icy crust of the moon is covered in 'cracks' due to **tidal stresses**, and beneath the crust it is thought frictional heating results in a thin **ocean layer**



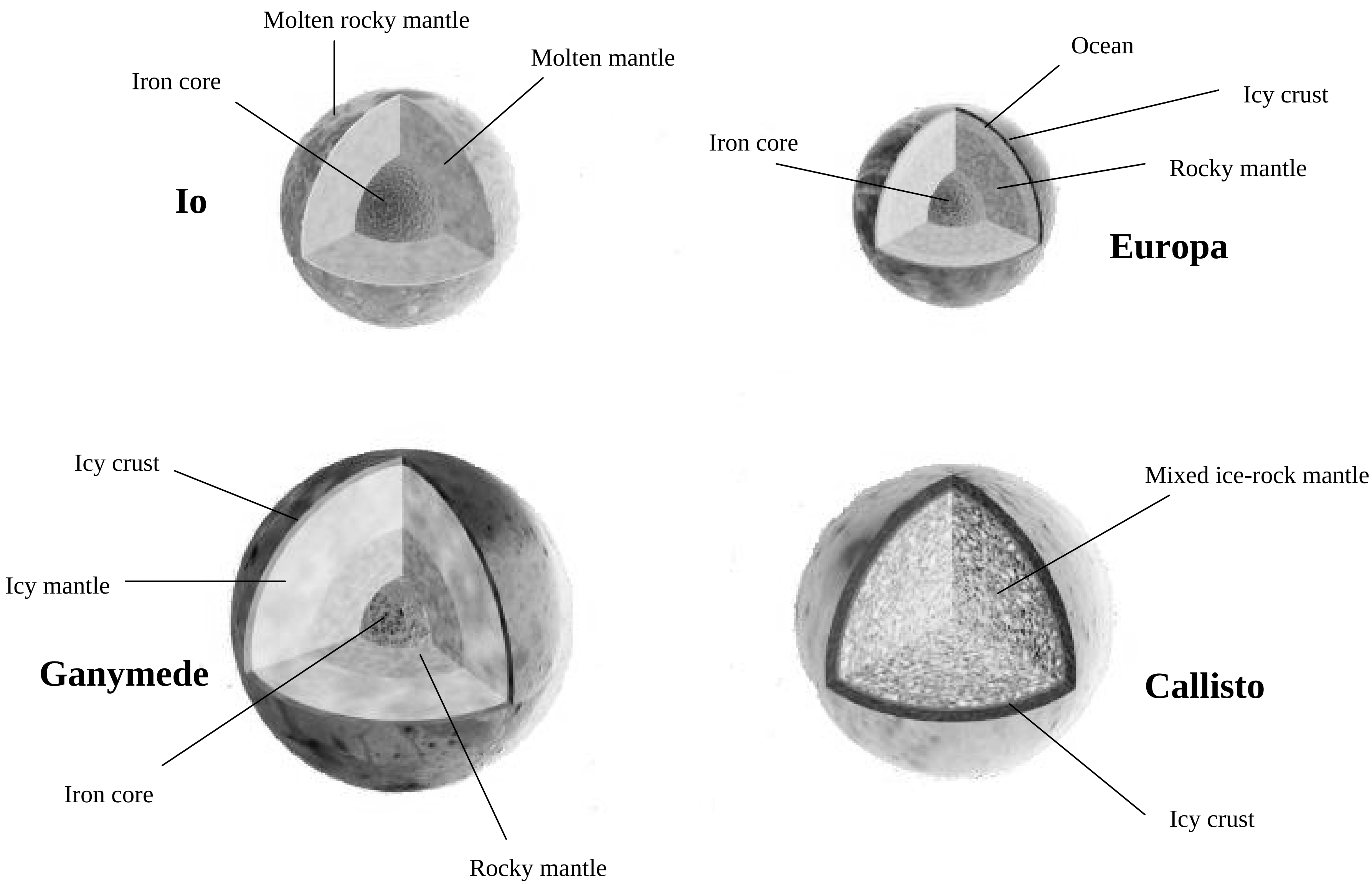




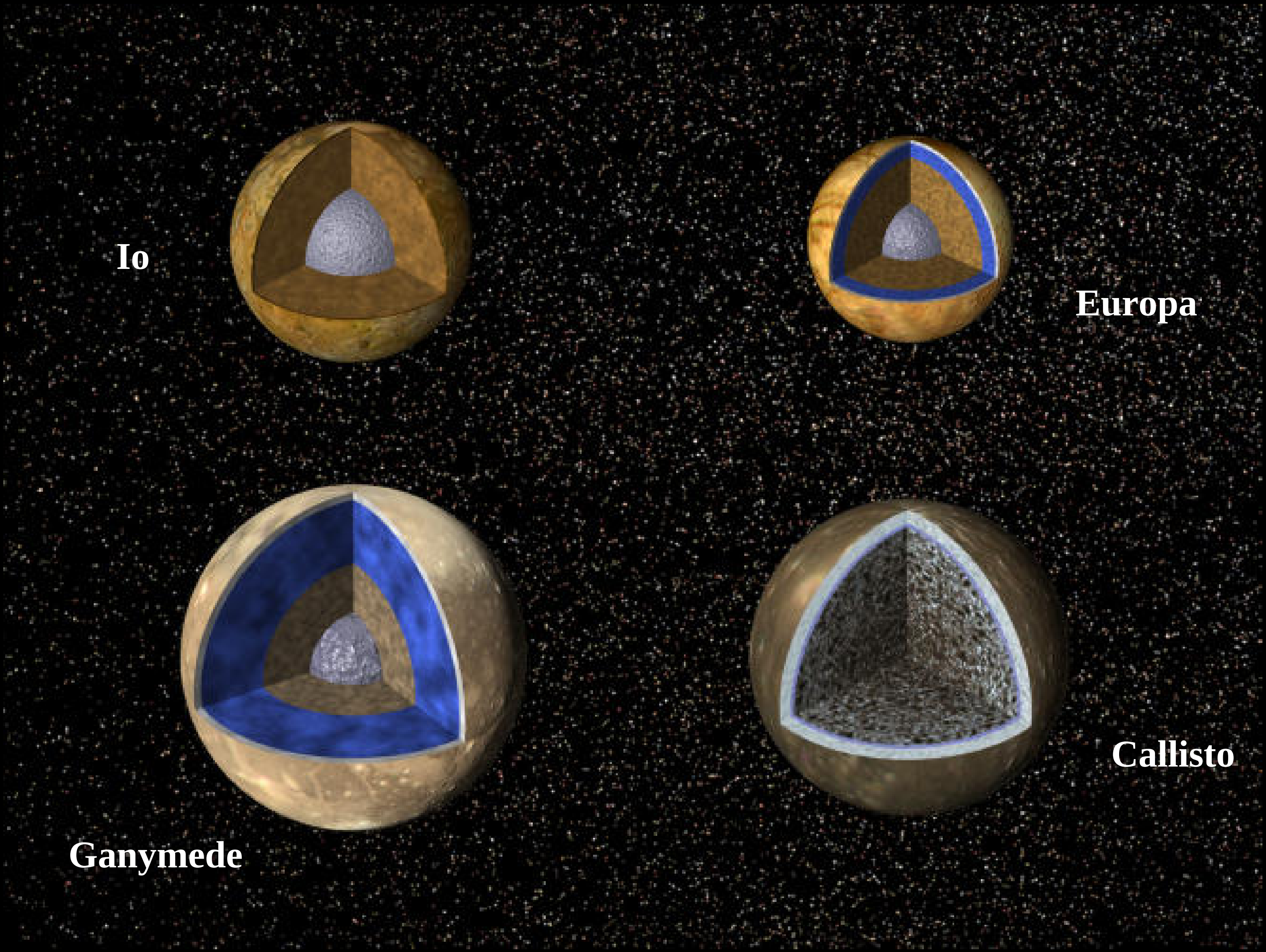
Inside Europa



