Voyage to the Planets
Lecture 9:
The formation of the Solar System

Presented by

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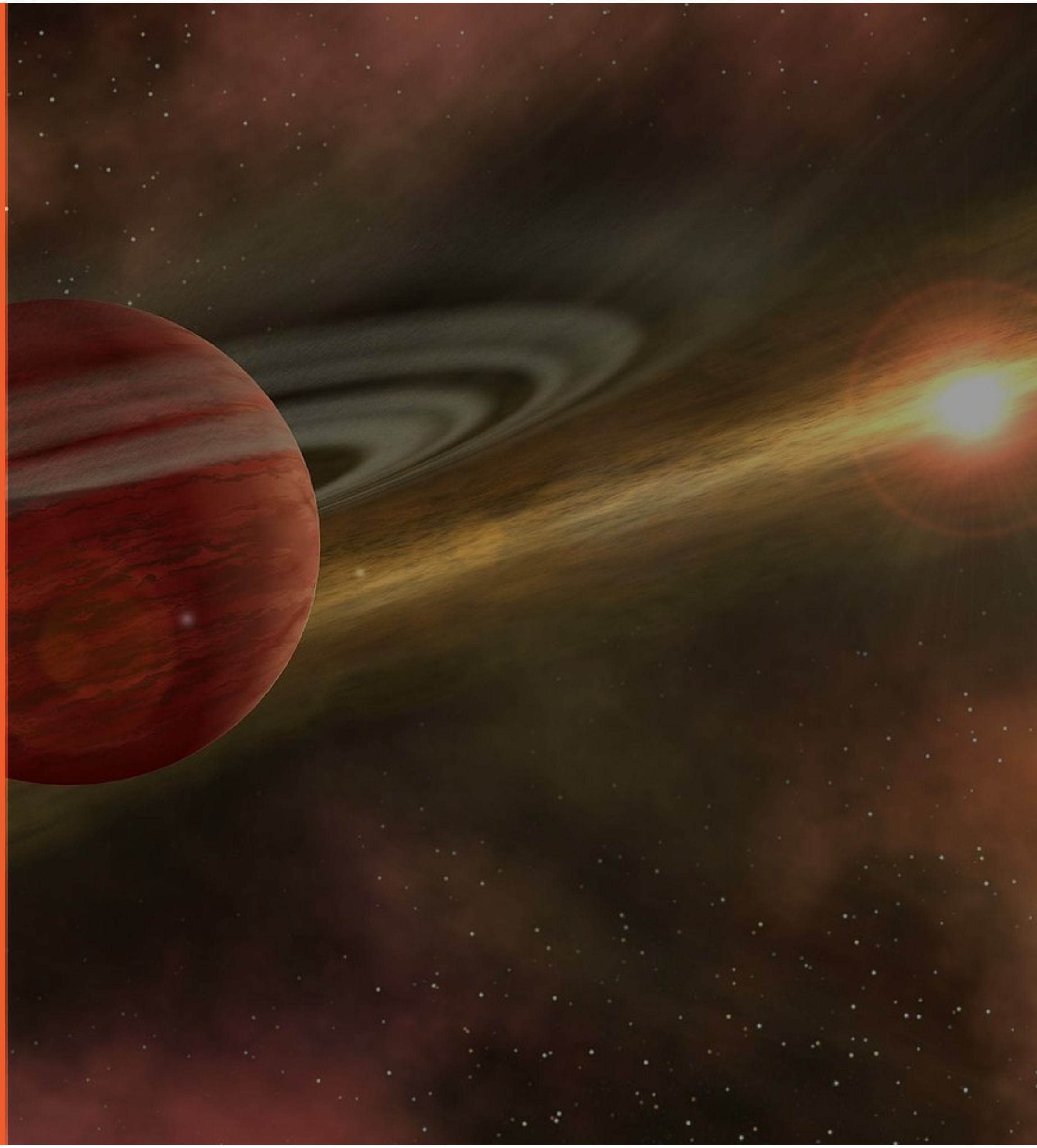
THE UNIVERSITY OF SYDNEY



Tonight

- The facts to explain
- How stars form
- How planets form
- The problems...

Humans are fascinated with the questions of origins. Together with the question of the origin of life, the formation of galaxies, and the origin of the universe, the origin of the Solar System is one of the "big questions" in understanding where we come from.

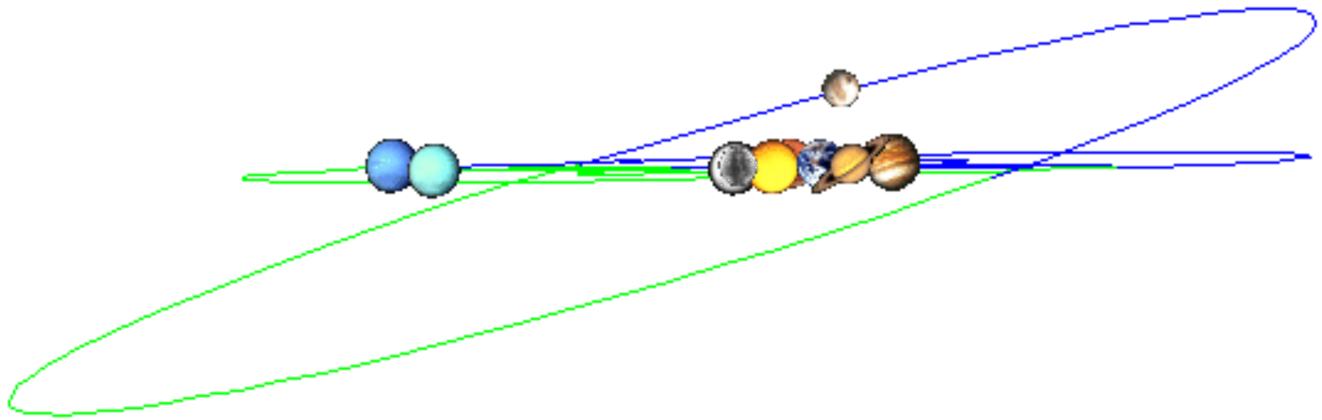
Unfortunately, we only have one planetary system to study in detail, so we have no real idea of the diversity of systems which could arise in other circumstances. Theoretical models have, naturally, concentrated on trying to reproduce the variety of worlds we see in this system. Only recently have we come to have new data from other stars... but we'll leave discussion of that till next week.

The Solar System, a summary

Let’s take a quick look at the general features of the Solar System again. We’ve spent a long time looking at the details of the many marvellous worlds; here’s a quick summary of the overall features, before we try to explain them.

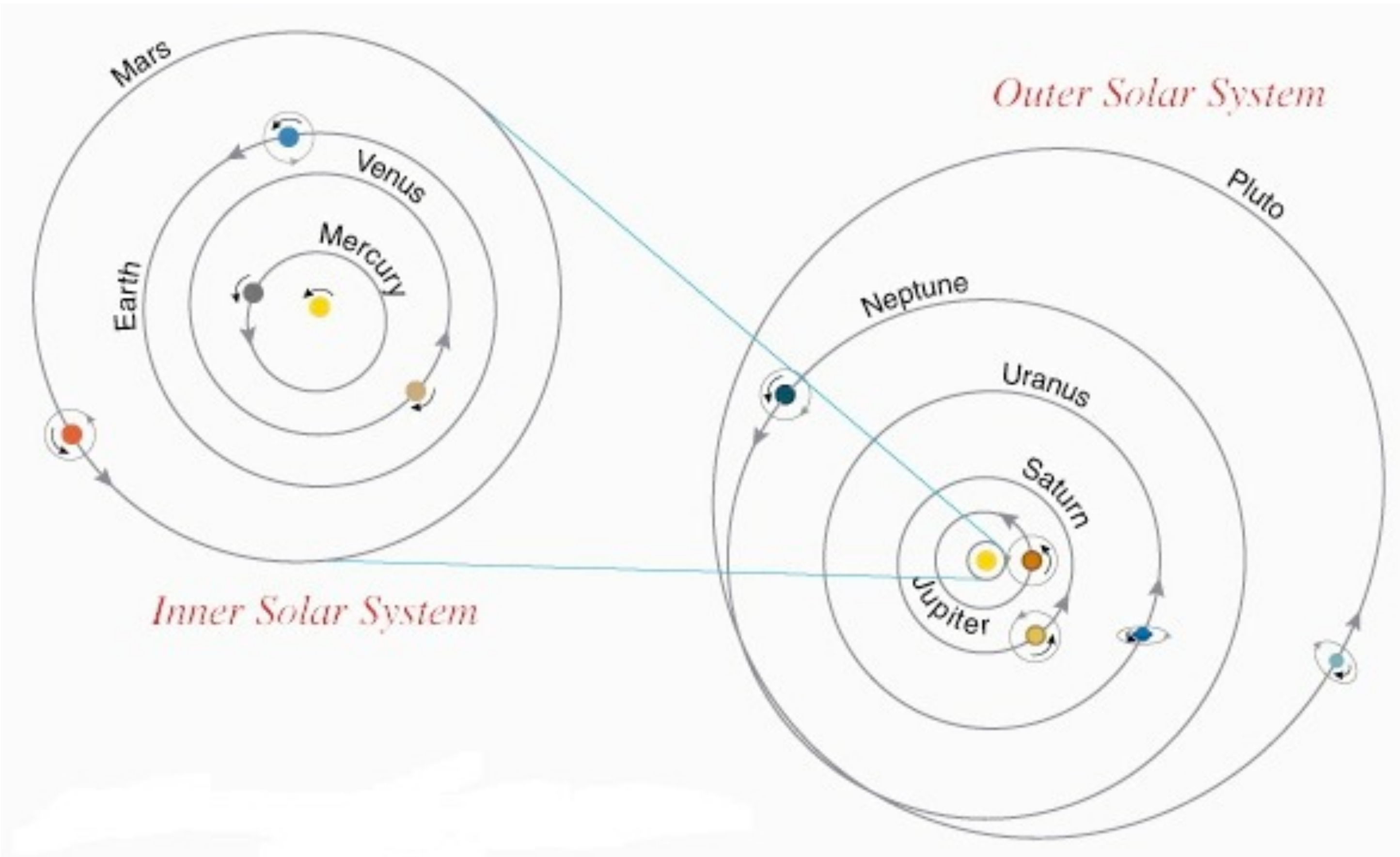
Any theory for the formation of the Solar System must be able to account for the following features.

The orbits of most planets and asteroids lie nearly in the same plane, and this is the plane of the Sun's equator.

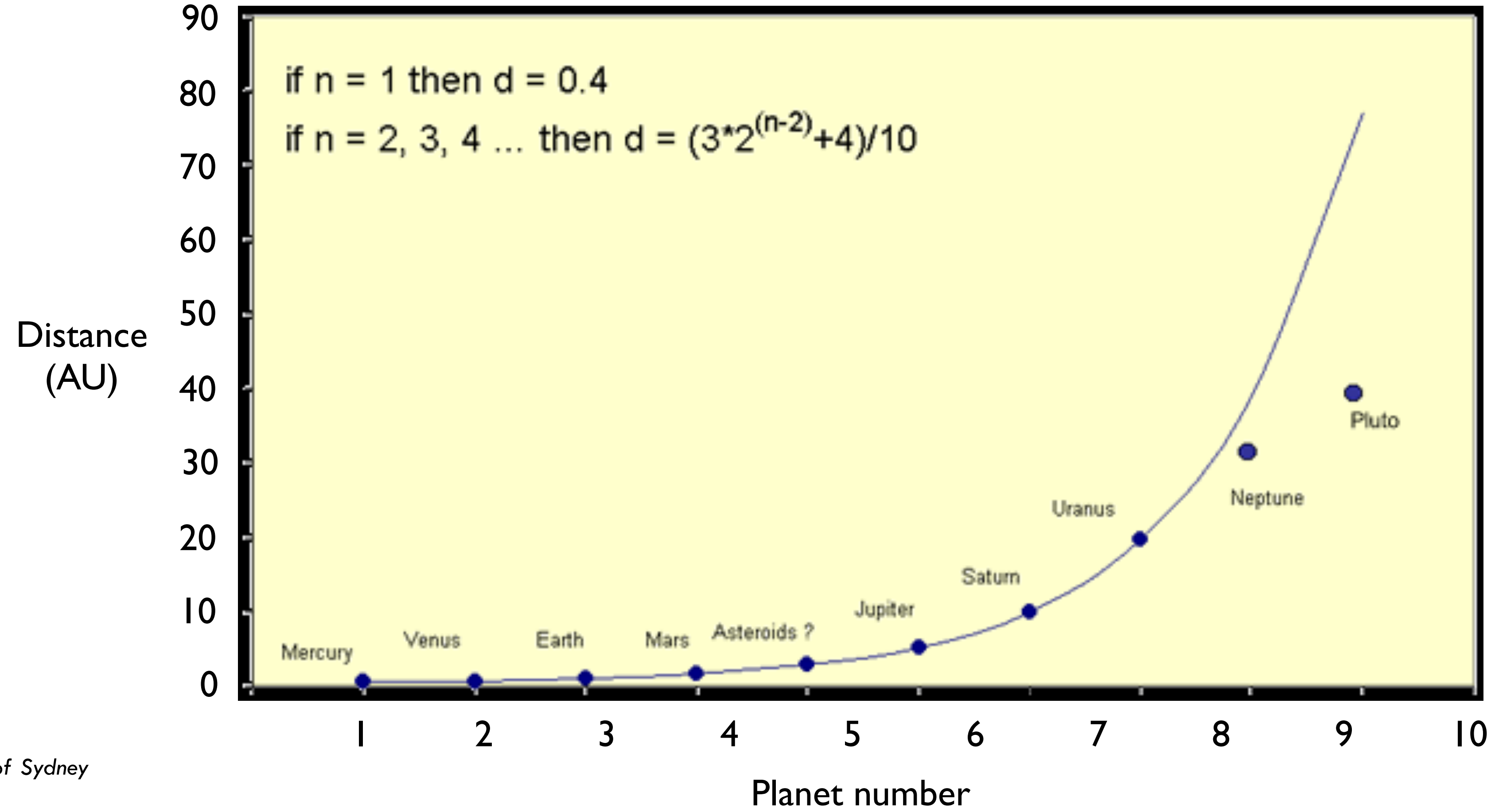


Position of the planets on 1 March 2005

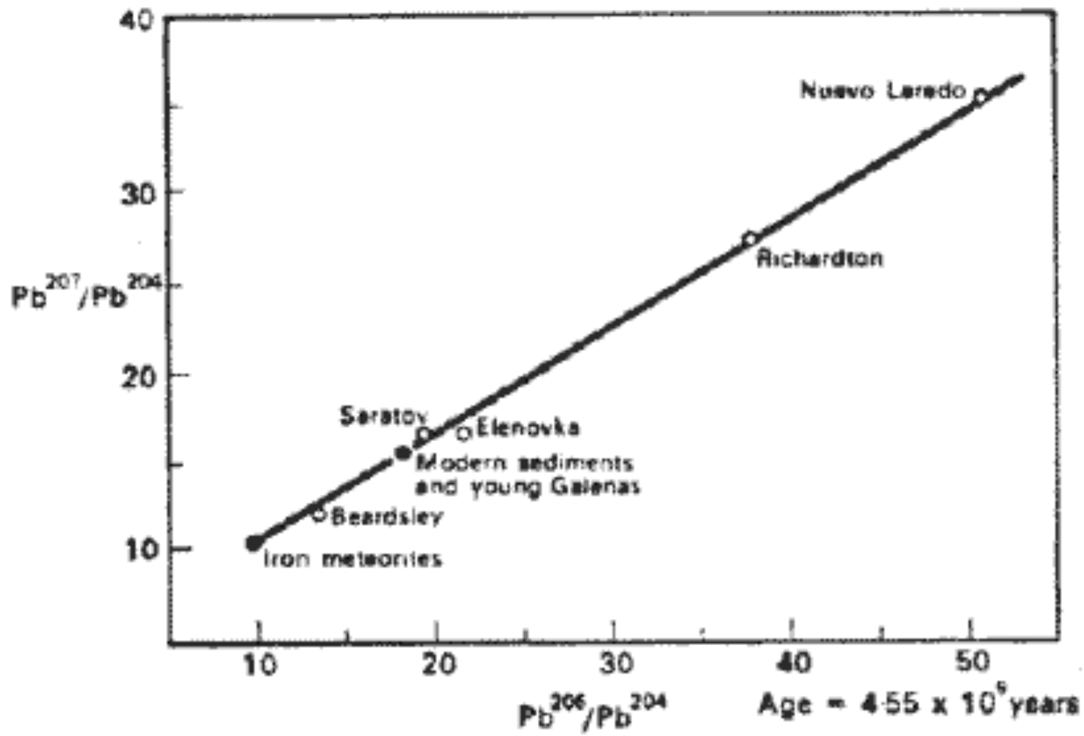
All planets (except Pluto) have orbits which are very close to circular.
Most planets rotate in the same direction as the planets revolve.



