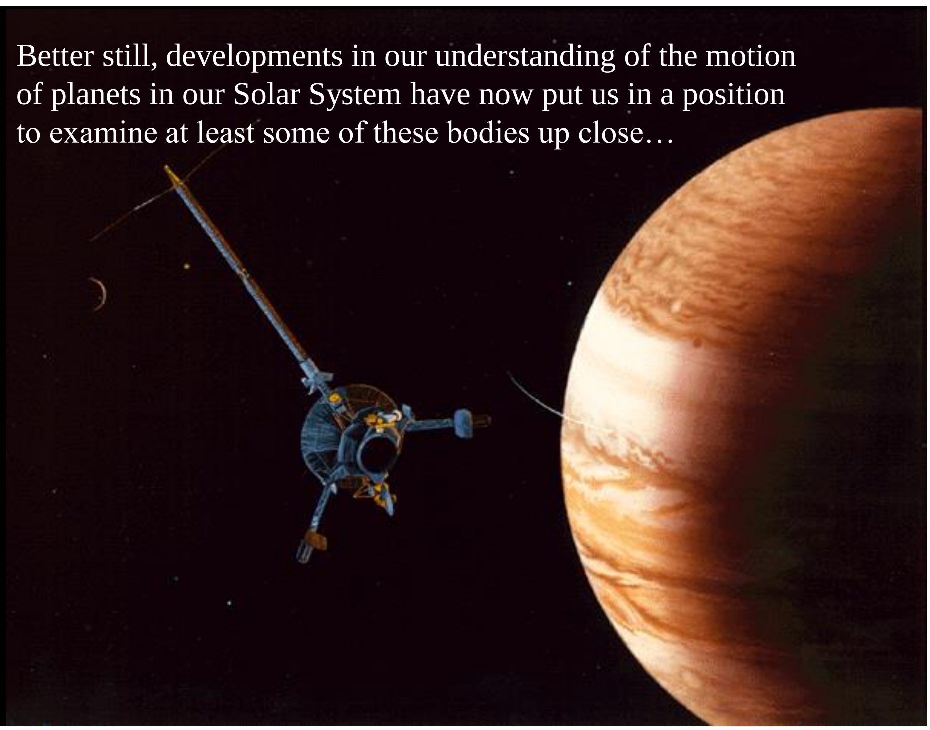
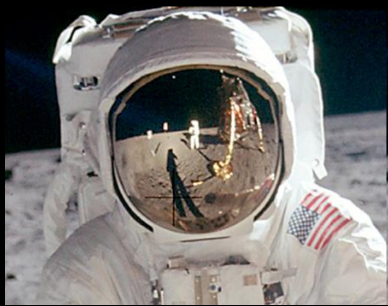
We saw last time how the work of Copernicus, Galileo, Kepler, and Newton (among many others!) helped to completely change our view of not only the Earth's place in the cosmos, but also the very nature of the cosmos itself. Thanks to their efforts – particularly Newton's formulation of the 'force' of gravity – we came to see the planets and stars as ordinary objects, bound by comprehensible physical laws and open to our study.

Better still, developments in our understanding of the motion of planets in our Solar System have now put us in a position to examine at least some of these bodies up close…



…and personal.

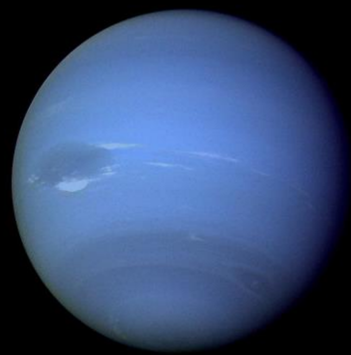


Thanks to our understanding of gravity (and the progress of technology in fields like telescope design, light detection, rocket flight, and robotics!), we are now able to truly ***explore*** the Solar System firsthand and uncover details of its history.

We'll start this exploration today by picking up with the ***planets*** we discussed last week – Mercury, Venus, the Earth (and its Moon), Mars, Jupiter and Saturn…

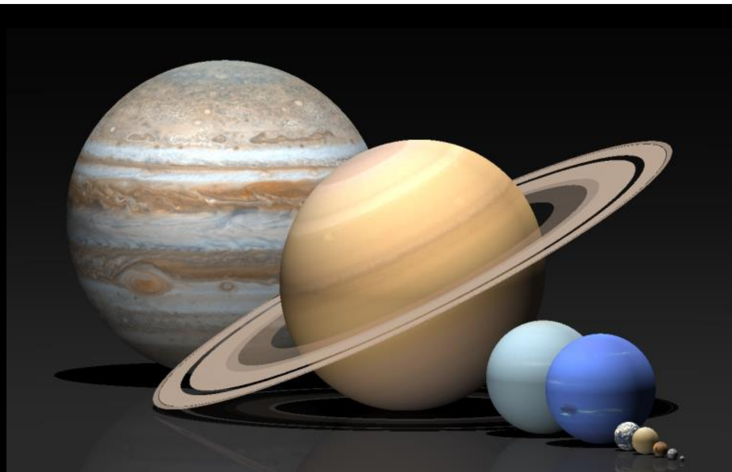
(NOTE: the sizes shown are very, **VERY** not to scale!)

Uranus, discovered 1781



Neptune, discovered 1846

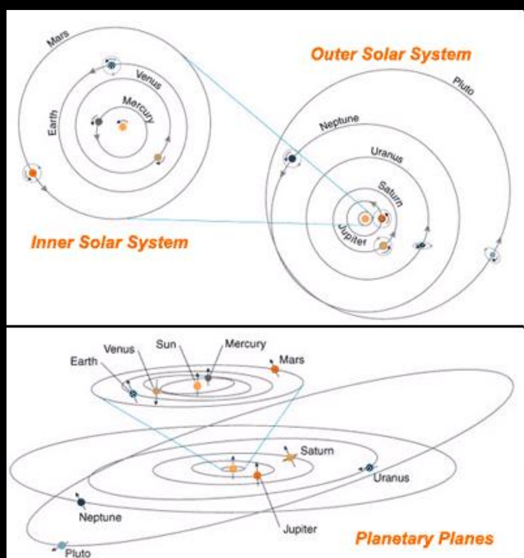
…along with two other (very blue!) planets that the ancients ***didn’t*** know about – Uranus and Neptune.

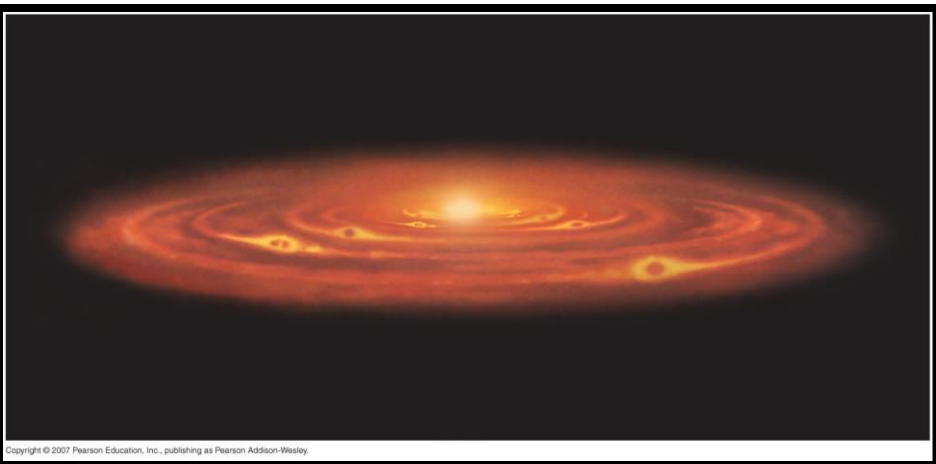


While each of these worlds has unique characteristics that we will discuss, we’ll really focus on uncovering ***patterns*** amongst the planets that might help us understand how the Solar System formed and changed over time.