Interior structure of the Galilean Moons



Interior structure of the Galilean Moons



Structure of the Galilean Moons

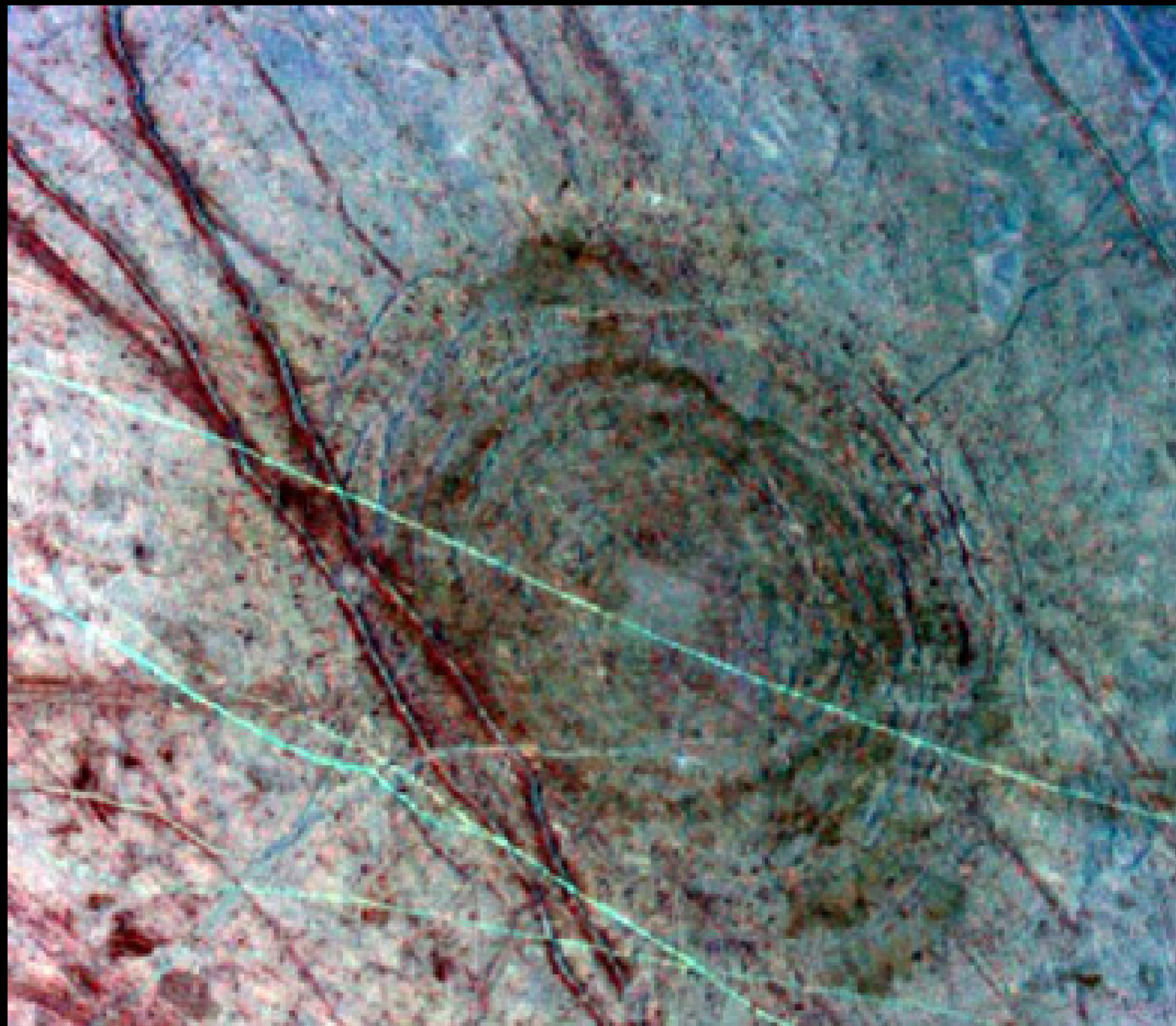
- Their mean density **decreases** with distance from Jupiter

- The fraction of ice which the moons contain **increases** with distance from Jupiter

  This is because the heat from 'proto-Jupiter' prevented ice grains from surviving too close to the planet. Thus, Io and Europa are mainly rock; Ganymede and Callisto are a mixture of rock and ice.