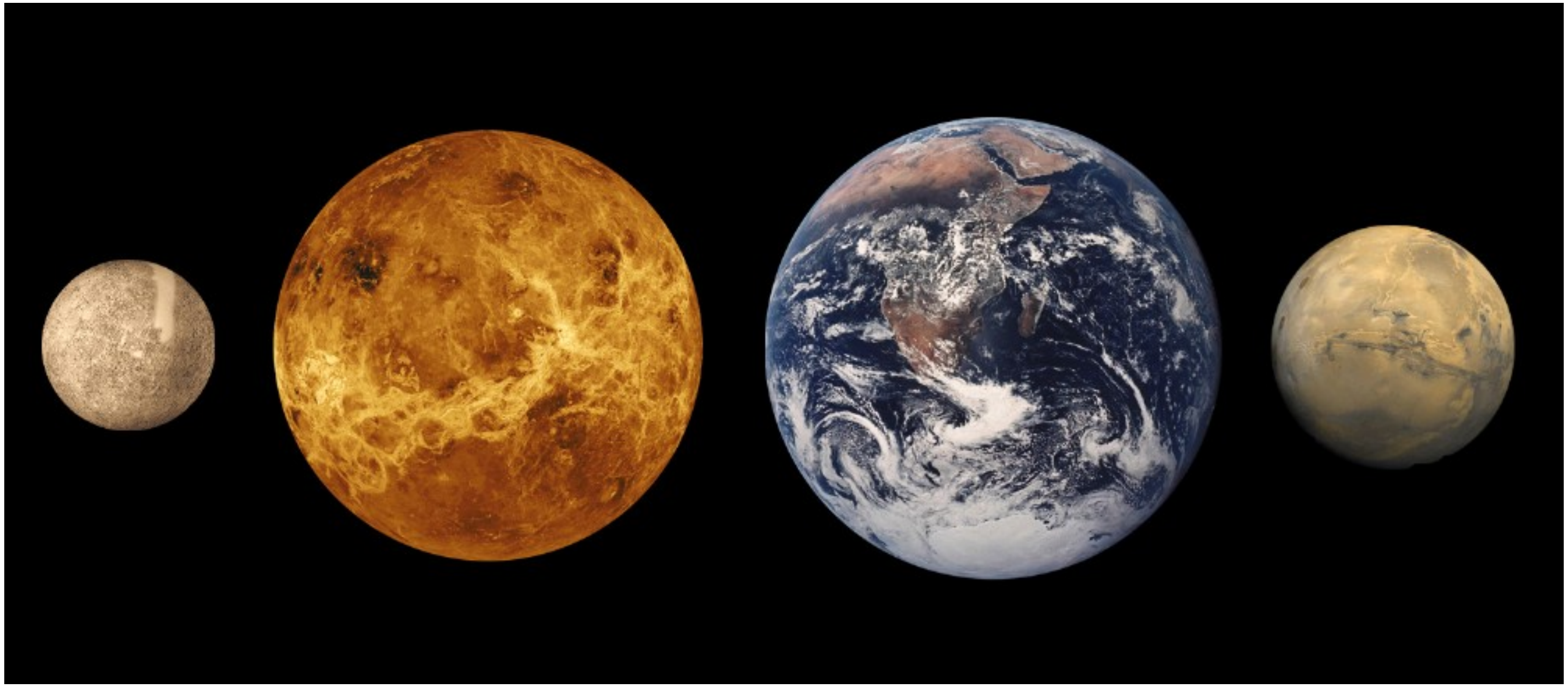
The planets are well separated, with the distance between planets increasing with distance from the Sun. (*Bode's Law?*). The space between planets, apart from the Asteroid Belt, is almost completely empty.



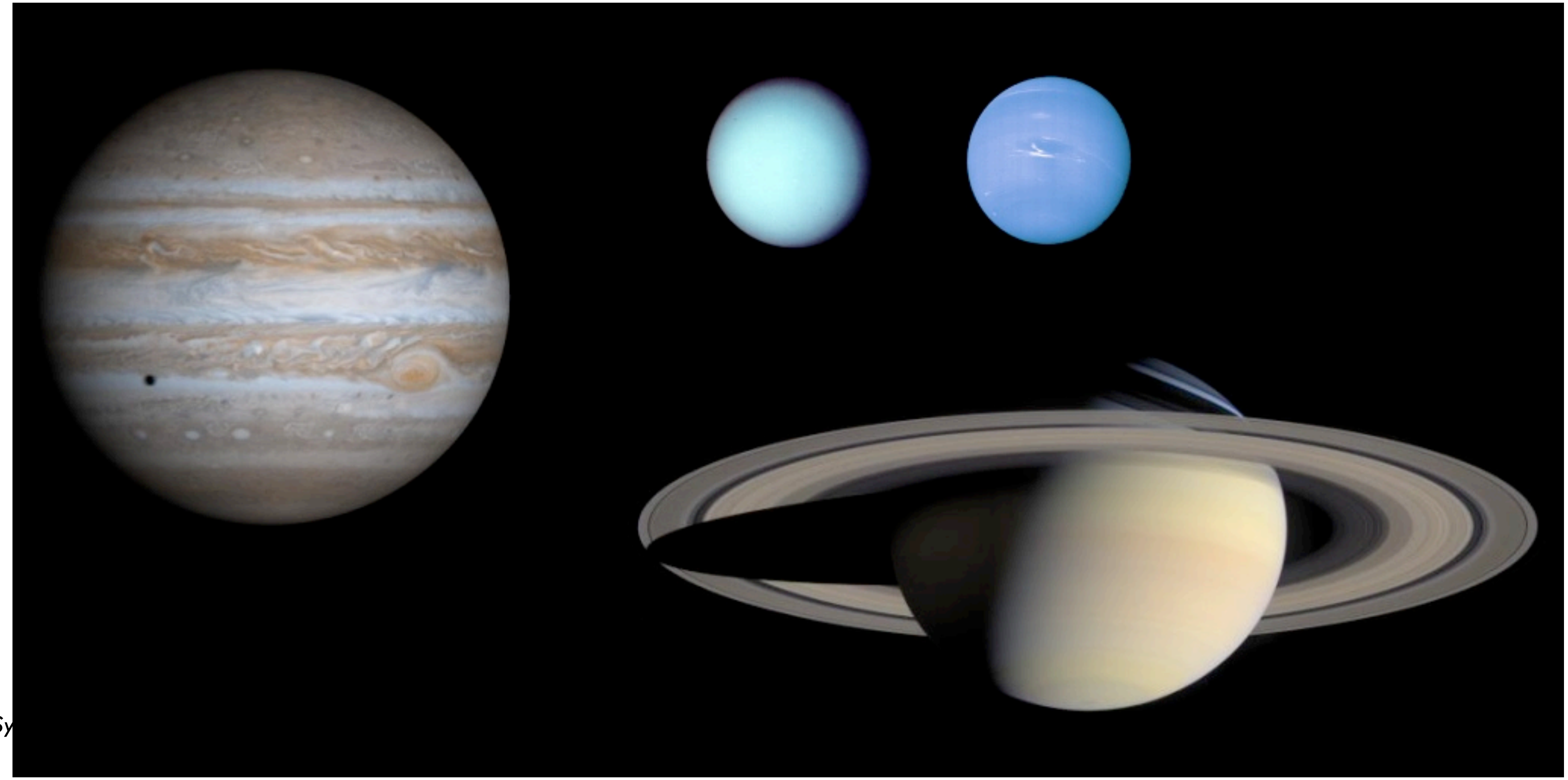
Meteorites have ages of 4.56 billion years. Rocks from the Moon and the Earth are younger, with lunar rocks typically being 3–4.4 billion years old, and terrestrial rocks are less than 3.9 billion years.



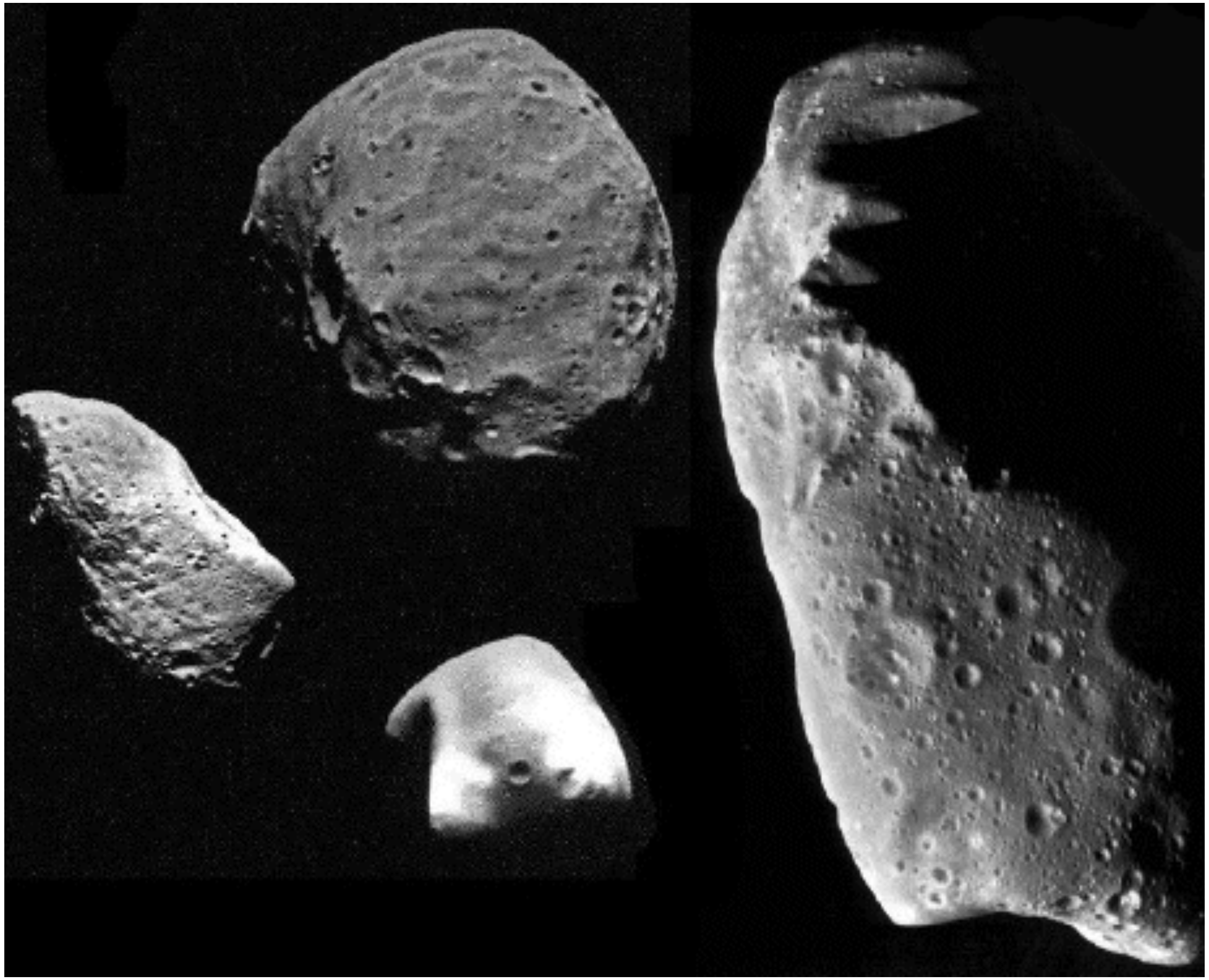
The small rocky terrestrial planets and asteroids lie closer to the Sun (all within 2AU). The closer planets are significantly denser than the further ones.



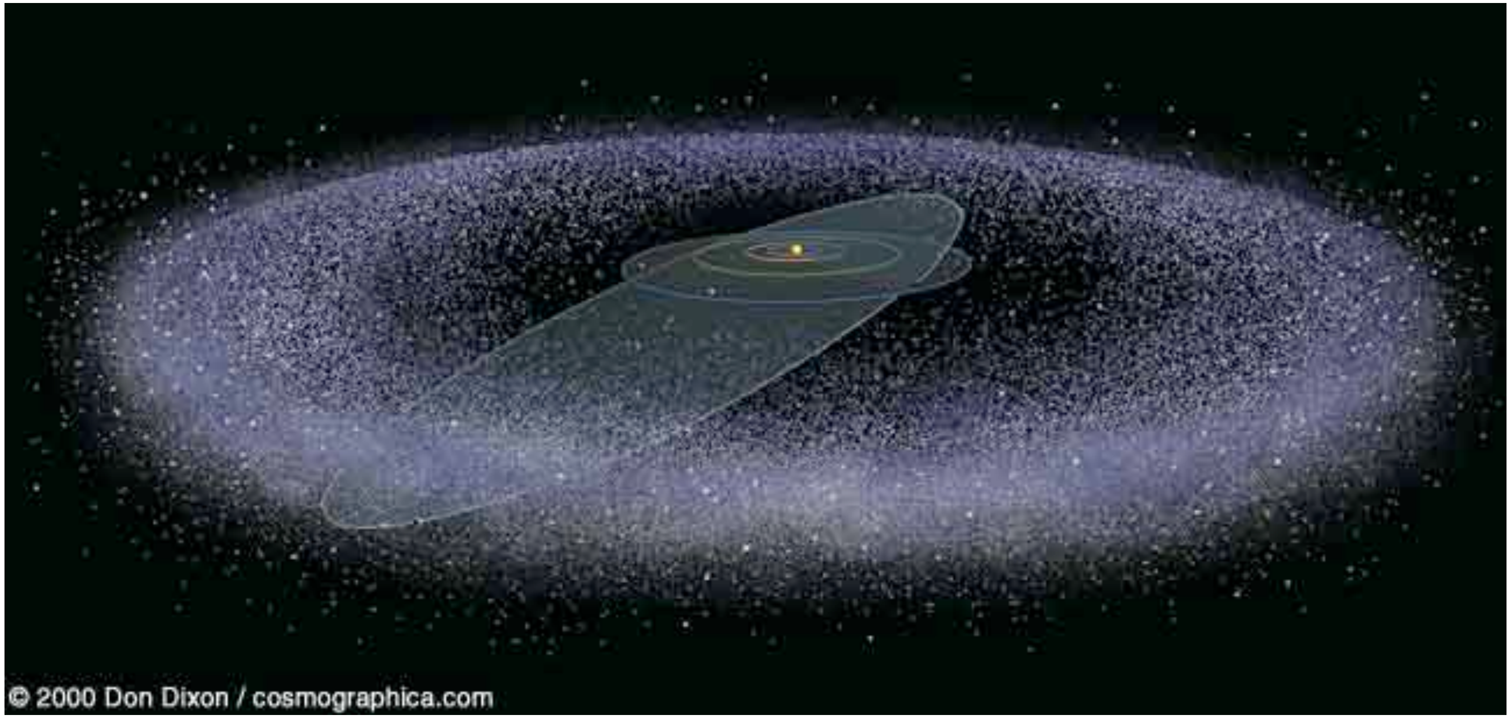
At larger distances (between 5 and 30 AU), we find the giants Jupiter and Saturn and then the somewhat smaller Uranus and Neptune. Jupiter and Saturn are mainly composed of hydrogen and helium, while Uranus and Neptune contain large amounts of ice and rock.



Between Mars and Jupiter is a large number of minor planets, with a total mass about 1/20 the mass of the Moon, and a range of sizes.