The first pattern is one we've already seen, and was visible to even ancient astronomers – the planets all appear to orbit in the same general plane (the ***ecliptic plane***), and in the same direction.

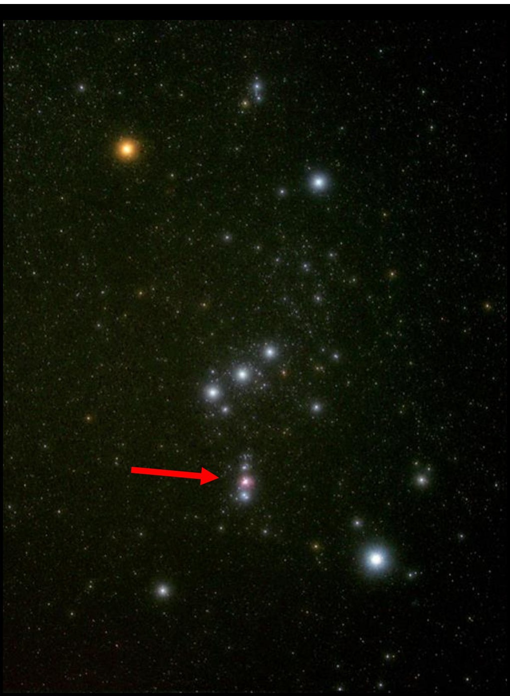
This highly ordered, decidedly 'non-random' arrangement makes it clear that the planets must have formed at roughly the same time, and in a way that had some *preferred plane* and *axis of rotation*.

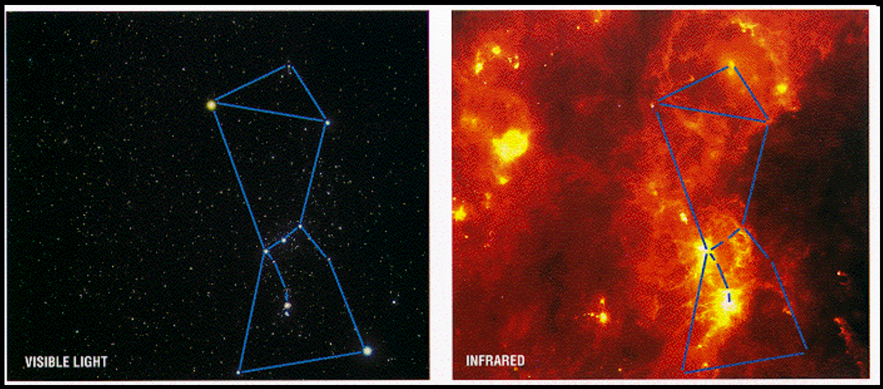




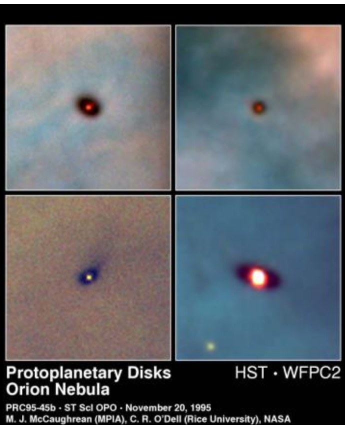
Scientific explanations for this flattened, orderly rotating system turned very early on to the notion that the planets must have been formed in a flattened, rotating system of material, in which planetesimals steadily ***accreted*** material till they reached the sizes we see today. This is the basic premise of the ***Solar Nebula*** model.

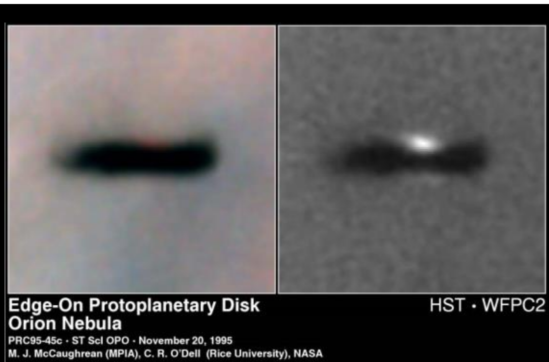
Fortunately we do see such flattened, rotating disks of material – mostly hydrogen and helium gas, along with carbon and silicate dust – in nearby regions of our Galaxy where stars are known to be forming, such as in the ***Great Nebula in Orion***.



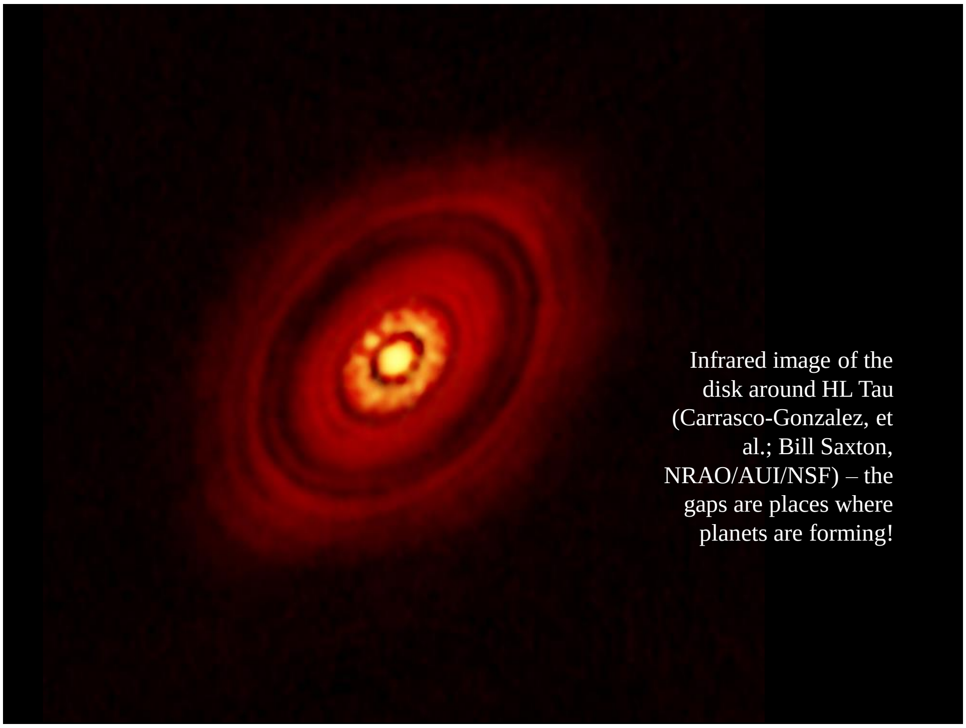


An infrared image of the region around Orion reveals areas of gas and dust heated by the radiation of newly forming stars.

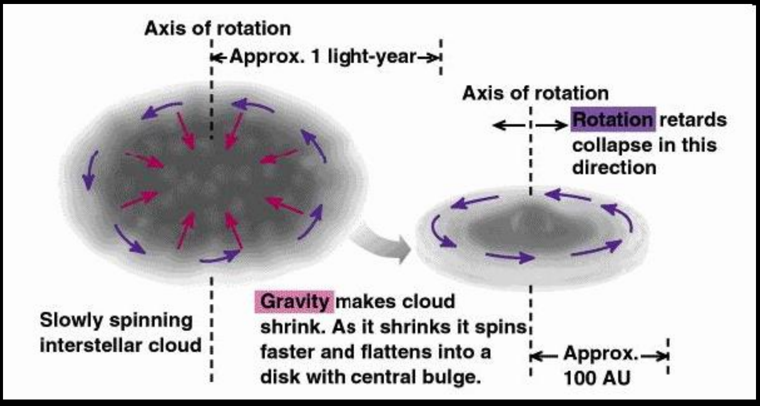




Many of these forming stars are clearly surrounded by disks of gas and dust – as seen in these HST images. In fact we see such disks around almost all young stars near enough to closely examine.