- The **surface** of the Moons reflects their formation history:

Io:	surface continually renewed by volcanic activity. No impact craters
Europa:	surface young (< 100 million years), regularly 'refreshed' – hardly any impact craters



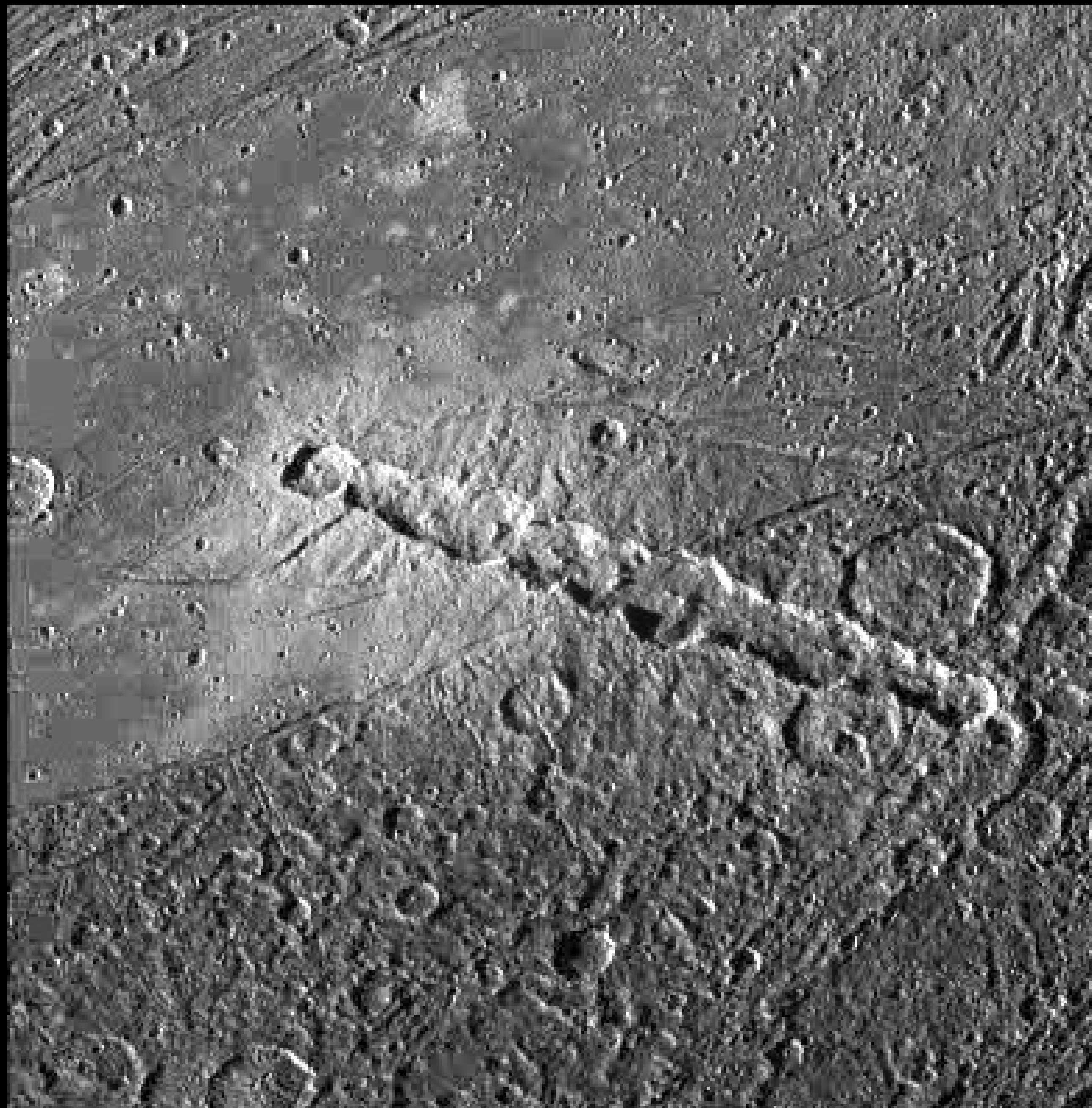
Structure of the Galilean Moons

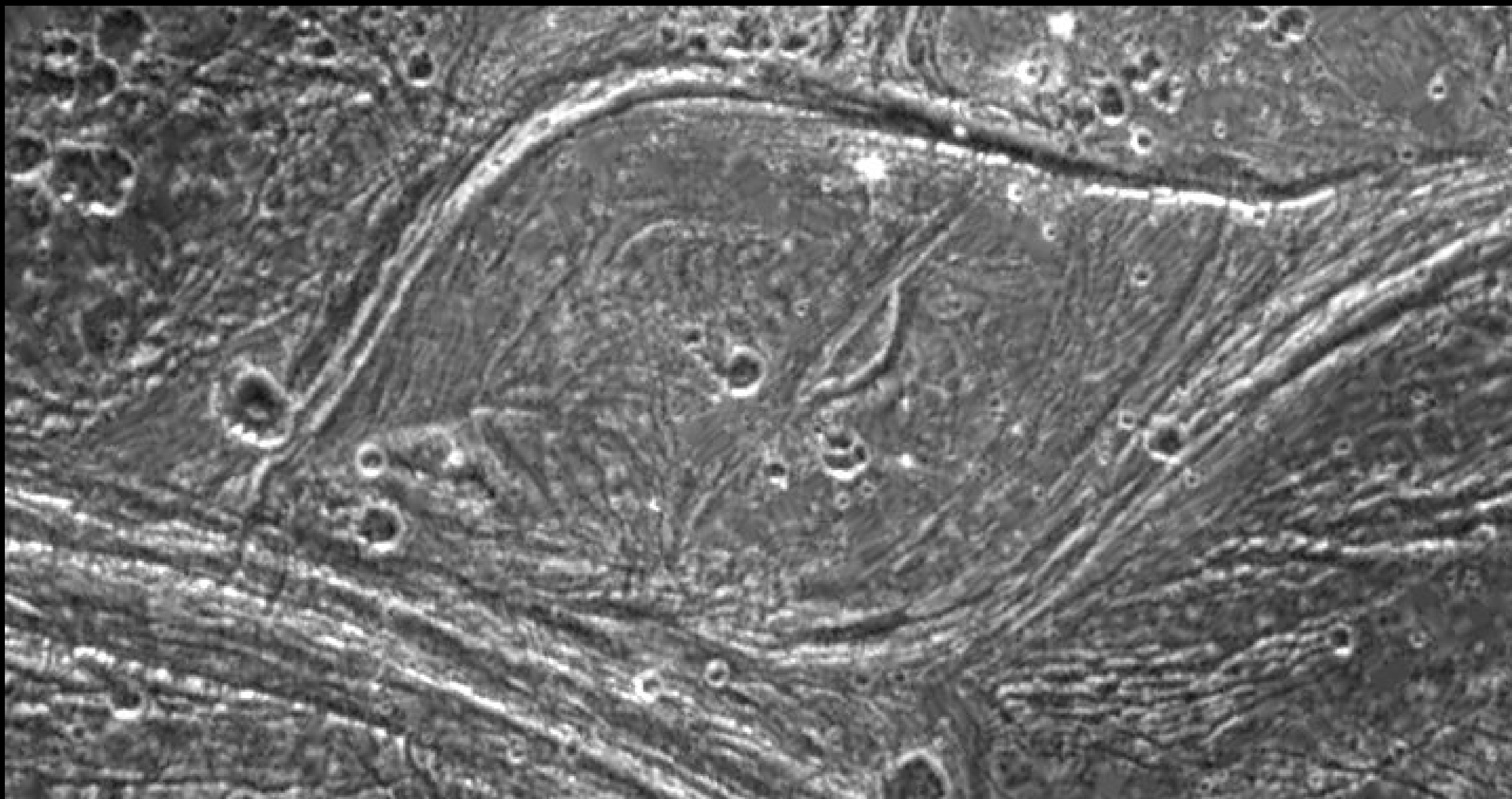
- Their mean density **decreases** with distance from Jupiter
- The fraction of ice which the moons contain **increases** with distance from Jupiter

This is because the heat from 'proto-Jupiter' prevented ice grains from surviving too close to the planet. Thus, Io and Europa are mainly rock; Ganymede and Callisto are a mixture of rock and ice.

- The **surface** of the Moons reflects their formation history:

Ganymede:	Cooled much earlier than Io and Europa. Considerable impact cratering; also 'grooves' and ridges suggest history of tectonic activity





Structure of the Galilean Moons

- Their mean density **decreases** with distance from Jupiter

- The fraction of ice which the moons contain **increases** with distance from Jupiter

  This is because the heat from 'proto-Jupiter' prevented ice grains from surviving too close to the planet. Thus, Io and Europa are mainly rock; Ganymede and Callisto are a mixture of rock and ice.

- The **surface** of the Moons reflects their formation history:

Ganymede:	Cooled much earlier than Io and Europa. Considerable impact cratering; also 'grooves' and ridges suggest history of tectonic activity
Callisto:	Cooled even earlier; extensive impact cratering