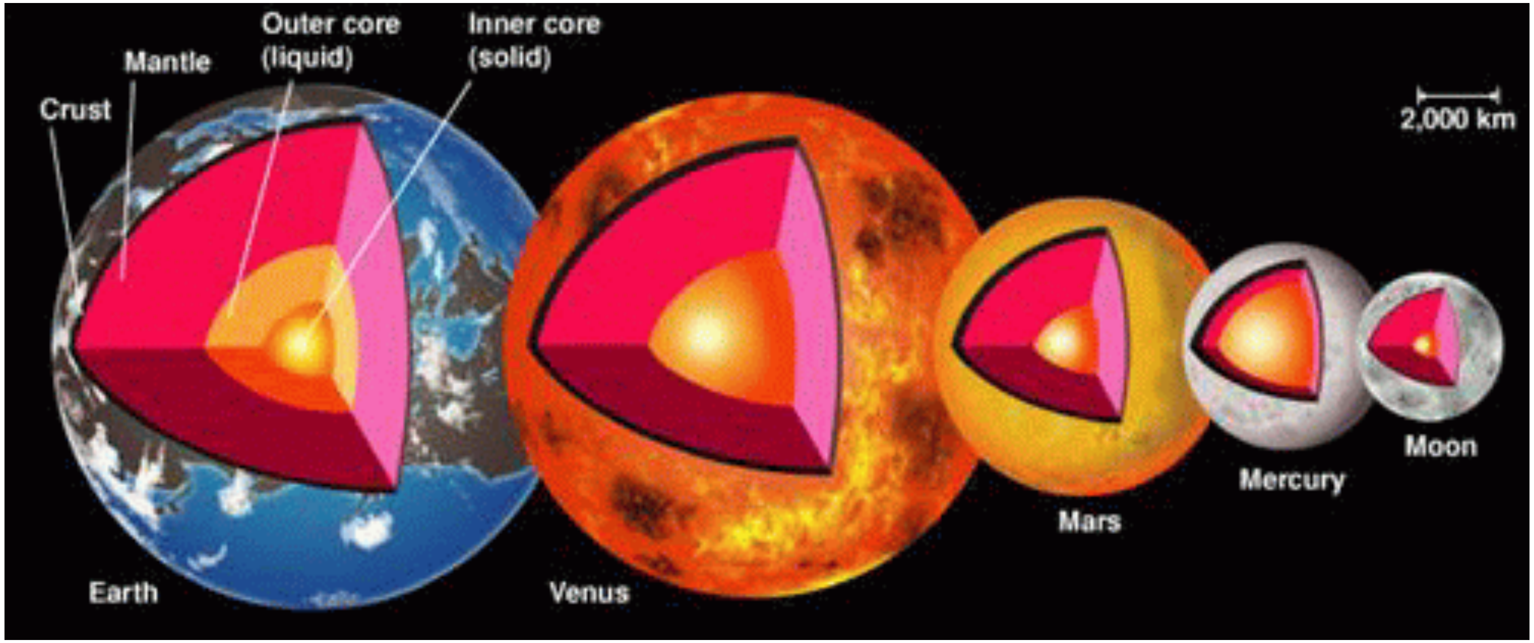
There is a large, roughly spherical collection of icy bodies circling the Sun beyond about 10,000 AU, called the Oort Cloud. Closer in, between 35 and 100 AU, is a flattened disk of similar bodies, known as the Kuiper Belt.



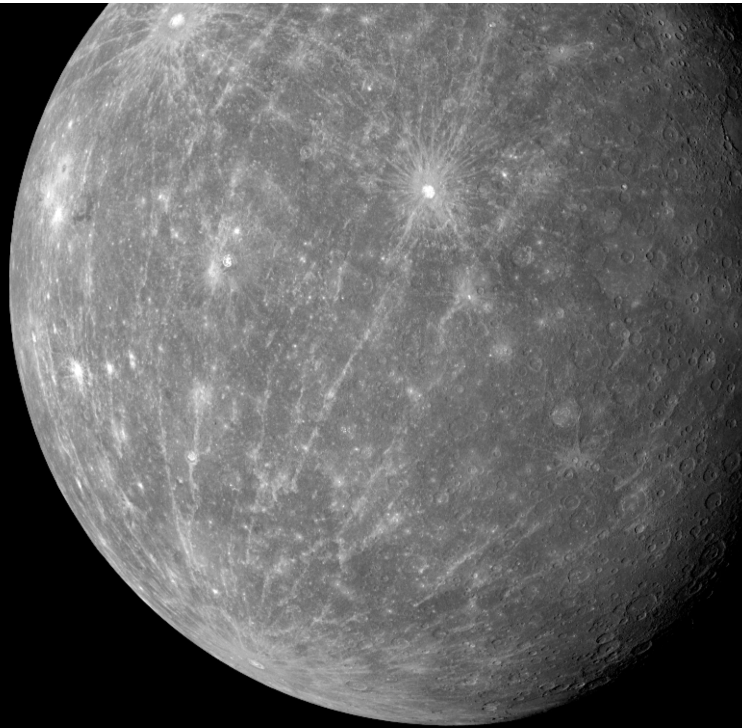
Most planets, and all giant planets, have satellites. Most close-in satellites orbit in the same direction as the planet's orbit, in the same plane as the planet's rotation. Satellites are all made of rock and ice, and Jupiter's satellites have the same density gradient as the inner planets.

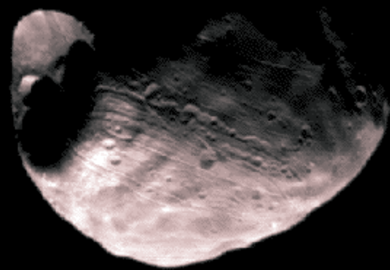
Some of the smaller, more distant satellites (and Triton) orbit in a retrograde sense or in highly elliptical or inclined orbits.

All the major planets and most large moons and asteroids are differentiated, with the heavier metals sunk to the core and the lighter material on the outside. This implies that all these bodies were warm at some stage in the past.



Most planets and satellites show large numbers of impact craters, far more than could be produced over the age of the Solar System at current impact rates.





The Moon, Mercury, Phobos and Mimas

How do we go about creating a model for planet formation?

We need to combine several ingredients:

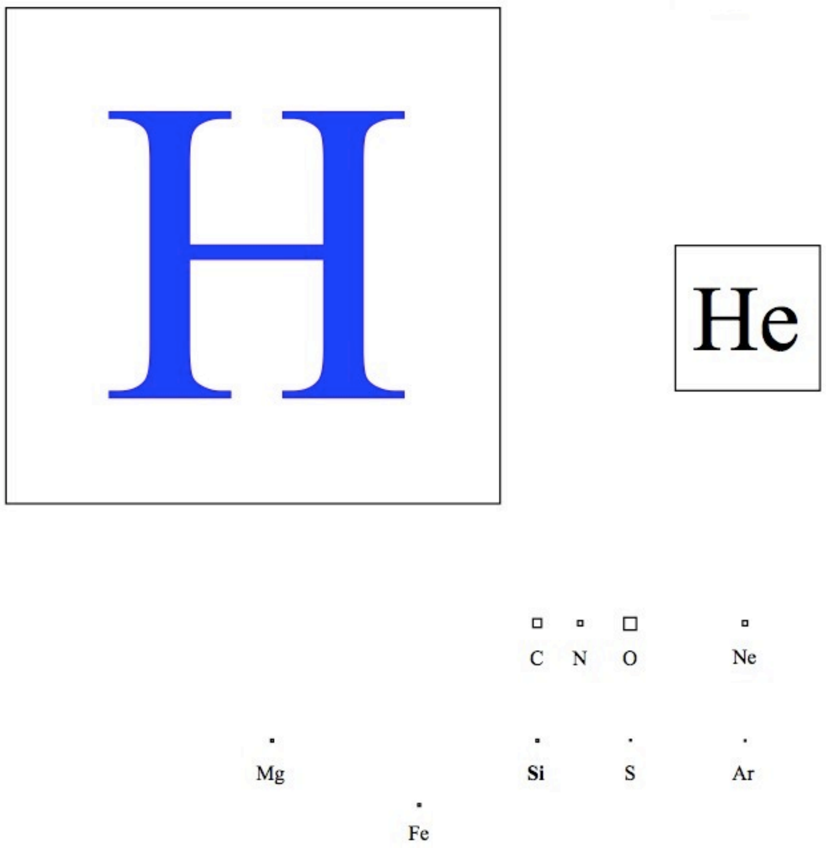
- our observations of the Solar System
- observations of newborn stars
- physics to understand gravity, rotation etc
- chemistry to understand how materials condense and clump
- geology to measure ages of rocks
- computer models to test hypotheses

The Great Nebula in Orion, M42

This gas is made up mostly of hydrogen and helium, formed in the Big Bang. However, a small but vital fraction consists of heavier elements like oxygen, carbon and silicon. These elements were manufactured deep in the cores of stars, and returned to the interstellar medium when those stars expired. Without these heavier elements, no rocky planets could form.

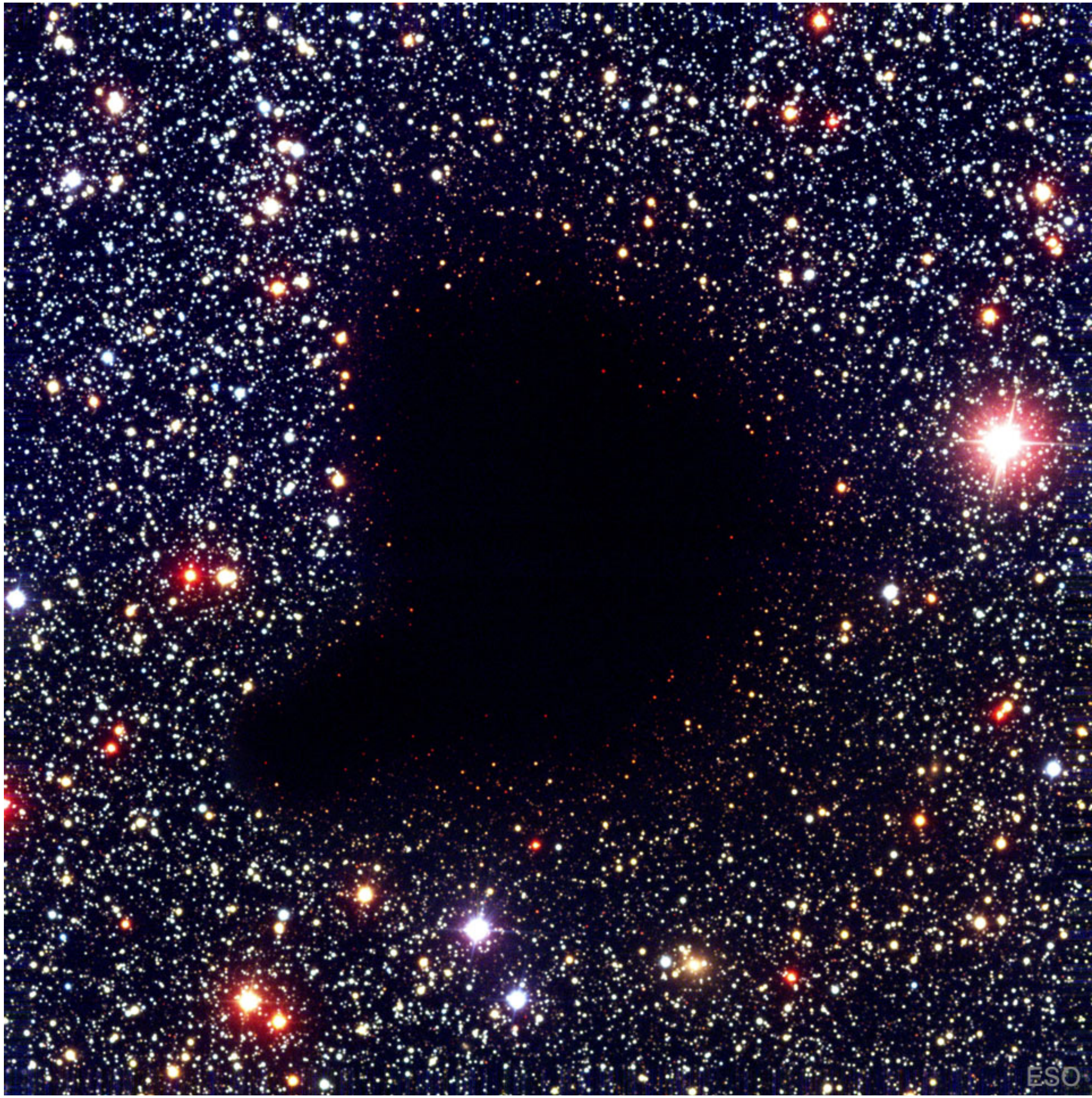
The "Witches Broom" Nebula, NGC6960, left behind by a supernova explosion about 10,000 years ago

The interstellar material from which the solar system formed consists mostly of hydrogen and helium, with other elements less than one-thousandth as abundant as hydrogen.



The "Astronomer's Periodic table", with the size of the element indicating its abundance by weight. (Figure by Ben McCall)

The gas swirls around in space and collects in dense clouds. These clouds mix with the remaining primordial gas, and are known as *giant molecular clouds*.



Here is a molecular cloud you can see: the Coalsack Nebula

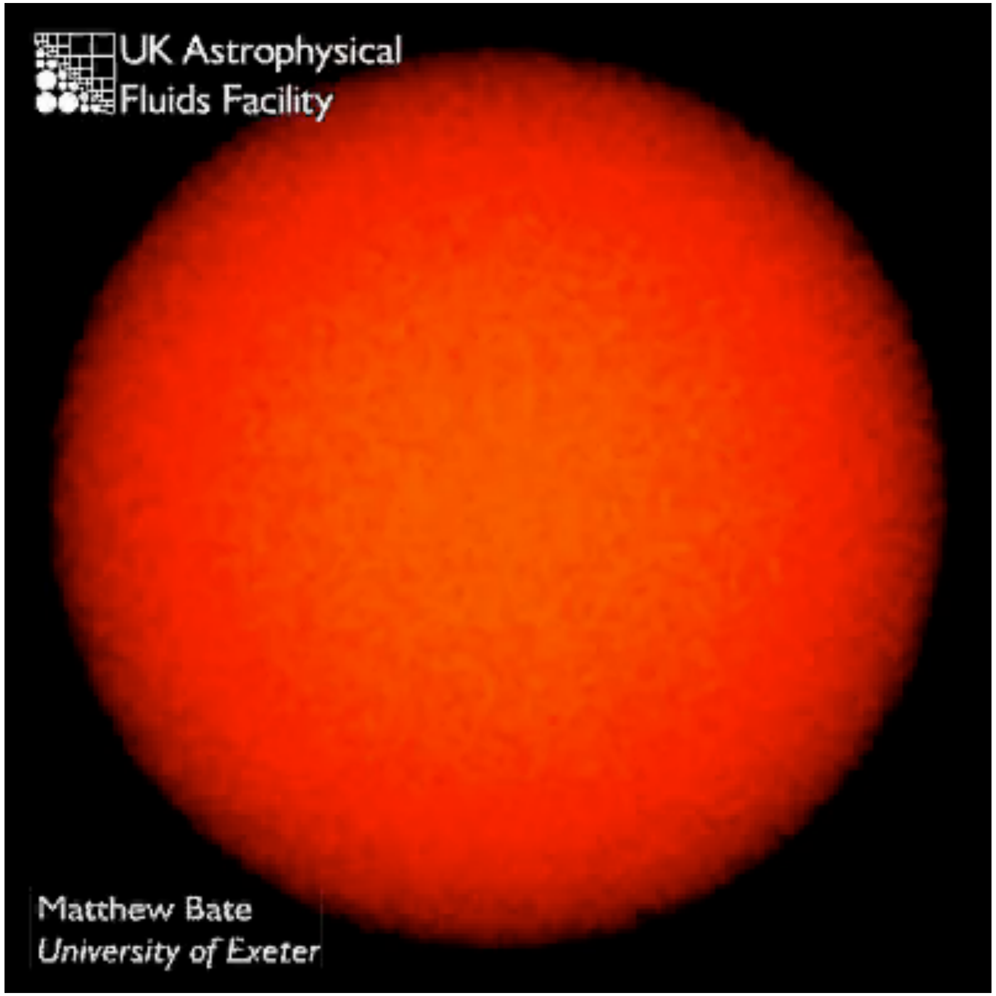
Orion and the
Horsehead Nebula


Dark globules in IC2944

Gravity, which attracts everything to everything else, tries to make the whole cloud collapse. But this inward force is resisted by *gas pressure*, which pushes outward against gravity.

As the cloud gets colder and denser, it eventually reaches a threshold where the pressure is not sufficient to support it, and it starts to collapse.