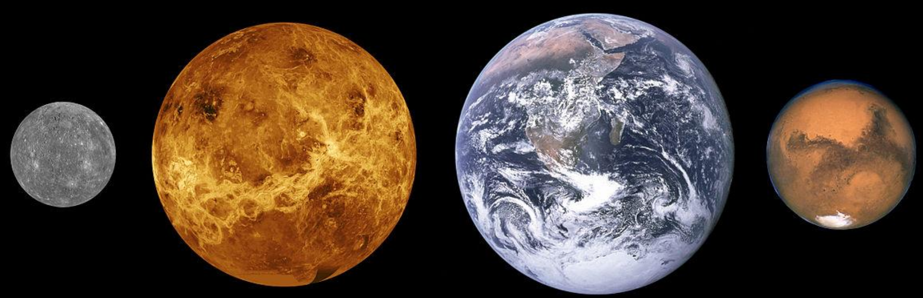


Infrared image of the disk around HL Tau (Carrasco-Gonzalez, et al.; Bill Saxton, NRAO/AUI/NSF) – the gaps are places where planets are forming!



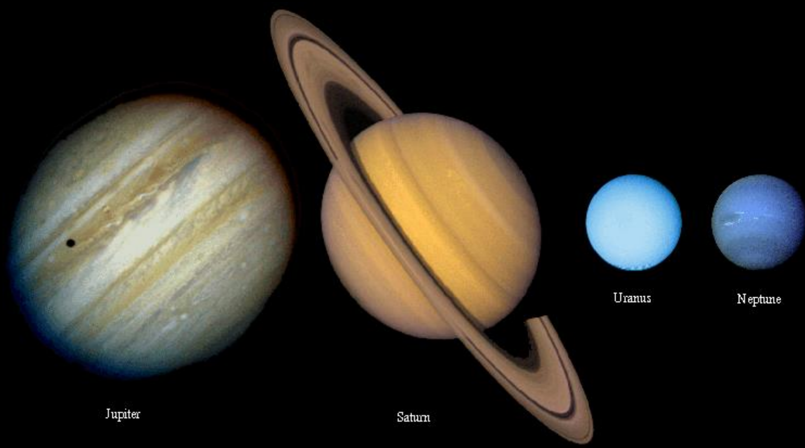
These flattened disks appear to be an inherent part of the formation of stars – as the giant gas clouds that form stars begin to collapse under their own gravity, they naturally spin faster. That spinning shapes the cloud into a disk as it collapses, because material in the equatorial plane has a harder time falling in to the center due to centrifugal accelerations.

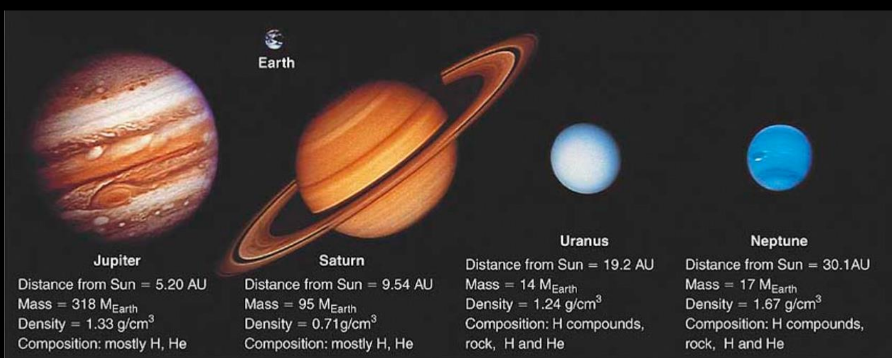
As *our* solar nebula collapsed into a flatter, denser disk, the small amounts of solid material began to clump together, or “accrete” – preserving the orbital and angular momentum “spin” characteristics of the orbiting particles that they formed from, and producing the orderly orbits of the planets we see today.



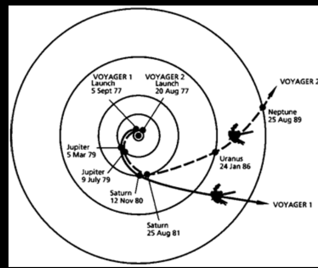
And that brings us now to a *second* major pattern seen in the Solar System – a distinct division between terrestrial worlds…

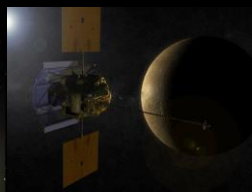
…and so-called “Jovian” Worlds of the Outer Solar System

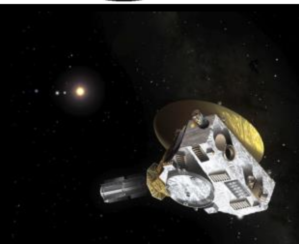




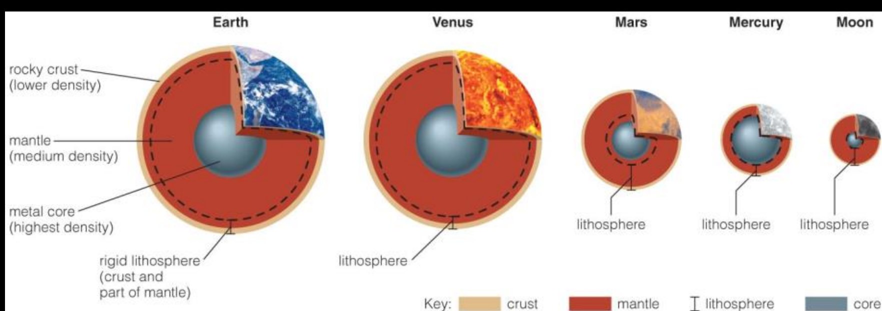
By the late 1800’s it had become clear that the worlds of the outer Solar System were far different from those of the inner Solar System. Not only were these planets much farther apart from each other, they were also much more massive.





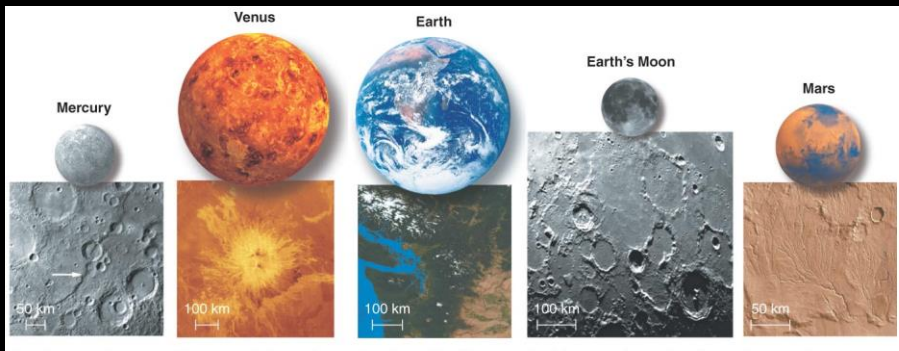


Through the 20th century, further telescopic and direct physical explorations revealed much more about each of the planets.

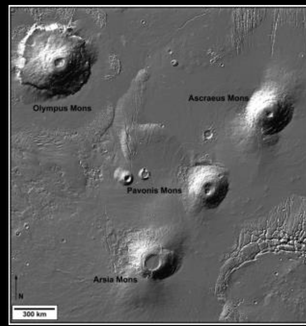


The terrestrial planets – as their name suggests – are all 'Earthlike' in that they share a similar internal structure to the Earth. They each have a rigid, rocky surface layer (lithosphere), and a highly dense, primarily iron core.

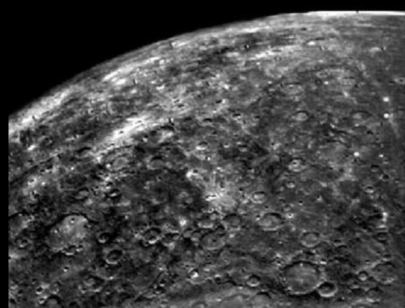
All of their solid surfaces also clearly bear the scars of impacts they suffered during the late parts of that “accretion”, and indeed throughout the history of the Solar System.