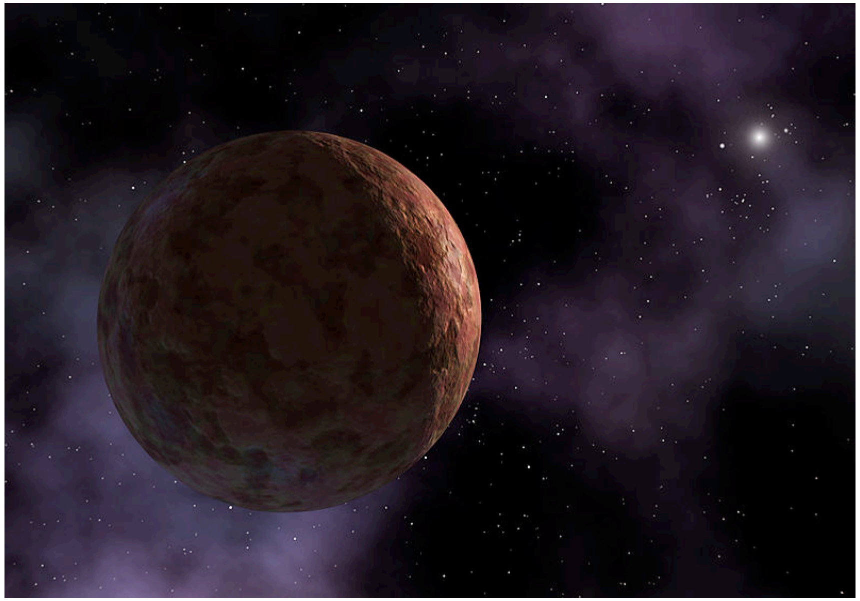
The collapsing cloud breaks into hundreds of fragments, each of which continues to collapse: the Sun was born in a cluster of young stars, all born from the same gas cloud.

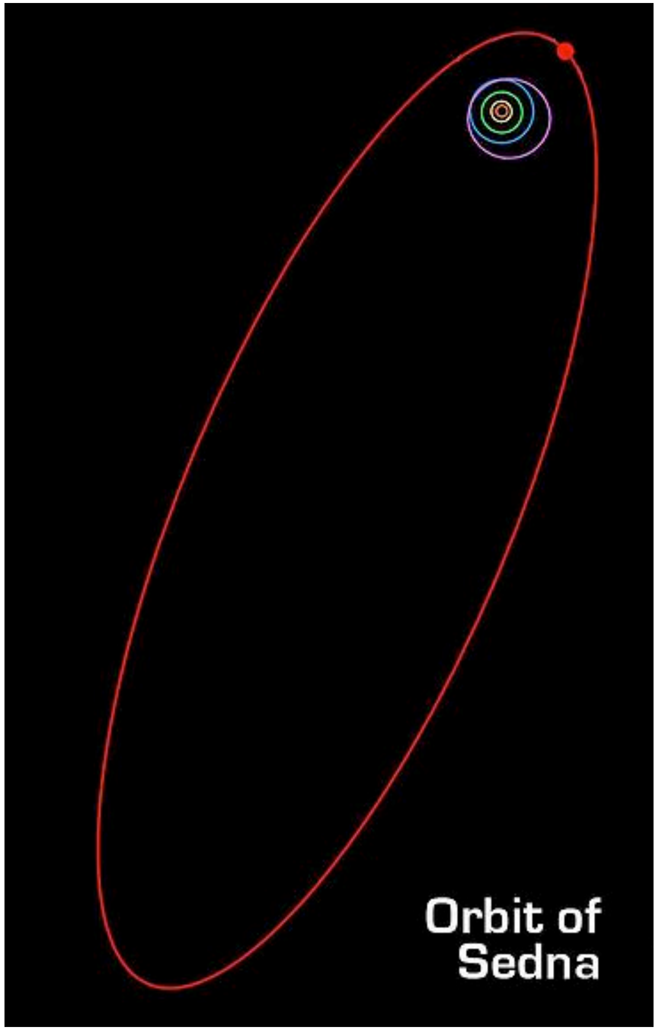


A simulation of the collapse of a 50 solar mass gas cloud, 1 light-year across, eventually forming a cluster of about 50 stars (Bate et al. 2002)

Recall that the highly eccentric orbit of Sedna must have been produced by a close encounter with another star. To perturb Sedna's orbit as much as this requires another star to approach within 200–300 AU.

A star born in a typical cluster will usually have such a close encounter once in 10 million years.



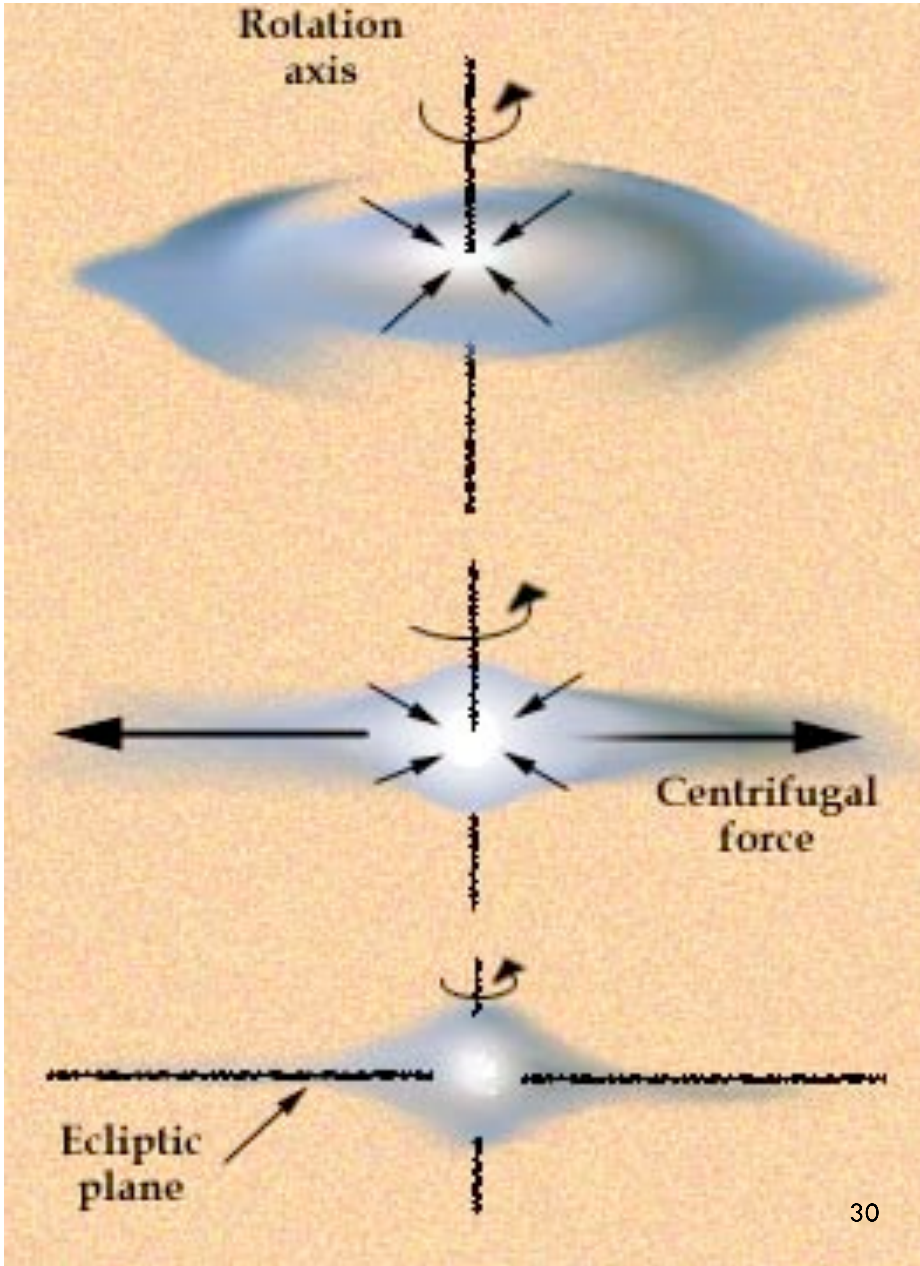


As each cloud fragment collapses, it tends to flatten into a disk. The central region collapses fastest, and begins to heat up: the cloud is collapsing from the inside. As the density increases, the cloud becomes opaque, trapping the heat within the cloud. This then causes both the temperature and pressure to rise rapidly. The collapsing cloud is now a *protostar*, surrounded by a disk of gas.

Artist's impression of a young star surrounded by a dusty protoplanetary disk.

The collapsing cloud will be rotating slightly, even if only due to Galactic rotation. The cloud shrinks by a factor of 10,000 or more, so any slight rotation is greatly amplified and the cloud will end up rotating rapidly.

What's more, it will end up as a *disk*, because while angular momentum makes it hard to collapse to the centre, there is nothing to stop the gravitational collapse to the plane.

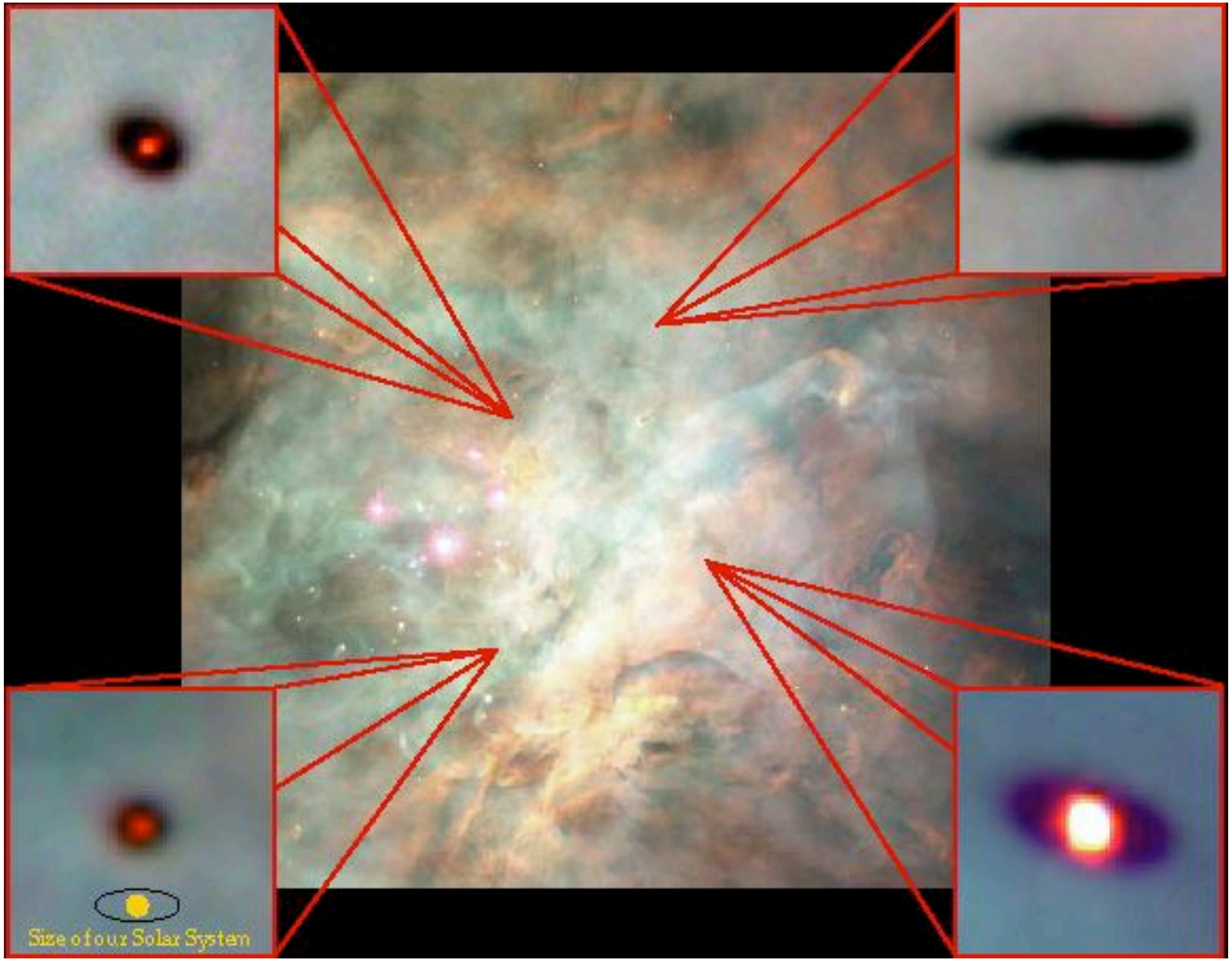


Conservation of angular momentum is what ice skaters use when they speed up a spin.

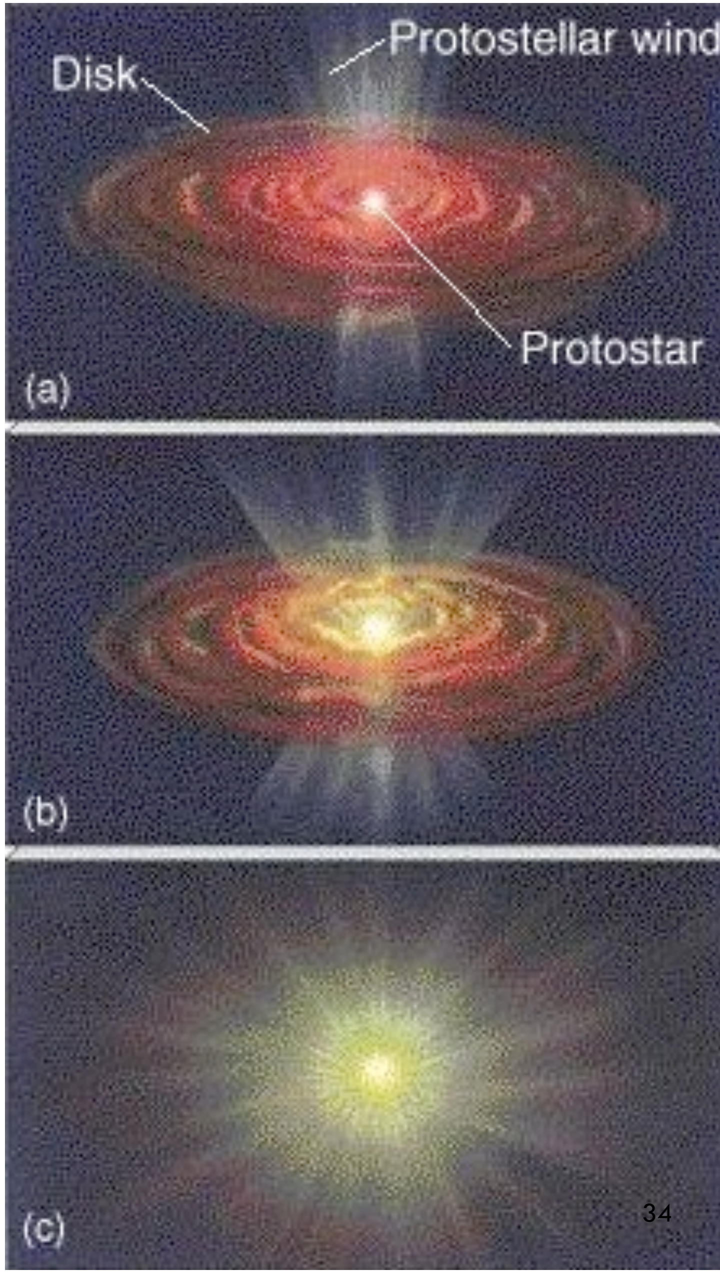
Nancy Kerrigan - 1994 Lillehammer Olympics free skating

By bringing her arms and legs into line, the skater reduces the average distance of her mass from the axis of rotation, so the rate of spin must increase.

We can actually see these disks around newborn stars.



As the central regions get denser, the collapse speeds up, so that the cloud collapses from the inside. As the density increases, the middle section of the cloud becomes opaque, trapping the heat within the cloud. This then causes both the temperature and pressure to rise rapidly – the collapsing cloud is now a *protostar*, surrounded by an orbiting disk of gas.



Here are some pictures from *HST*. The Eagle Nebula shows a region of star formation. The pillars in the centre are dense regions of gas.

Newborn stars evaporate the end of the pillar, revealing globules which are currently collapsing to form stars.


The Wizard Nebula, NGC 7380

Planet formation

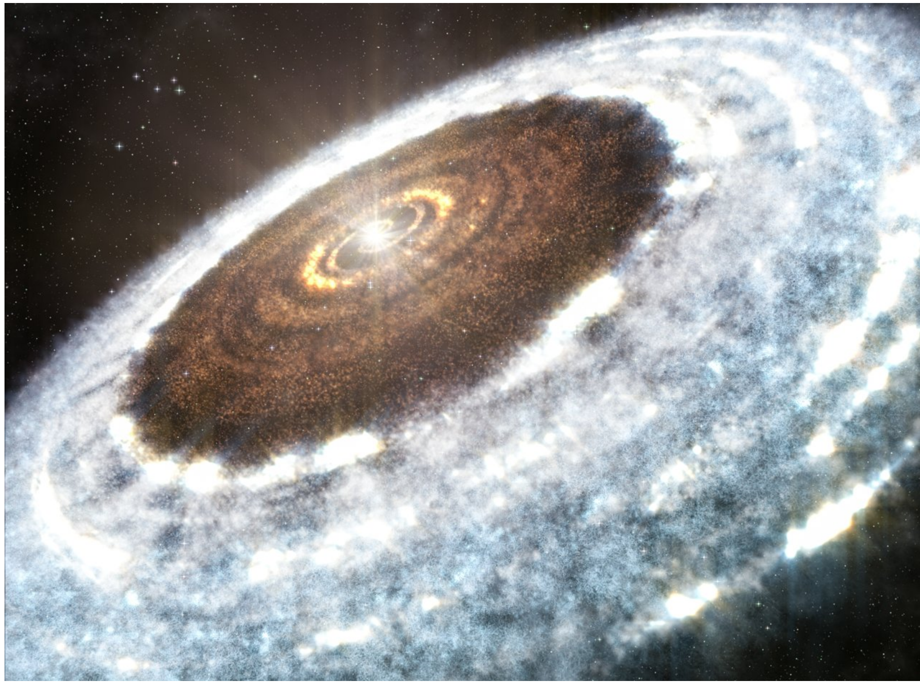
So we have formed a star. But what about the planets?

Clearly the planets form in the disk of gas and dust surrounding our newborn star. But how?

The central star is hot, but the disk begins to radiate heat and cool. Different materials start to condense out of the gas as solids.

Because the disk is hotter near the centre, close to the protostar, different materials condense out at different radii.

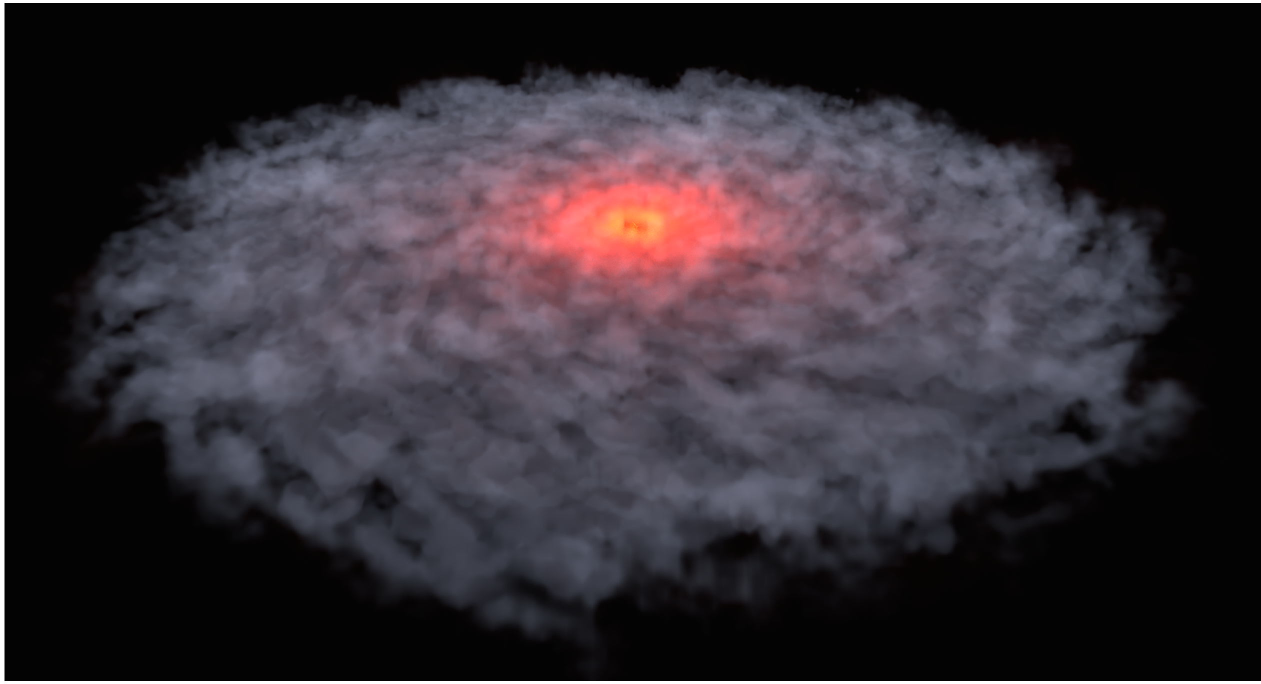
- At high temperatures (< 2000K) rocky minerals and metals like iron condense.
- Below about 270 K water ice condenses
- Below about 100K, ammonia, methane nitrogen etc. condense.
- Hydrogen and helium (which makes up the bulk of the disk) do not condense at all, so remain as gas.



Once solid particles form, they start to settle to the middle of the disk, so the young star is surrounded by a thick disk containing both gas and dust.

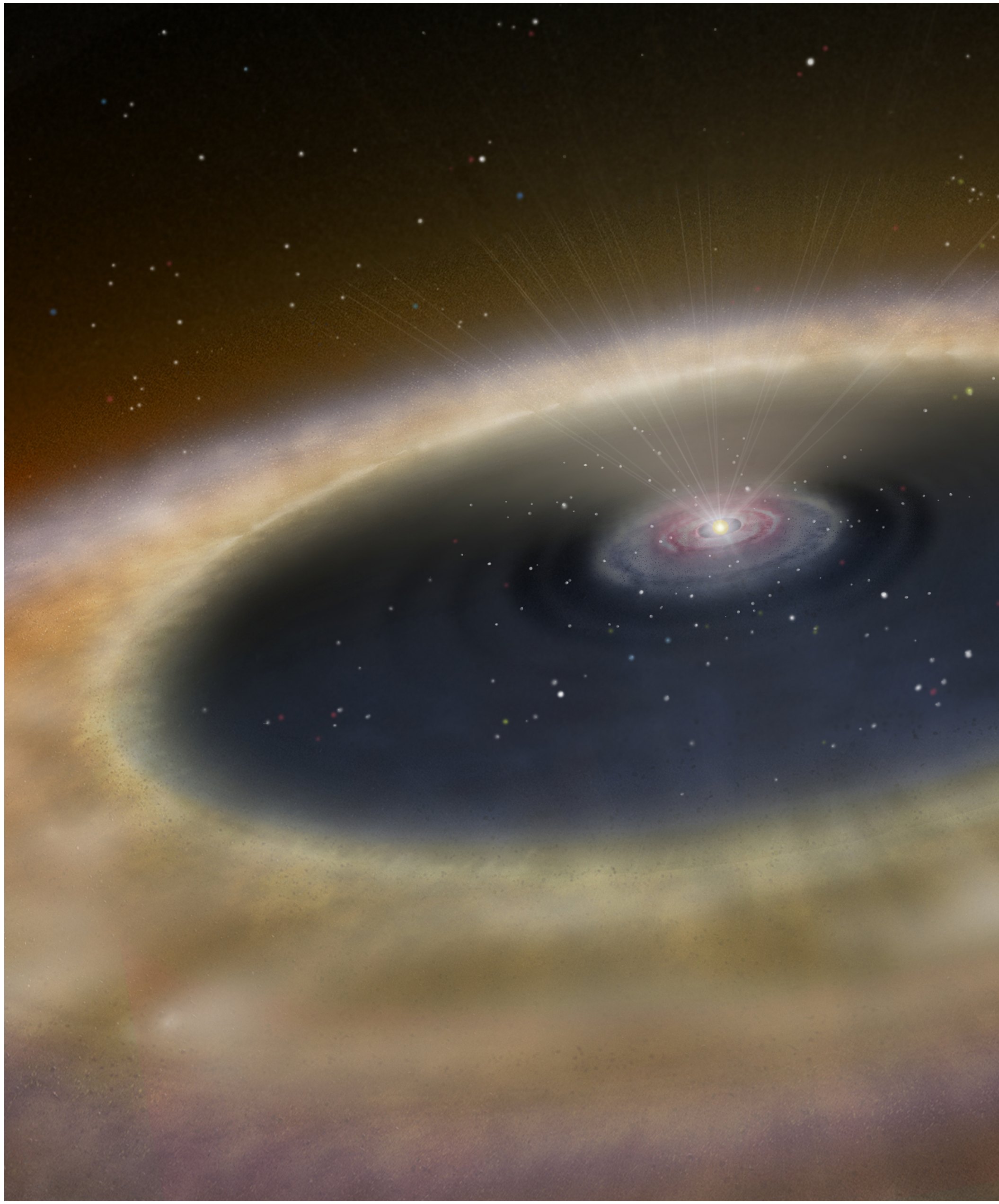
This dust starts to settle to the mid-plane of the disk, where the grains can grow bigger and bigger.

But there is a time limit. X-rays and winds from the new-born star evaporate the disk until it eventually disappears.

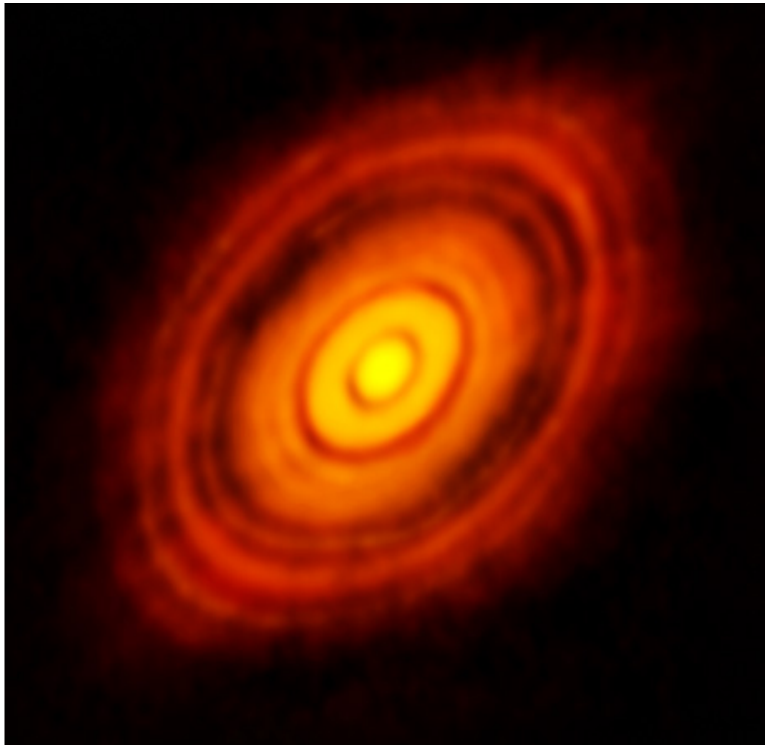


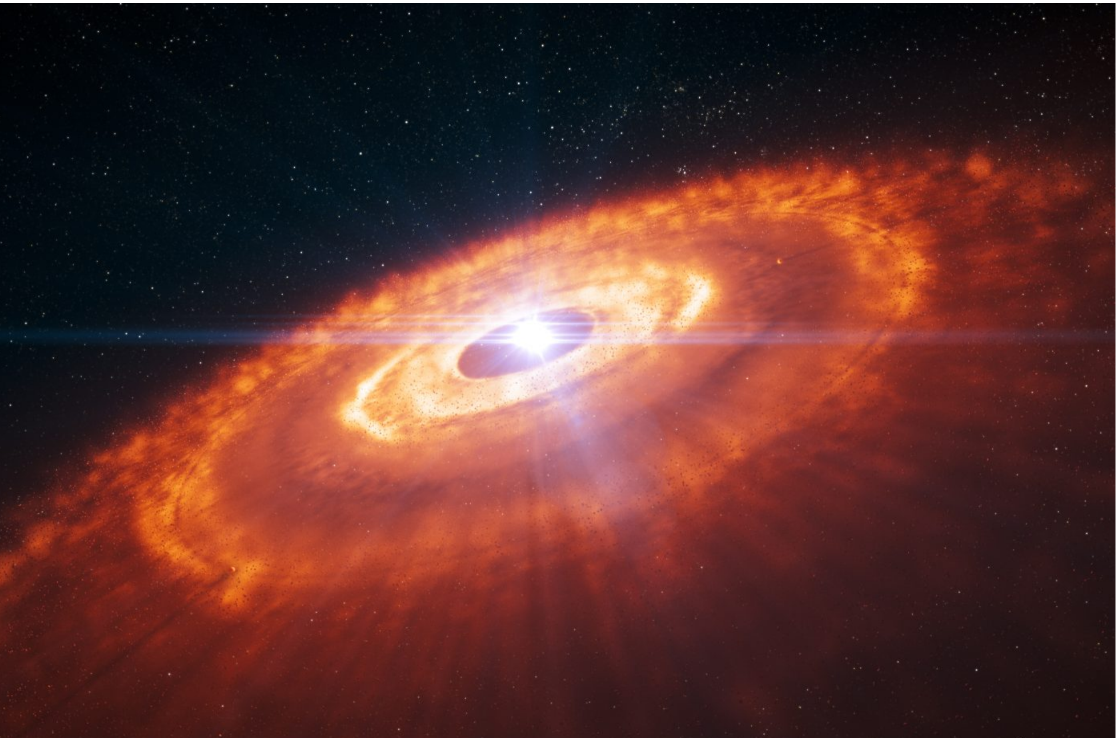
So the disk gets hollowed out by the young star. Any planets that are going to form need to do so before the dust gets blown away.

In fact, once the planets start to form, they also help to clear the dust away.



Images of disks around young stars, like this one of the young star HL Tau (taken by the ALMA radio telescope array in Chile) clearly shows a planet-forming disk around a young star.





The gaps in the disk indicate where planets are starting to form.

We have some clues about *when* the planets must have formed. You recall from our discussion of meteorites that there are several types, some showing they came from differentiated bodies, and some more primitive.

The ages of both these types can be measured, with surprising results. The parent bodies of meteorites began to form very soon after the formation of primitive grains: within 1 million years. Differentiated meteorites have ages which are only 10 million years younger than the oldest grains.

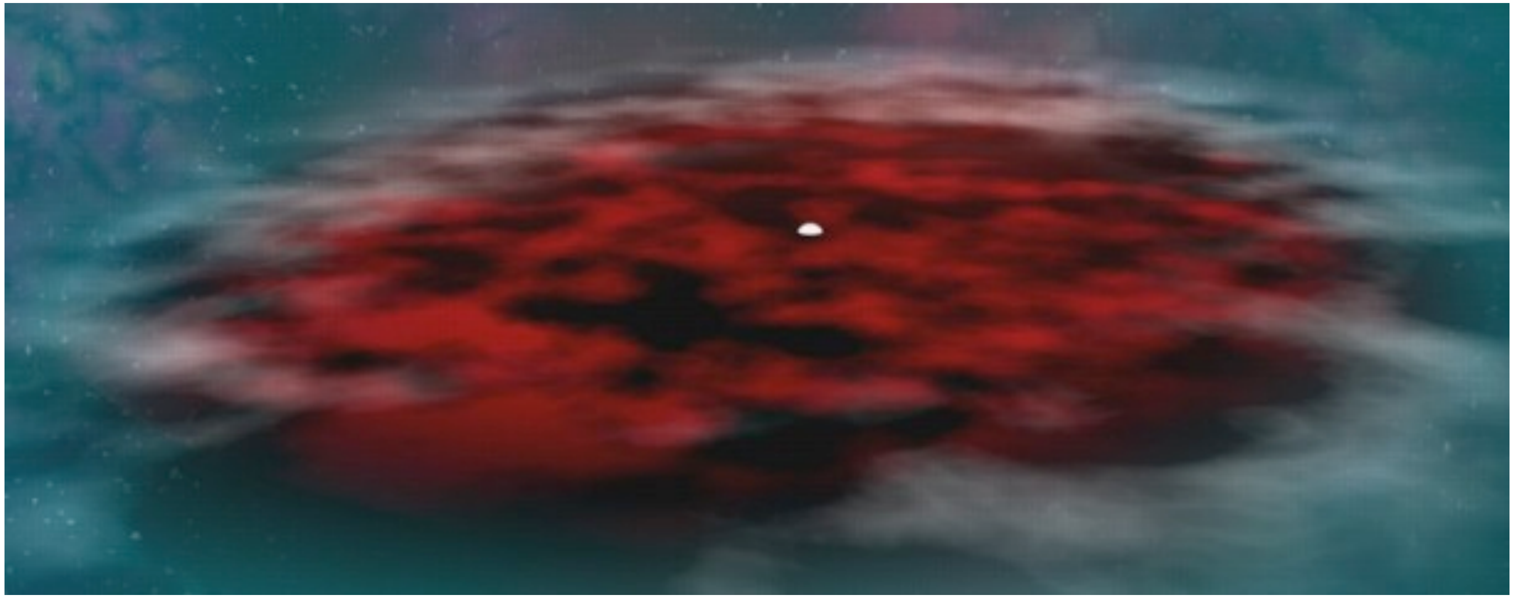
The giant planets must have formed within 10 million years, before the new Sun swept away the gas.