(including the Earth’s surface!)



Those craters are often 'erased' over time from the surfaces of larger terrestrial planets such as Earth, Venus, and Mars. These worlds are so massive that their interiors are still molten, and the action of volcanos and other geological activity such as plate tectonics slowly 'resurfaces' them over time.

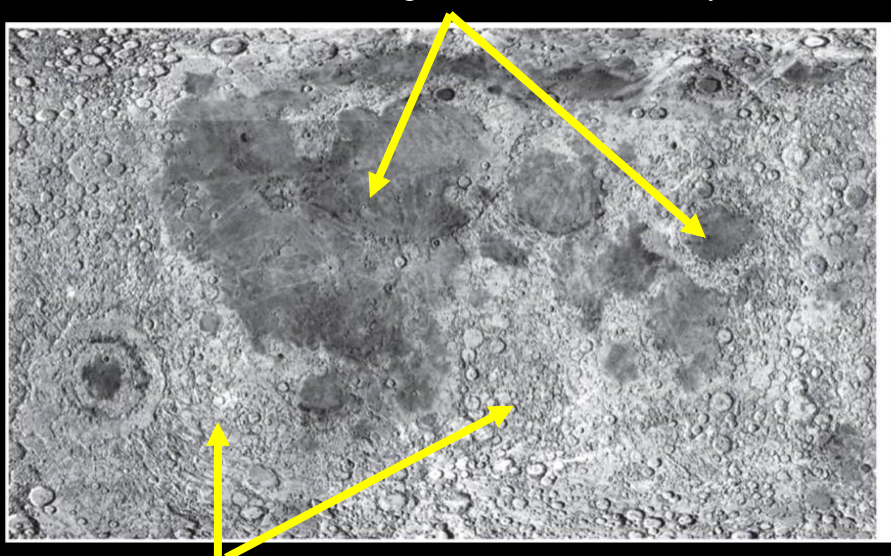


Impact craters are far better preserved on the surfaces of the Moon and Mercury, since they lack enough heat for extensive volcanism or tectonics. Their surfaces haven't changed from internal forces for a very long time – and in fact, hold vital clues to the deep history of our Solar System and its formation.

Lunar rocks in a "clean room" at Johnson Space Center in Houston, TX.

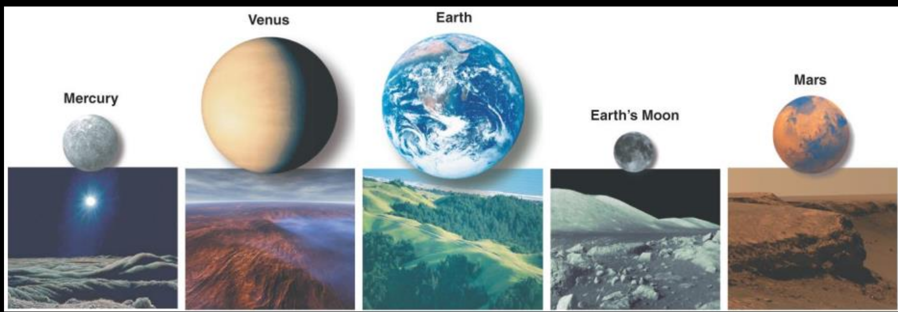
For example, dating of lunar rocks such as these seen here, taken from areas with more or less craters, tell us how long ago those different regions cooled from their molten states into the solid rocks that we found – and the answers are very, very old indeed.

"Younger" rocks ~ 3.8 billion years old



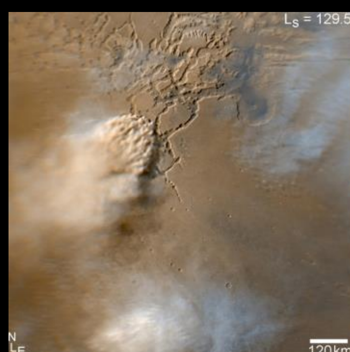
Oldest rocks ~ 4.5 billion years old

Another reason those craters are far less noticeable on Earth, Venus, and Mars is because of their ***atmospheres***.

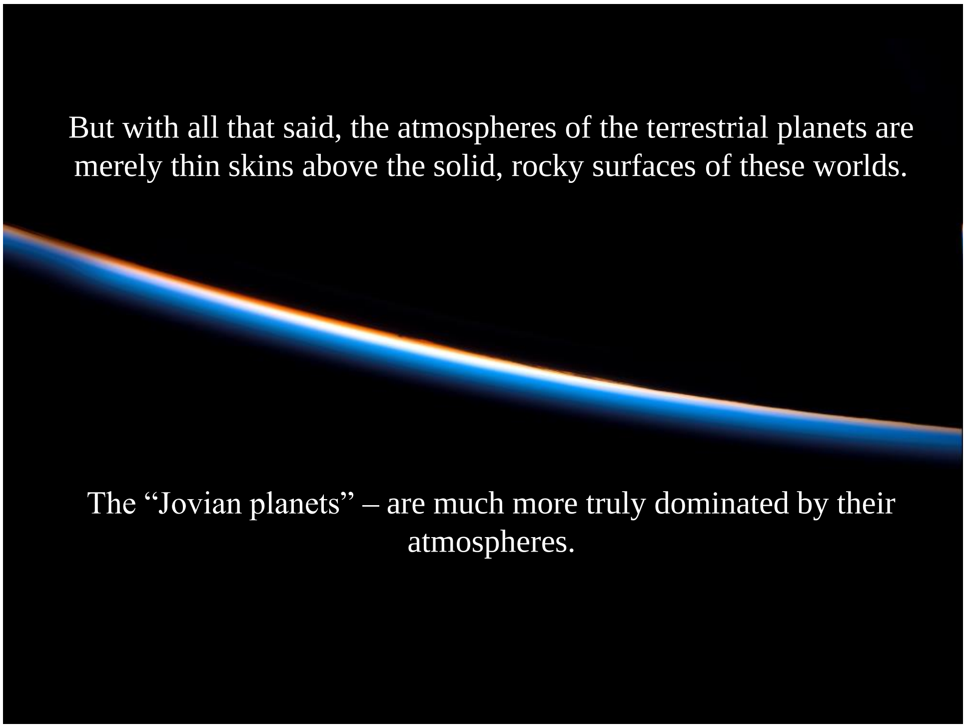


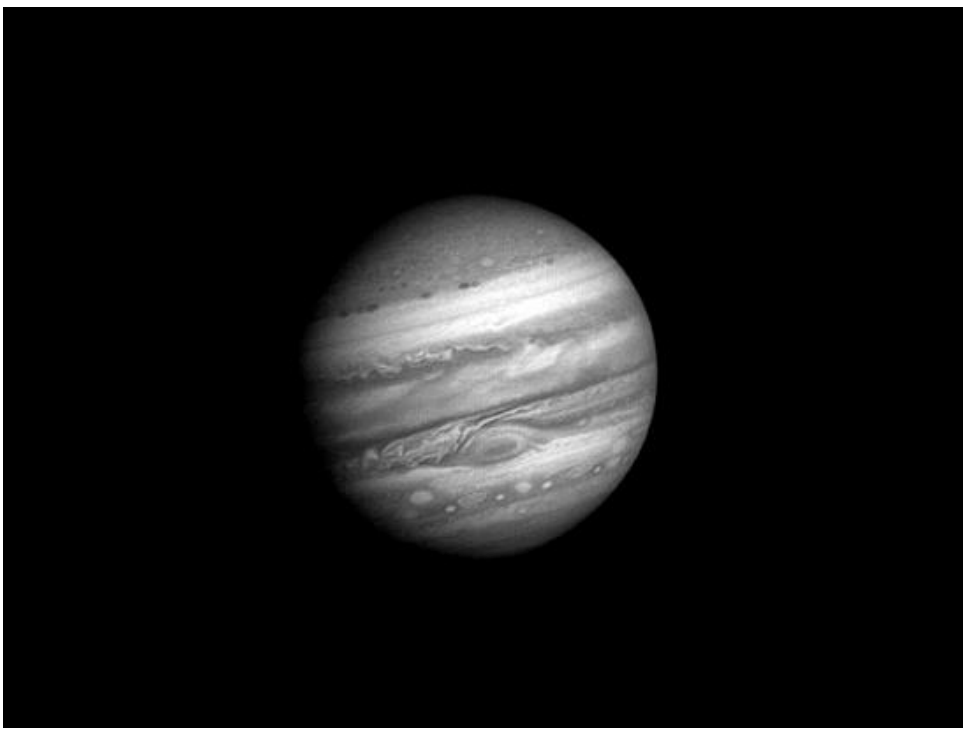
Each of the major terrestrial bodies in our Solar System is covered by a very thin layer of gasses – and sometimes fluids. The composition, temperature, and pressure of those elements determines what ***erosive*** forces are available to shape that world.

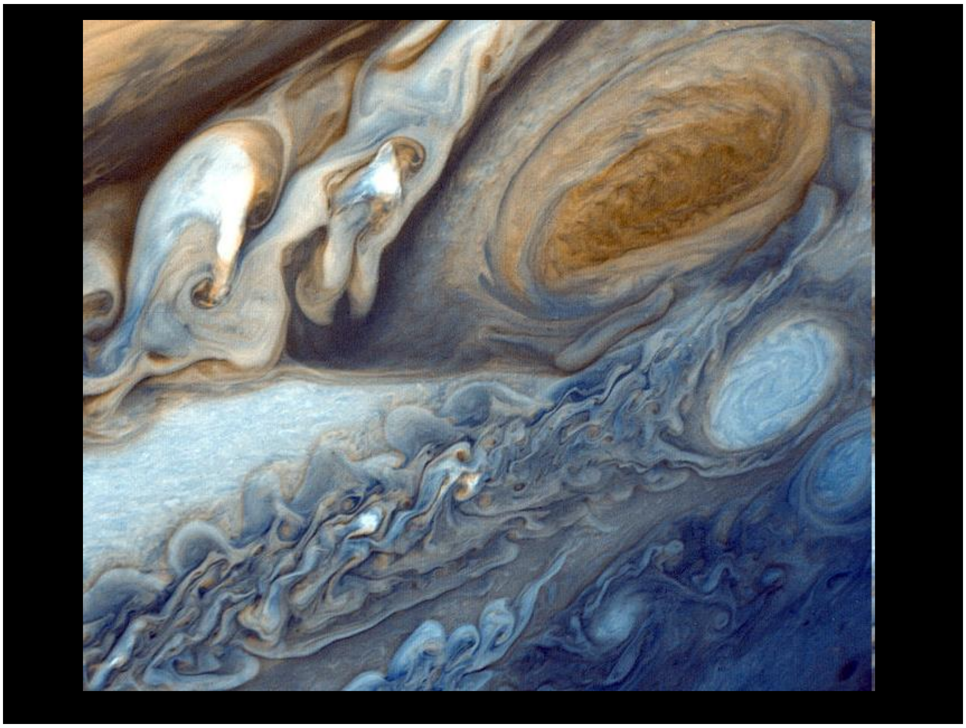
These forces – weather-driven erosion events that break down or transport rock, such as flowing water (frozen or liquid!) or wind – erase old craters, and create new features on planetary surfaces.

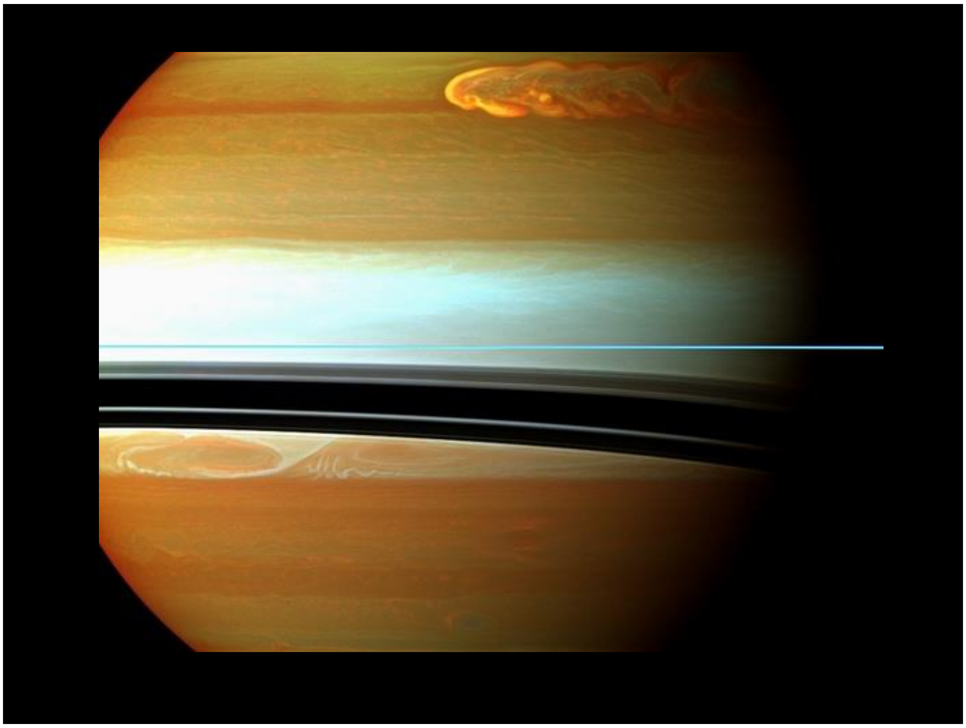


Erosion features on Earth (upper right), and on Mars (above, left).

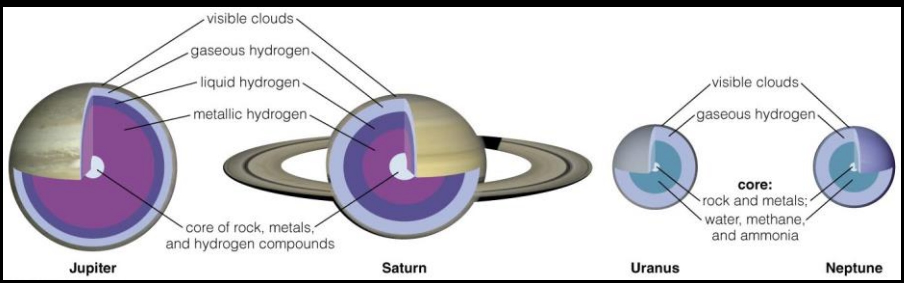

But with all that said, the atmospheres of the terrestrial planets are merely thin skins above the solid, rocky surfaces of these worlds.
The “Jovian planets” – are much more truly dominated by their atmospheres.





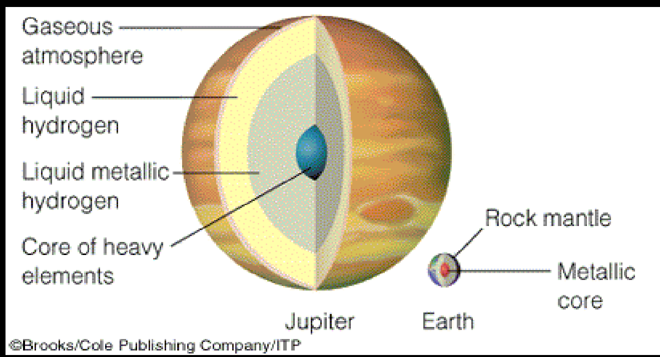


Watch some YouTube videos from the Juno spacecraft, currently in orbit around Jupiter!