There are several stages to forming planets:

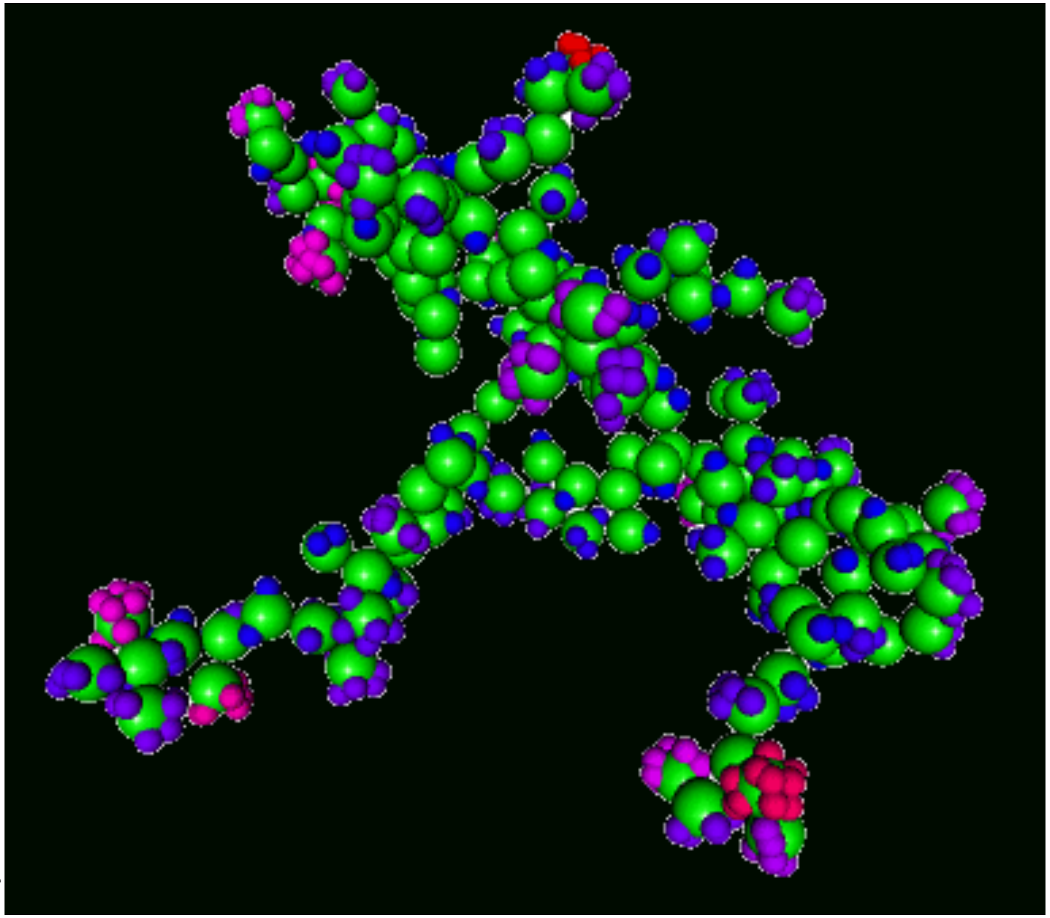
- *coagulation phase*: First dust forms from the interstellar gas cloud — 1 cm
- *accretion phase*: This dust then starts sticking together — 1 km
- *runaway growth*: Gravity becomes important as the protoplanets grow — 1000 km
- the *era of carnage*: The last few collisions have planet-shattering effects — 10,000 km

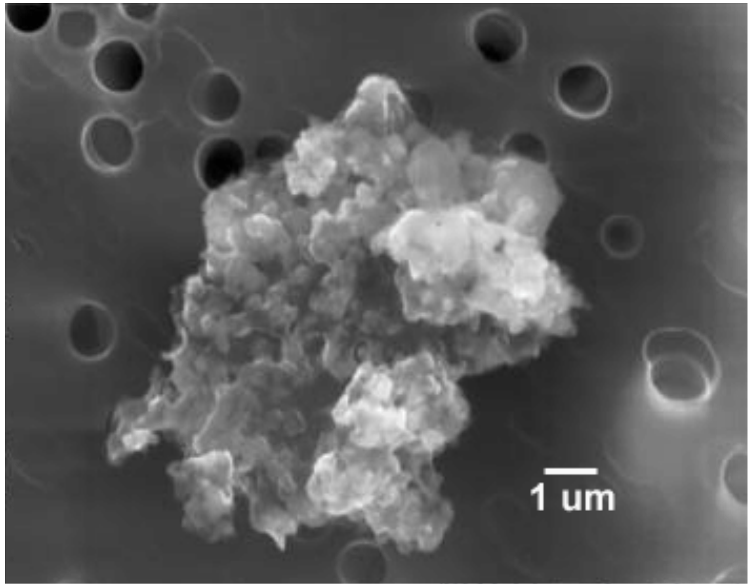
Phase 1: Coagulation

The disk starts out with the same elements which were in the molecular cloud. It consists almost entirely of gas, with a tiny amount of dust. Which molecules form depends on local conditions in the disk. Different molecules have different temperatures at which they can “freeze out” of the disk.



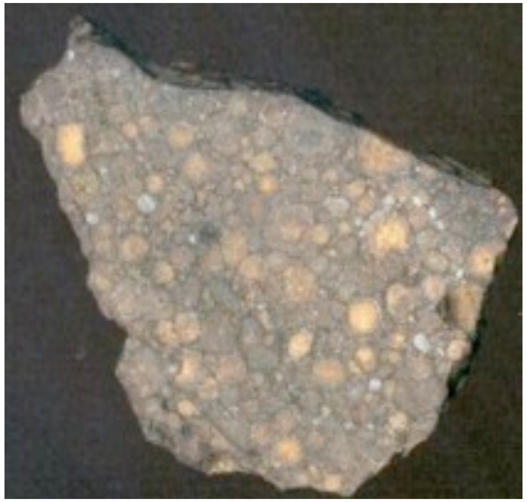
The condensing materials stick together by colliding and sticking together using normal chemical forces. They form loose fractal aggregates, described as “fluffy dustballs”.





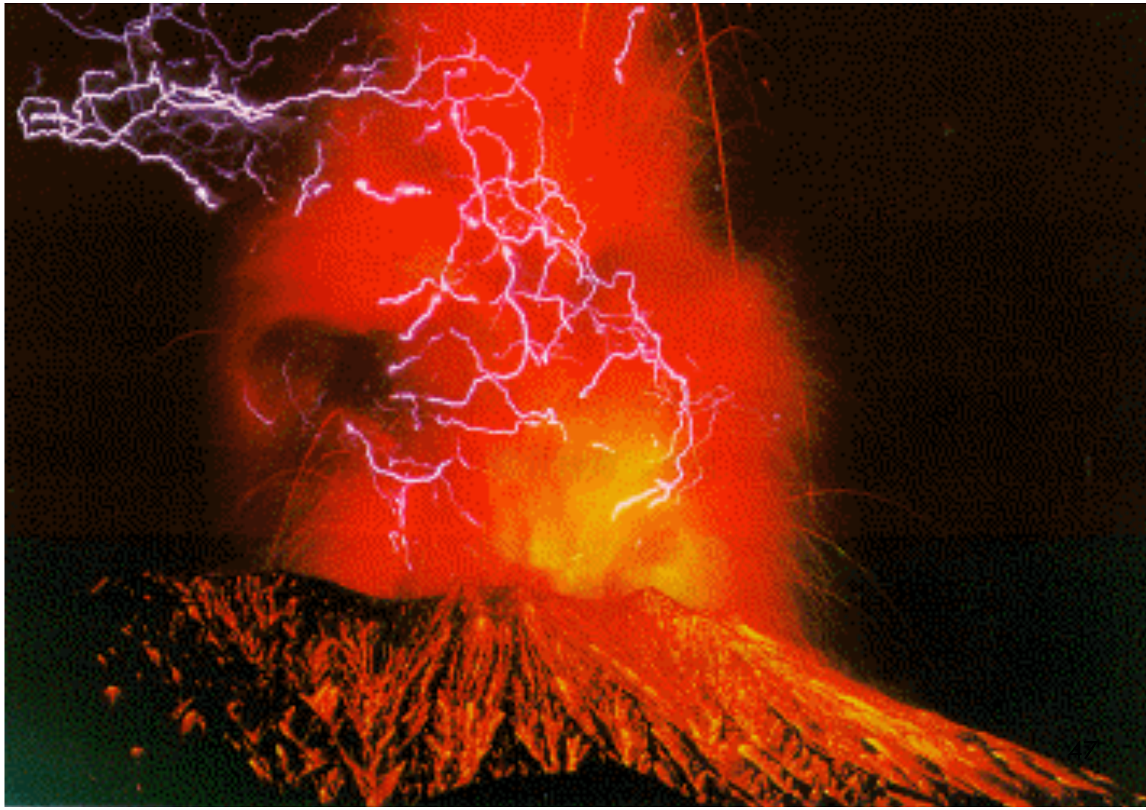
(NASA Johnson Space Center)

(left) Simulation of a molecular aggregate formed by collisions; (above) Electron microscope image of a typical cosmic dust particle



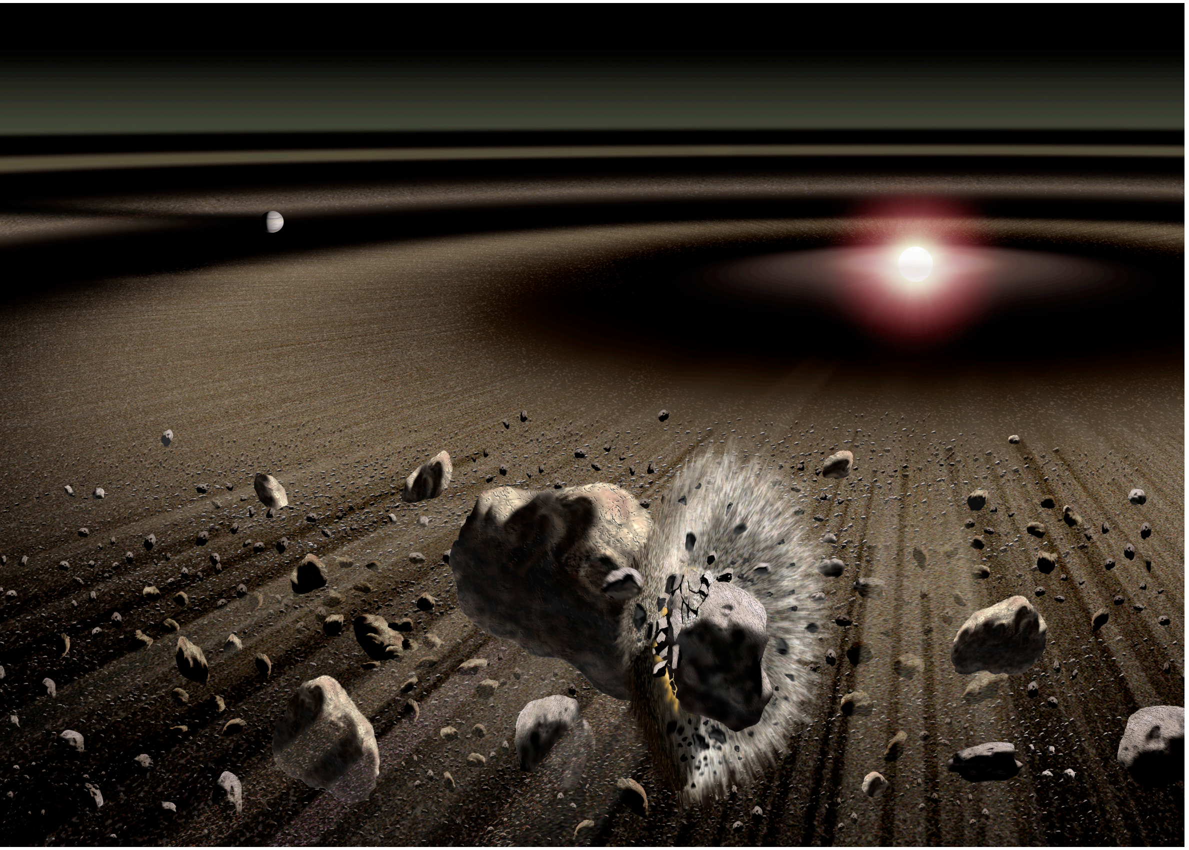
Many meteorites contain *chondrules*, which are the oldest objects in the Solar System. They have been melted and rapidly cooled, so the fluffy dustballs turned into smooth spheres.

But how were they melted? No-one knows for sure: perhaps passage through shocks in the disk, or lightning in the disk (seen in volcano plumes)



Phase 2: Accretion

The next phase is the formation of *planetesimals* (bodies up to about 1 km in size) through accretion.



The dust-ball aggregates settle to the plane of the disk, growing through direct contact all the time. Within 10,000 years, the particles have grown to a centimetre or more in size.

As particles grow, they experience substantial drag in the disk. This makes the particles slow down, and we can calculate that a rock of about 1m in size would spiral in to the Sun in only 100 years or so.

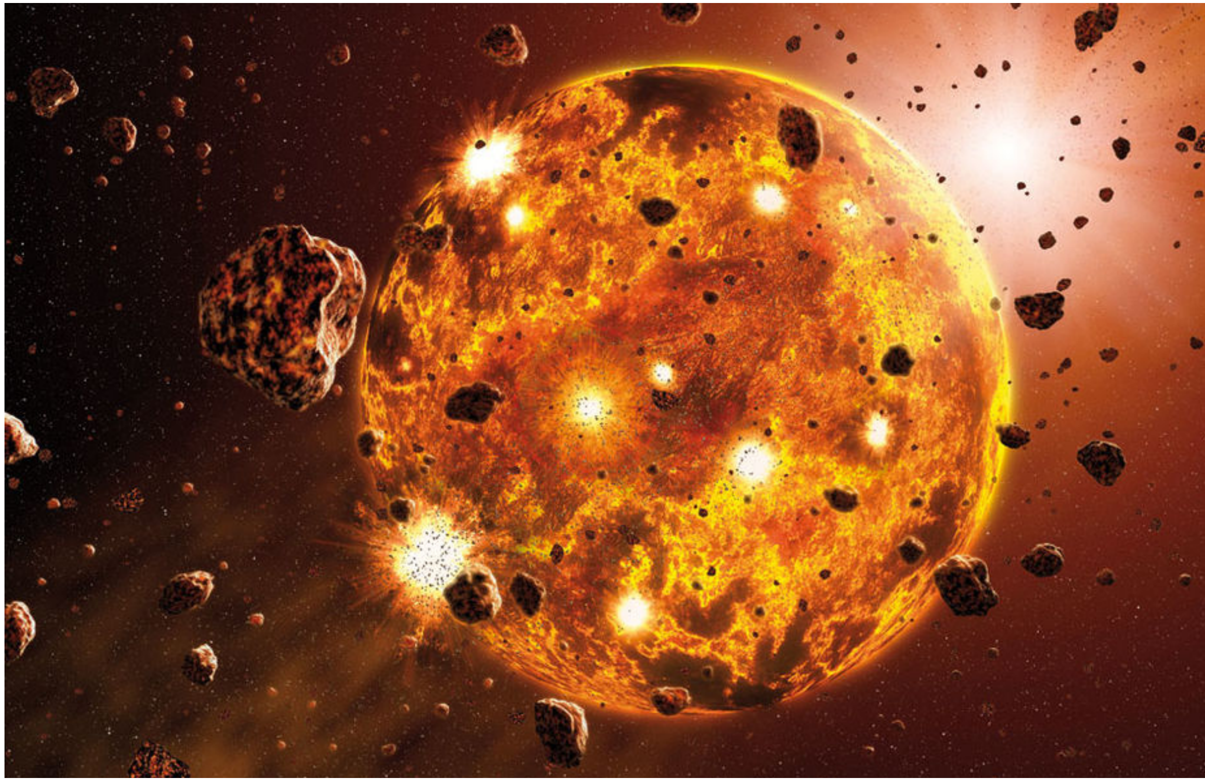
The only way to stop this if for the planetesimals grow very quickly to kilometre size, by which size the drag is less (because the surface area to mass ratio drops). We're not sure exactly how this happens.

Once a few bigger objects have formed, they grow quickly, because pebble-sized objects are slowed down by the gas and are captured by the planetesimals.