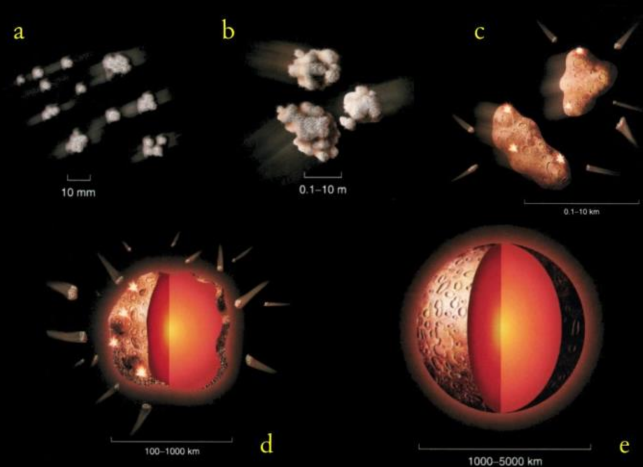


In fact, the Jovian planets do not appear to possess a solid surface at all underneath those bulky atmospheres. Their deep interiors are comprised of increasingly dense and turbulent layers of hydrogen and hydrogen compounds, such as water, ammonia, and methane. In the case of Jupiter and Saturn, the hydrogen and helium is under such high pressure and temperatures that we believe they achieve liquid and even metallic states.

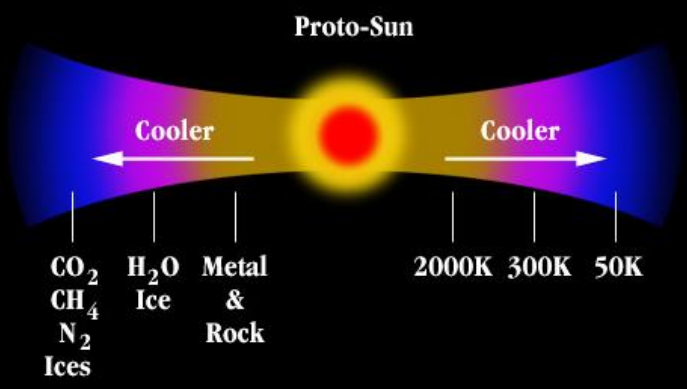
Why are Jovian planets so much larger than terrestrial planets, and why are they composed of such different materials?



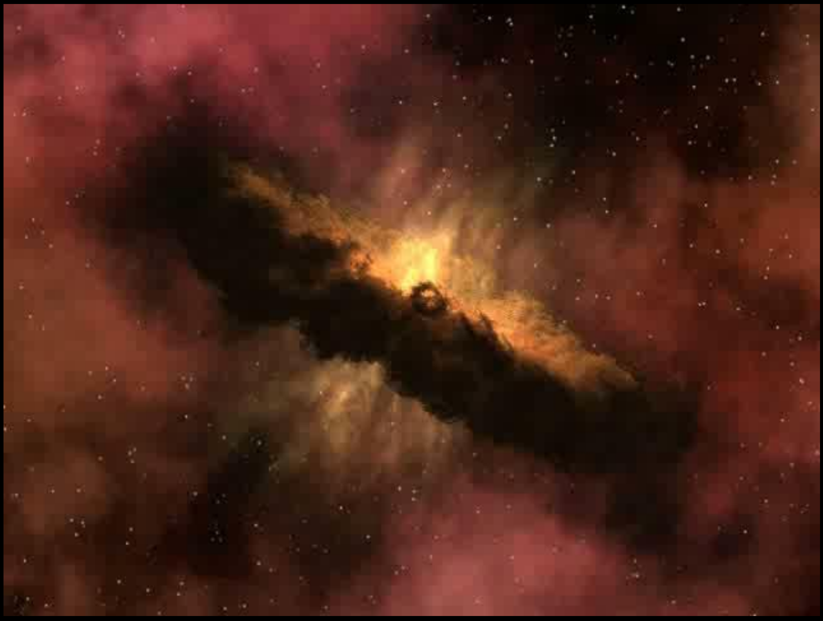
We believe the answer lies in their formation – and the materials in the Solar Nebula that they originally accreted from.

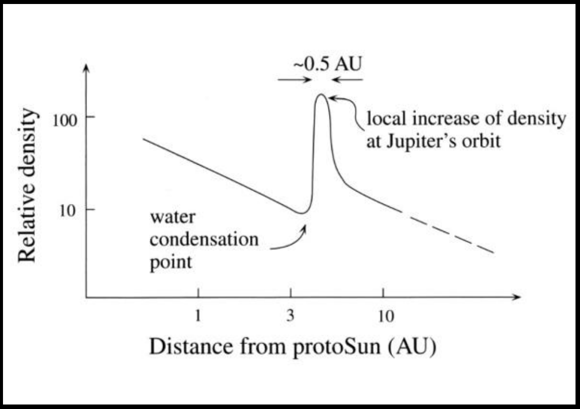


Early in the Solar System's formation, the accretion process steadily built up all of the planets from solid, grain-sized particles (similar to the dust we still see falling on the Earth!).



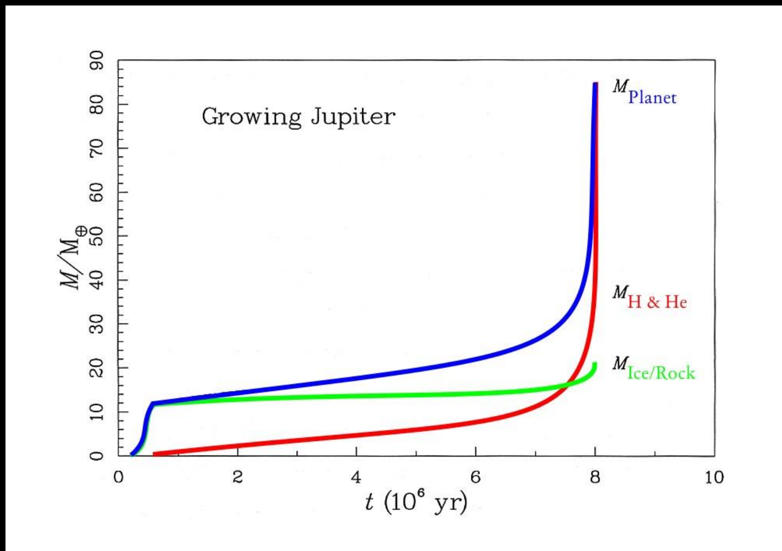
Near the forming Sun itself, only heavy elements such as metals and rock could form such grains – but farther away from the Sun, water ice and other hydrogen compounds were able to condense ("freeze") into solid, planet-building material.





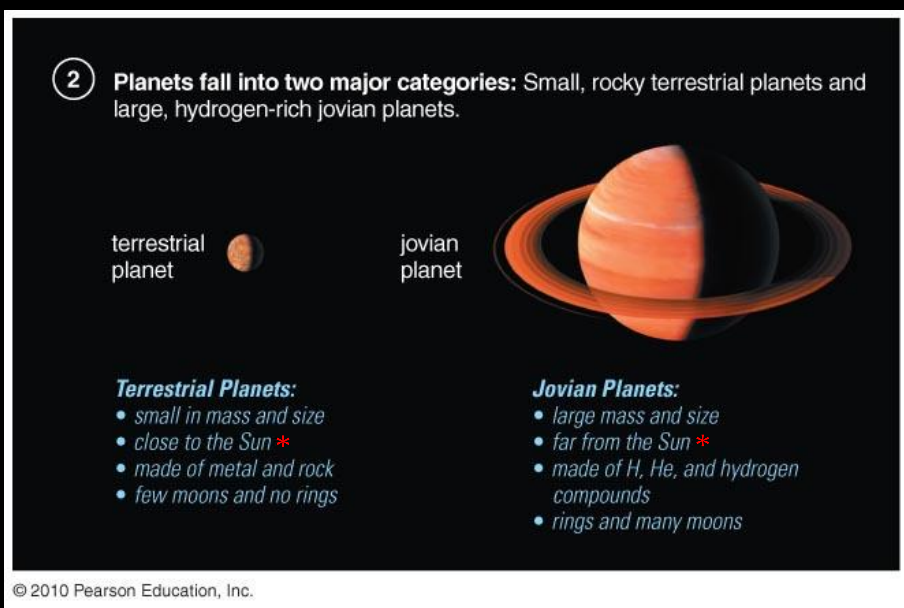
This meant that, even though the total amount of gas and dust was smaller in the outer parts of the disk, ***just beyond*** this so-called "frost line" there were relatively larger amounts of ***solid*** material to build proto-planets from – enough to make worlds dozens of times larger than the forming Earth.

At those sizes they were large enough for their gravity to begin attracting and holding on to hydrogen and helium gas, ***by far*** the most abundant materials in the Solar Nebula. Tapping into this resource produced a burst of runaway growth, and those worlds went from 'super-sized' terrestrial planets to full-blown gas giants!

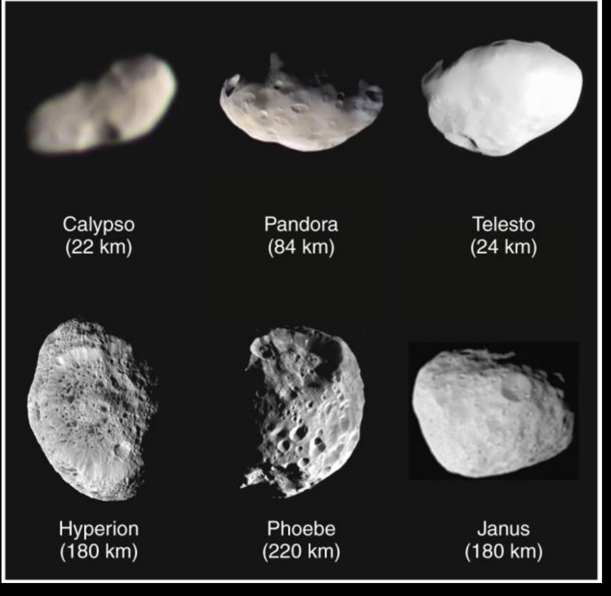


Results of a computer simulations of Jupiter's growth by gravitational accretion.

This ***gas capture phase*** helps explain much of this second pattern.

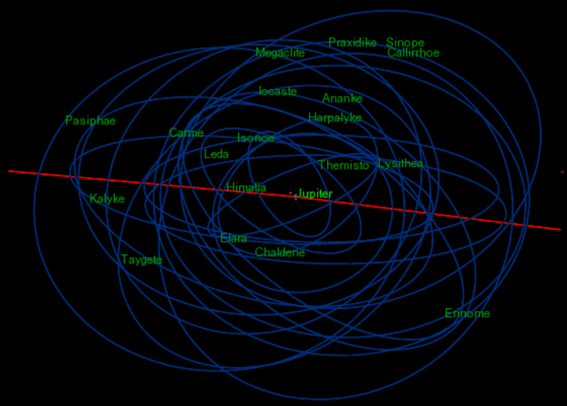


Another significant difference between terrestrial and Jovian worlds is the large numbers of moons that orbit Jovian planets – over 170 in all, with more than 60 each around Jupiter and Saturn



Most of these moons are quite small, and do not have enough self-gravity to be spherical – instead they are lumpy and "potato-shaped."

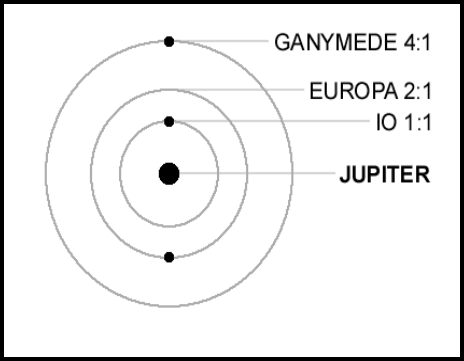
Because their orbits are very elliptical and randomly distributed around their planet, we don't believe they formed where they are currently located, but instead are captured asteroids or comets, encountered at random times in the planet's history.



Orbits of several of the small moons of Jupiter

Many Jovian moons are much larger, however, and are massive enough that their self-gravity has forced them into roughly spherical shapes. From density measurements we also know that, in addition to rock and metals, they have substantial amounts of ice – much more than we see in similarly sized bodies like Mercury and the Earth's Moon.

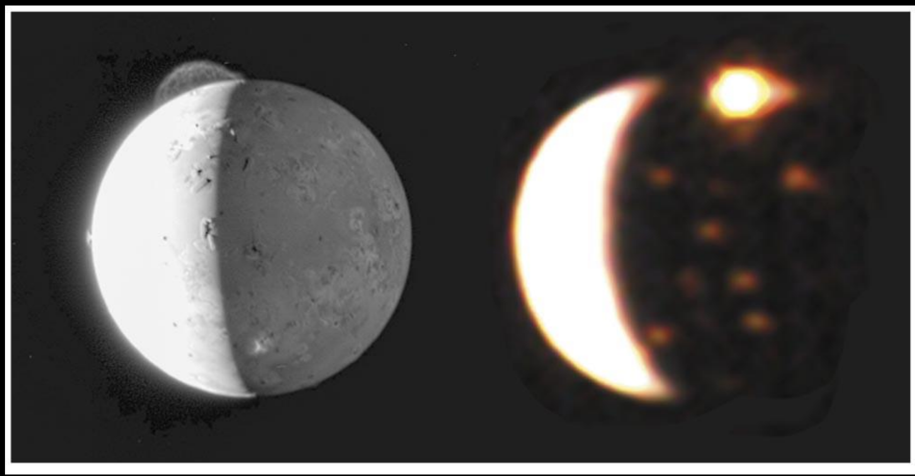
In addition, most of these larger moons have nearly circular orbits, and orbit in the same direction as their planet's rotation. This orderly arrangement suggests these bodies must have formed more or less at the same time, where they are now, locked into (sometimes highly!) regular orbits around the jovian planets.



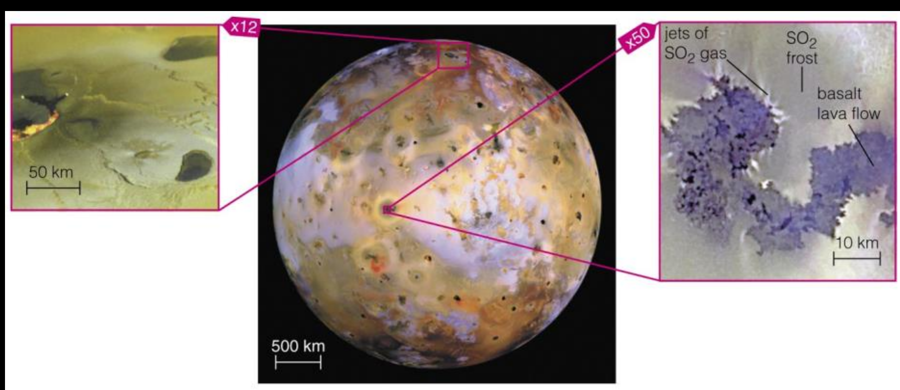
The orbital "resonances" of the inner moons of Jupiter

Of these larger moons, perhaps the most historically compelling have been the "Galilean" moons of Jupiter.

Not only did these bodies help bring about the Copernican Revolution, but they have more recently taught us new lessons about how geological activity can persist on even small worlds.

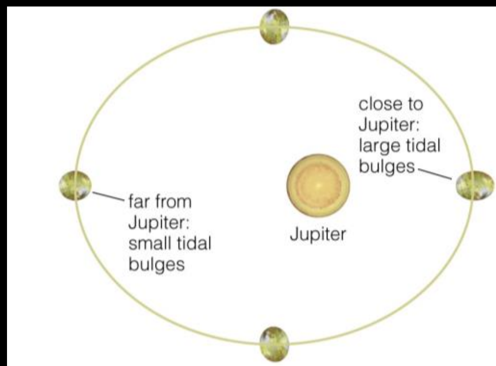


For example, Jupiter’s moon Io is a very volcanically active body, with dozens of active eruption sites on its surface at all times.