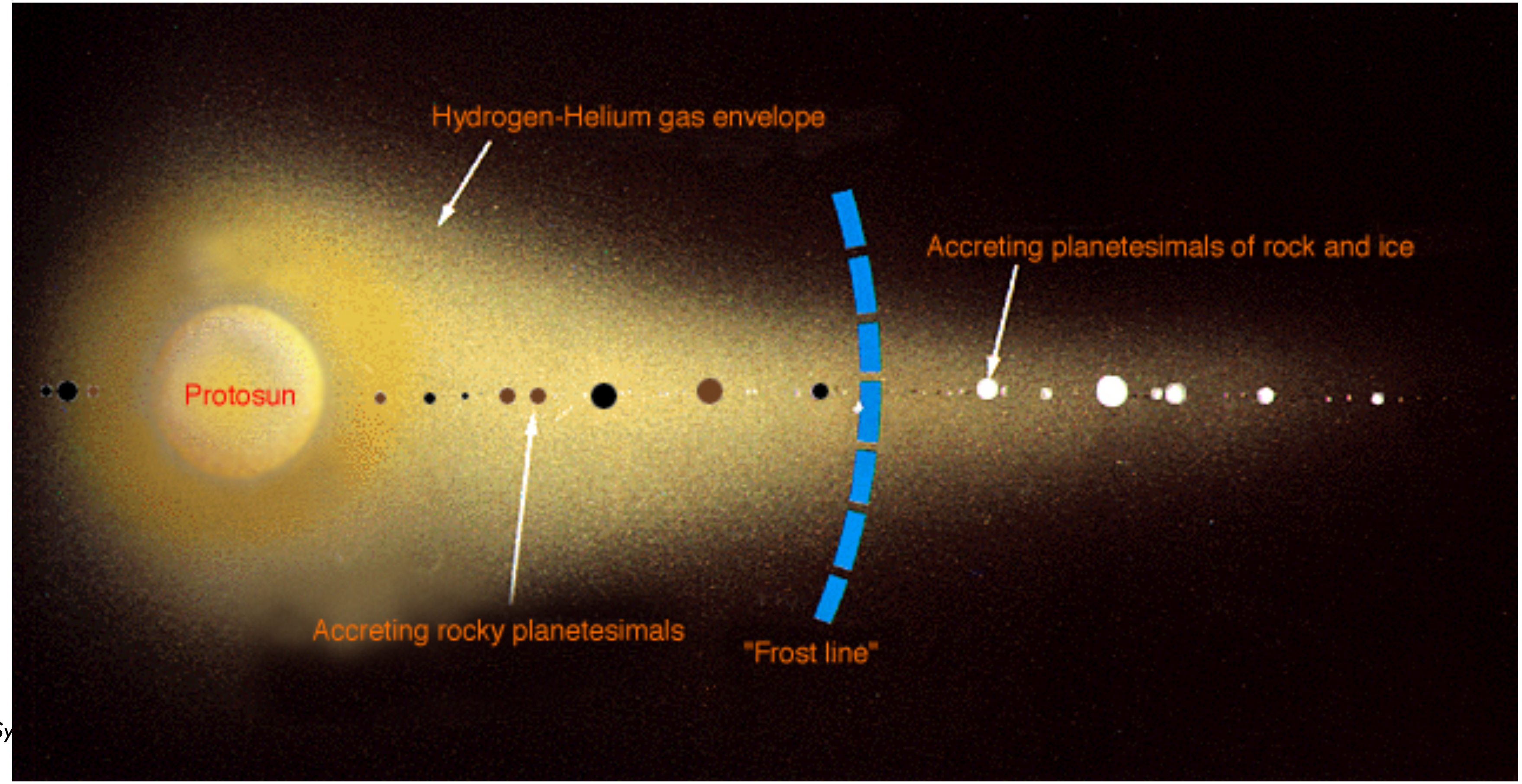
Phase 3: Runaway growth

Once the particles reach about 1 km in size, gravity starts becoming important. The larger planetesimals can sweep up more material, so the biggest bodies grow much faster than smaller ones – a process known as runaway growth.

Runaway growth ends when the planetesimal (now called a *planetary embryo*) has consumed nearly everything within its reach.

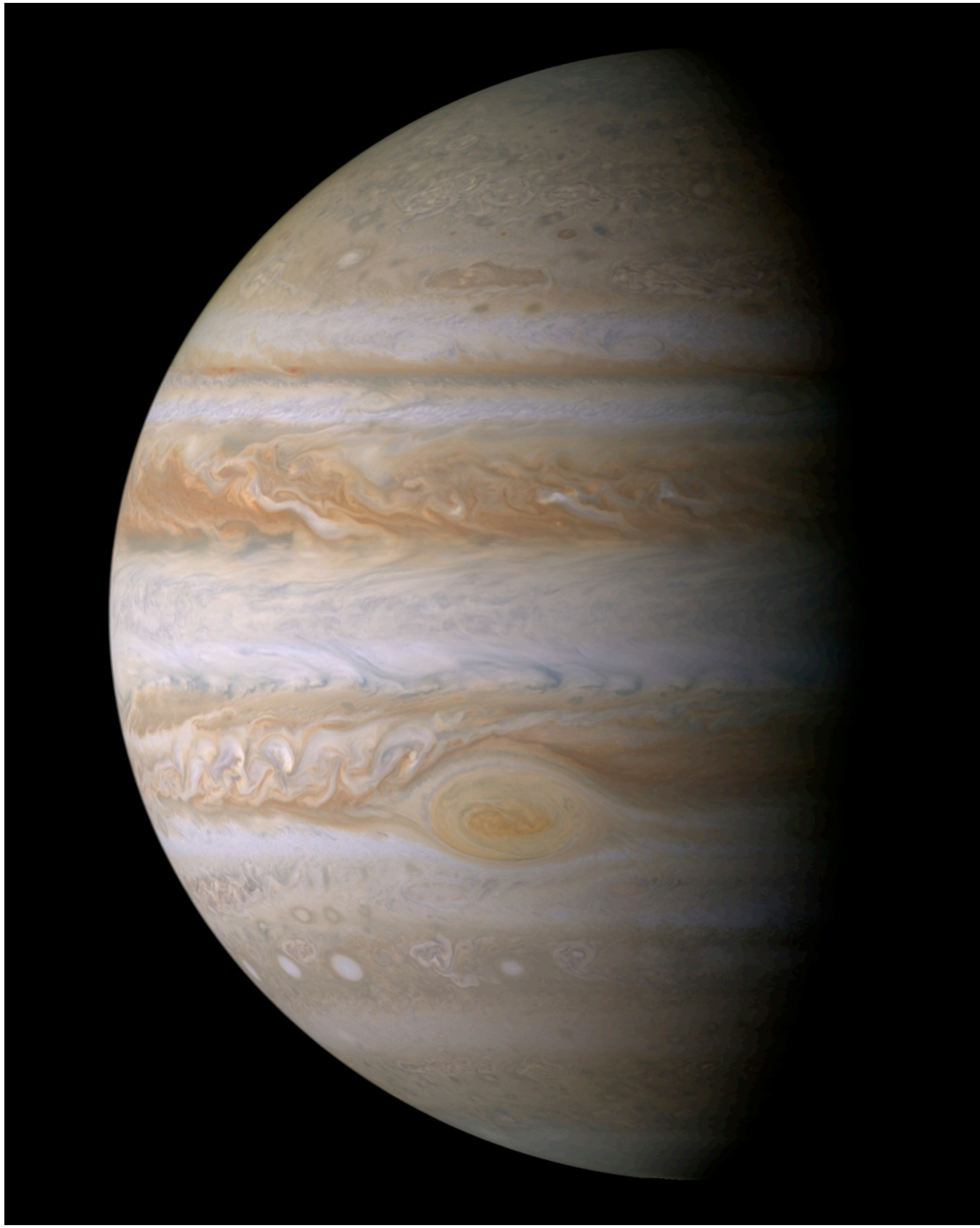


Beyond the frost line, there is much more mass available, so planetesimals in the outer part of the solar system can grow much bigger.

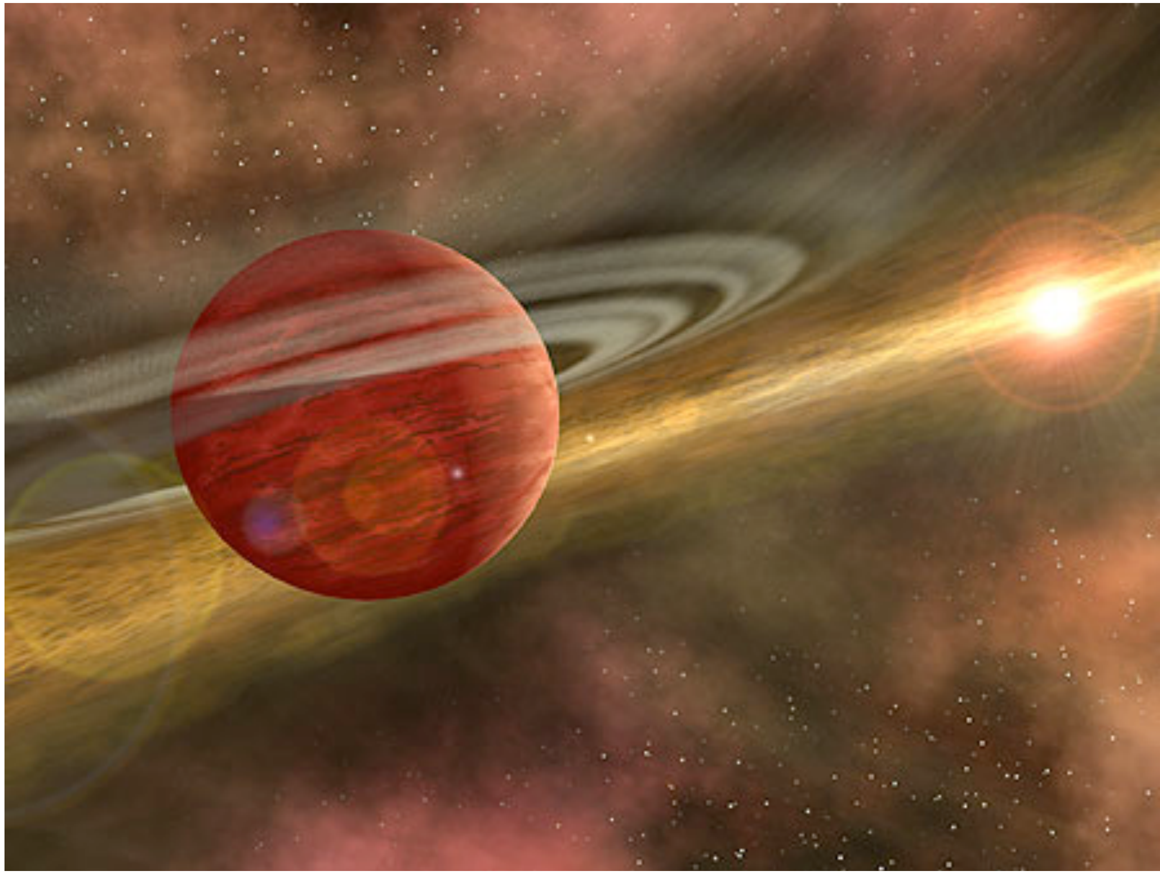


The giant planets appear to have formed by first accreting a core of several Earth masses. Once this mass is heavy enough, the planet can start accreting gas directly, in a *runaway gas accretion* phase. Smaller objects don't have enough gravity to hold on to gas.

Jupiter and Saturn grew much larger than Uranus and Neptune because they formed closer to the Sun, where the disk was thicker.



The giant planets were hot when they were accreted. This expanded their atmospheres to vastly larger dimensions than they have today. Gradually they radiated away this heat and shrank, leaving a disk of gas, ice and dust in orbit: a small-scale analogue of the solar nebula. From these disks emerged the regular satellites and ring systems.



Satellites must have formed from a disk around their primary, just like miniature planetary systems. This disk was heated by the forming planet, leading to gradients of composition just like those we see in the planets.

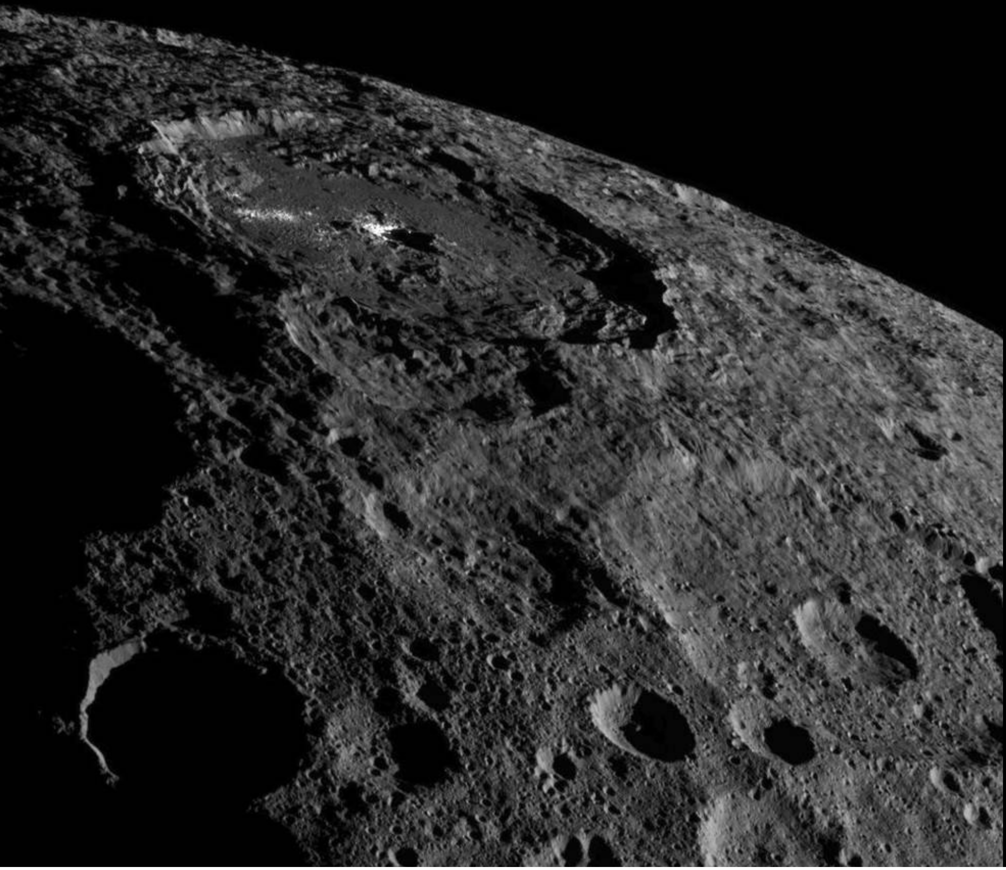
The irregular satellites are captured planetesimals, captured by the gravitational field and/or the extended atmospheres of the proto-planets.

The Earth's moon and Charon have a different origin.

Phase 4: The era of carnage

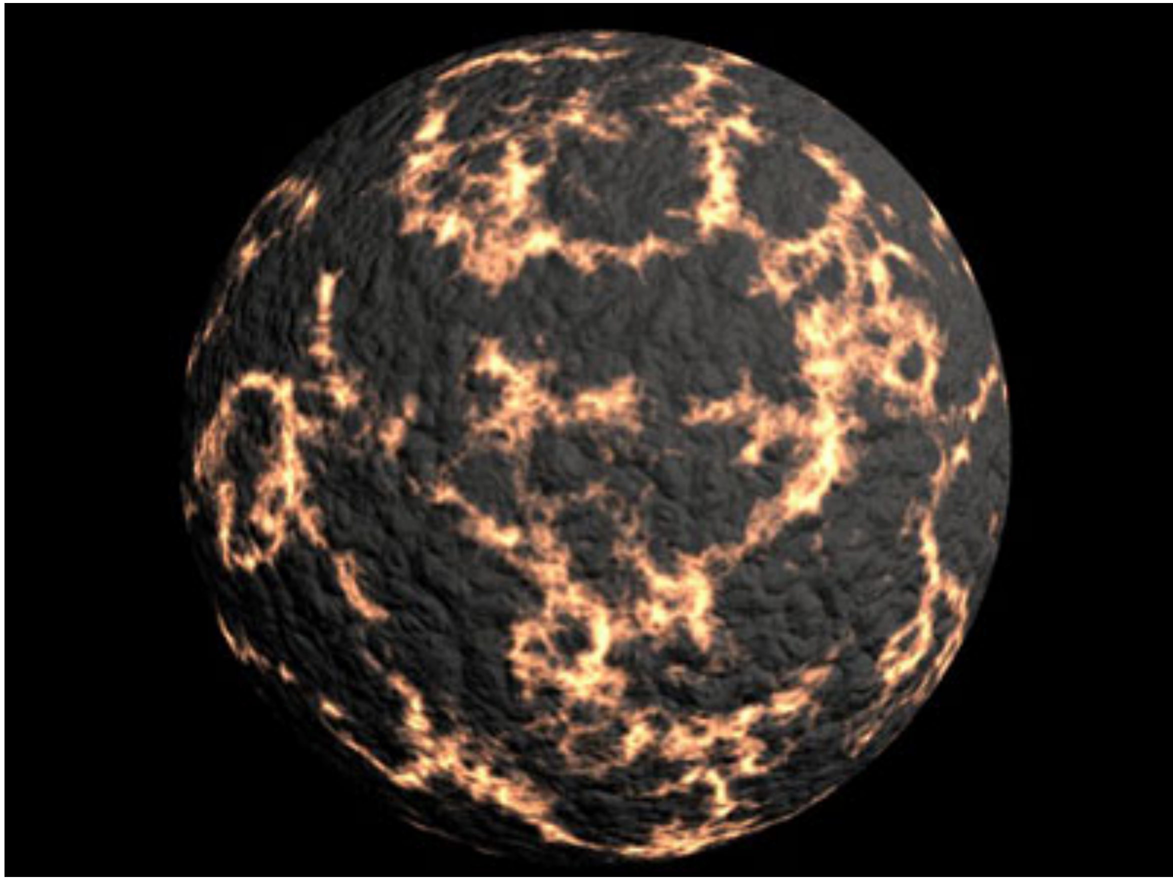
Once the protoplanets have reached the size of the Moon, or larger, the final stages of planet formation begins, where the hundred or so protoplanets are reduced to the current handful. The planetary embryos perturb each other into crossing orbits, leading to giant impacts. This last handful of impacts has left permanent scars on nearly every member of the Solar System.