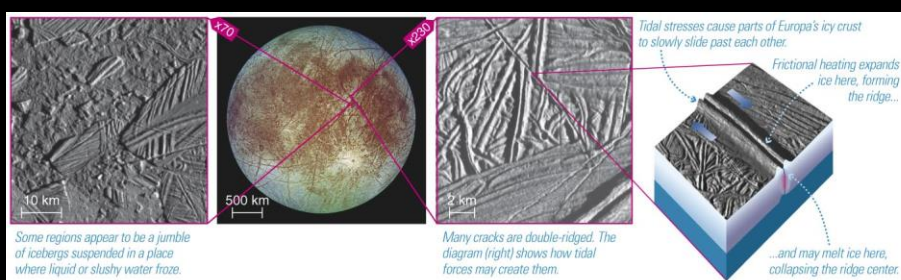


In fact, Io is the most volcanically active body in the solar system – but why? How could such a small body retain so much internal heat over the age of the Solar System?

Io stays warm internally because of ***tidal heating***. It has a slightly but significantly more elliptical orbit than most of Jupiter's large moons, and as a result, the distance between it and Jupiter varies a good deal as Io orbits the planet. This strongly affects the tidal forces felt by Io from Jupiter.

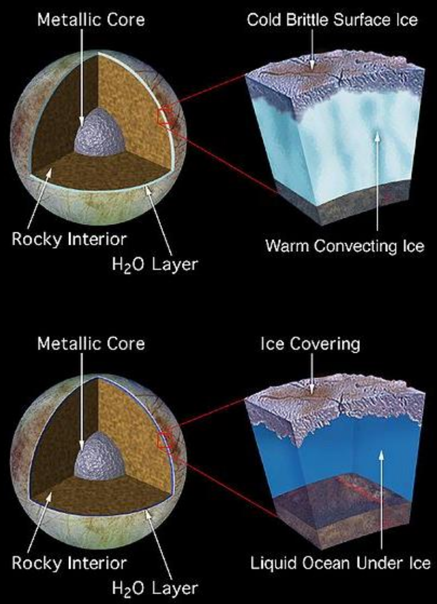


Because Io is closest to Jupiter, the effects of tidal heating that its orbit produces is most significant and readily seen there – but other Galilean moons are also heated in this manner.

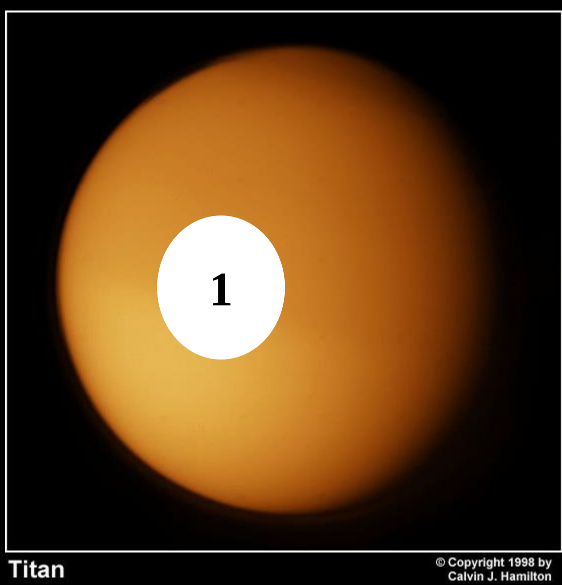


Tidal forces appears to be resurfacing the icy surface of Europa – which, like Io, has almost no impact craters at all on its surface.

Tidal heating provides enough heat to keep 'tectonic' processes active on Europa, and may be sufficient to keep a large part of Europa's ice permanently melted – in a subsurface ocean with twice as much water as all the Earth's oceans combined! Intriguing? You bet!



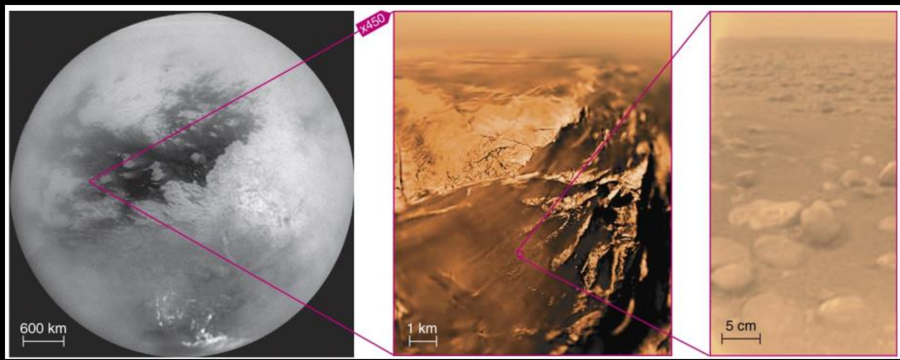
Two models of Europa's Interior



But arguably the most remarkable moon of the Jovian planets is Titan, the largest moon of Saturn.

Sure it looks like a number 1 pool ball – but that smooth appearance is the result of the thickest atmosphere possessed by any moon in the Solar System.

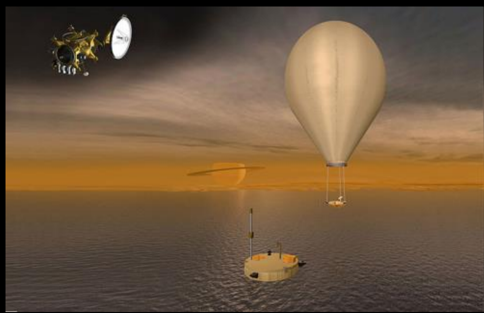
Largely because of this, Titan is the only moon (other than our own!) on whose surface we have directly landed a spacecraft.



The *Huygens* probe provided our first images from Titan's surface in 2005, and found liquid methane pools and "rocks" made of ice.

A large world with a thick atmosphere and liquids on its surface?

Very interesting…

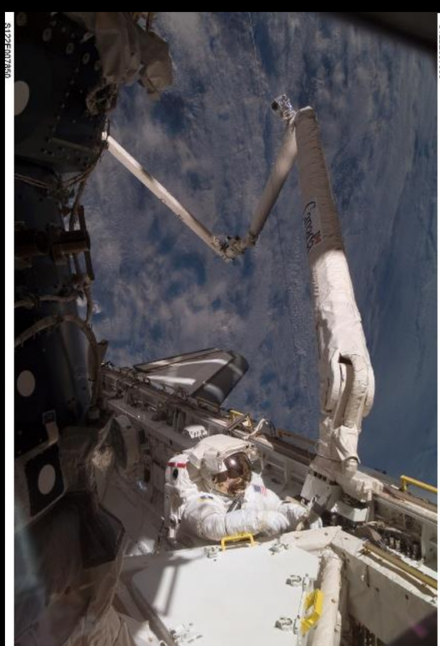
 

The possibilities of extraterrestrial life raised by worlds like Titan and Europa have caused a great deal of excitement here on Earth, and given new direction and inspiration to our efforts at exploring and adventuring amongst the planets.

And those adventures are happening today, right here at UW – do you recall this image from earlier?

Do you know what it this is a picture of?

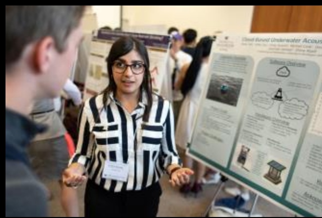
That image – of the Earth's thin atmosphere as seen from above the night side of the planet – was taken by astronauts aboard Space Shuttle mission STS-122, seen here lifting off on February 7, 2008.



Here are a couple of shots of one of the astronauts from that mission – Dr. Stan Love…

…a student from the University of Washington.

Just like you.



And it's not just Astronauts and Astronomers!

GO HUSKIES!

GO YOU!

(now go to your next class!)