The evidence for this late stage bombardment is all over the Solar System: *every* old surface bears witness to having been battered by impacts of all sizes.

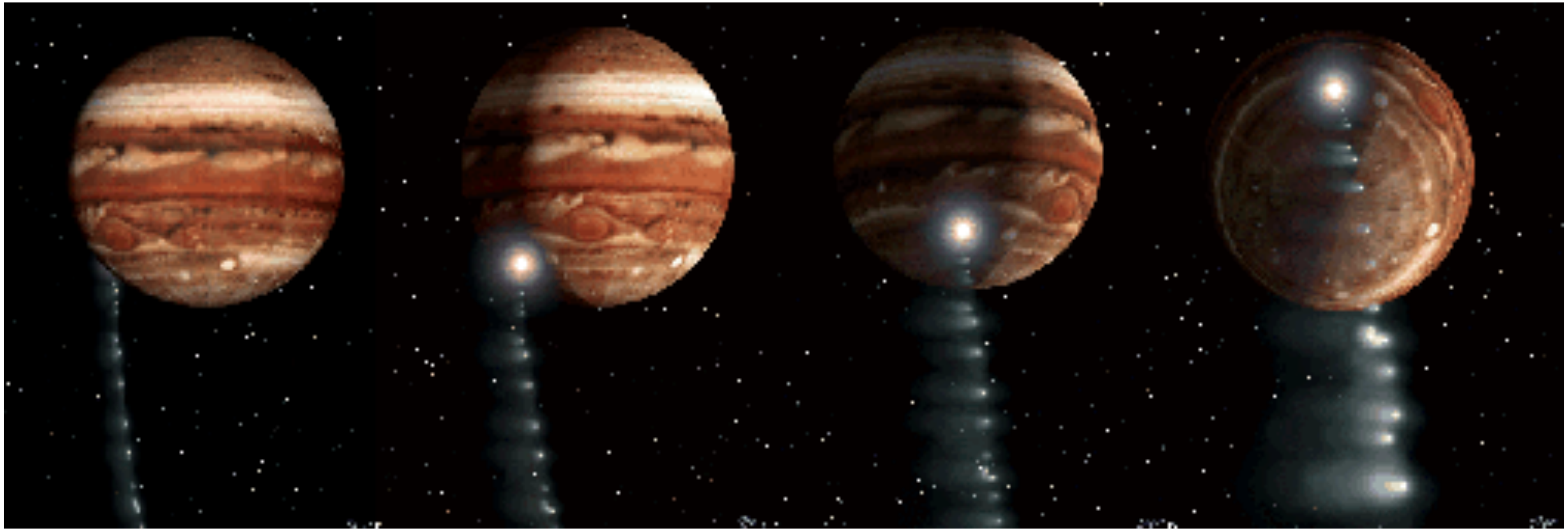


(from left) Ceres, Mathilde, Callisto and Mars

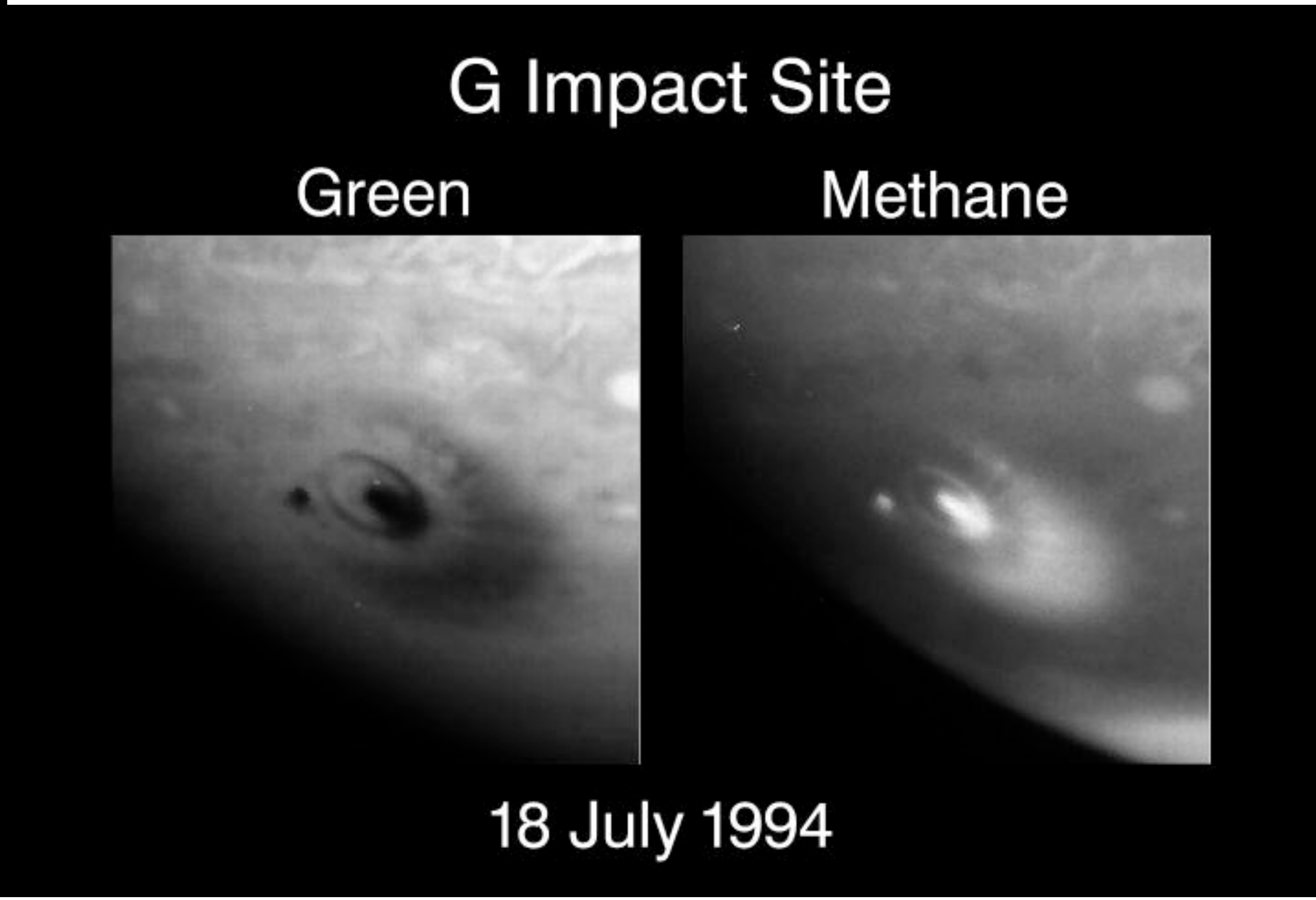
The collisions produced enormous amounts of heat, so the planets would have been molten, with surface temperatures of about 1500°. The surface of the planet melts, with heavier material sinking and lighter material floating: the interior *differentiates*.



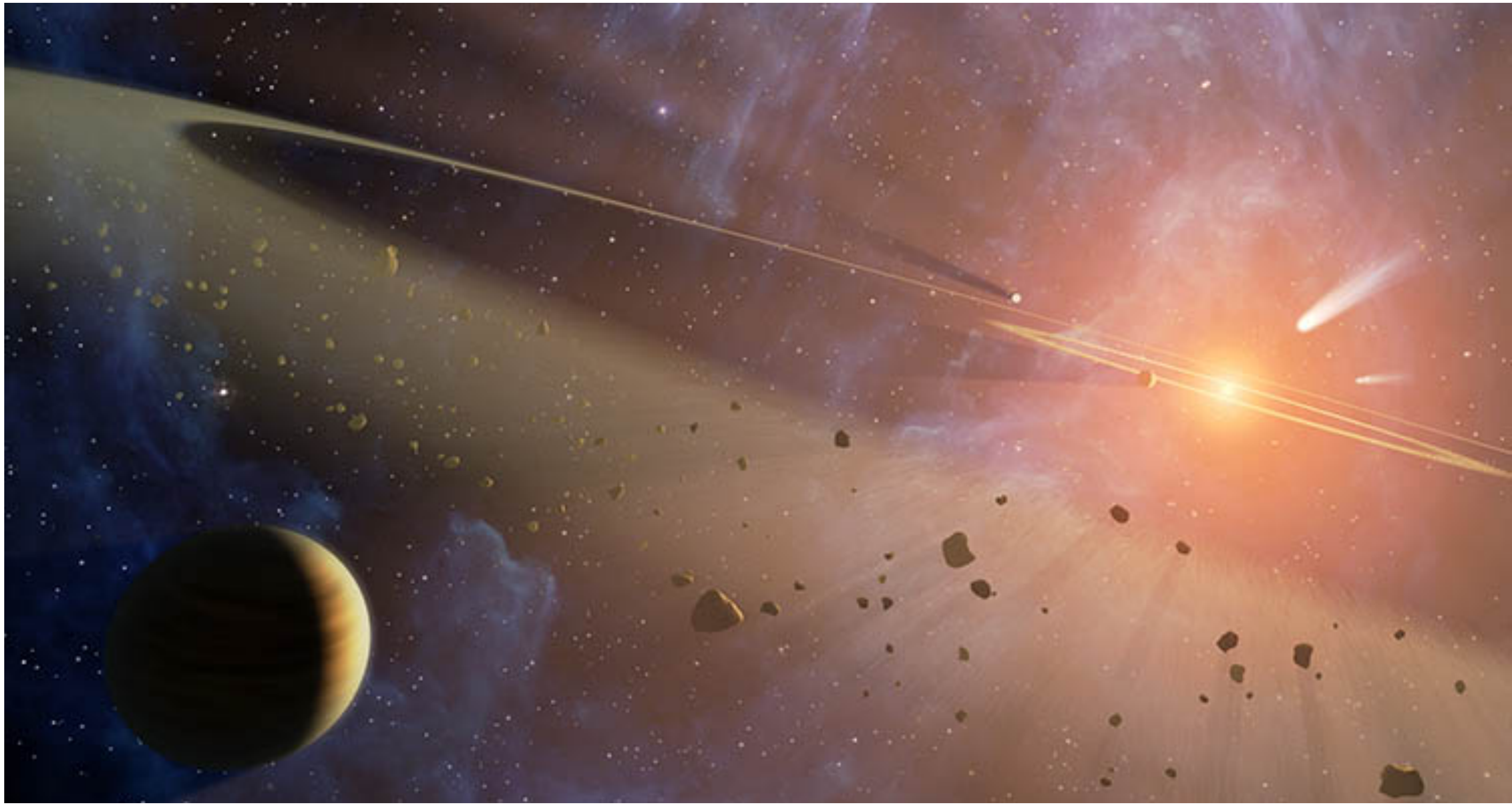
The bombardment of the Solar System has not stopped, only reduced in intensity. In July 2004, we got a chance to see an impact in detail, when Comet Shoemaker-Levy 9 impacted on Jupiter: the very-very-late stages of planetary accretion.



(left) Composite photo, assembled from separate images of Jupiter and Comet P/Shoemaker-Levy 9, as imaged by the Hubble Space Telescope. (below) The G impact site 1h45m after impact, seen by HST.



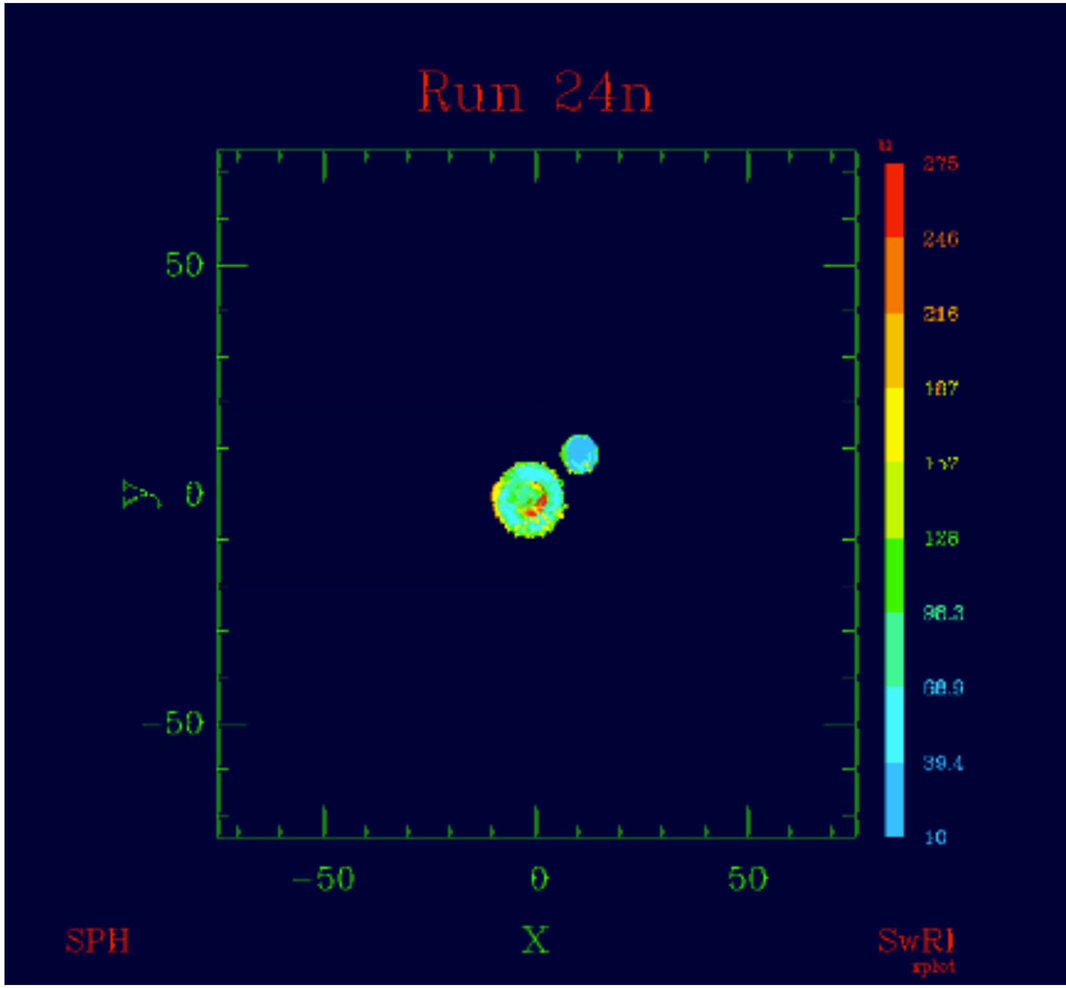
Since the last few impacts were so violent, the last stage of planetary accretion was far from orderly. The random nature of the impacts means we can't expect to find general, predictive laws which explain the current states of the planets.



The *Earth's moon* was formed as the result of a collision between the proto-Earth and another planet-sized body. Material from the impact was thrown into orbit and coalesced into the Moon.

This explains why the other terrestrial planets do *not* have a moon, because the Moon-impacting event was reasonably unusual.

Calculations showed that the impactor had to be the size of Mars in order to eject enough material into orbit to form the Moon.

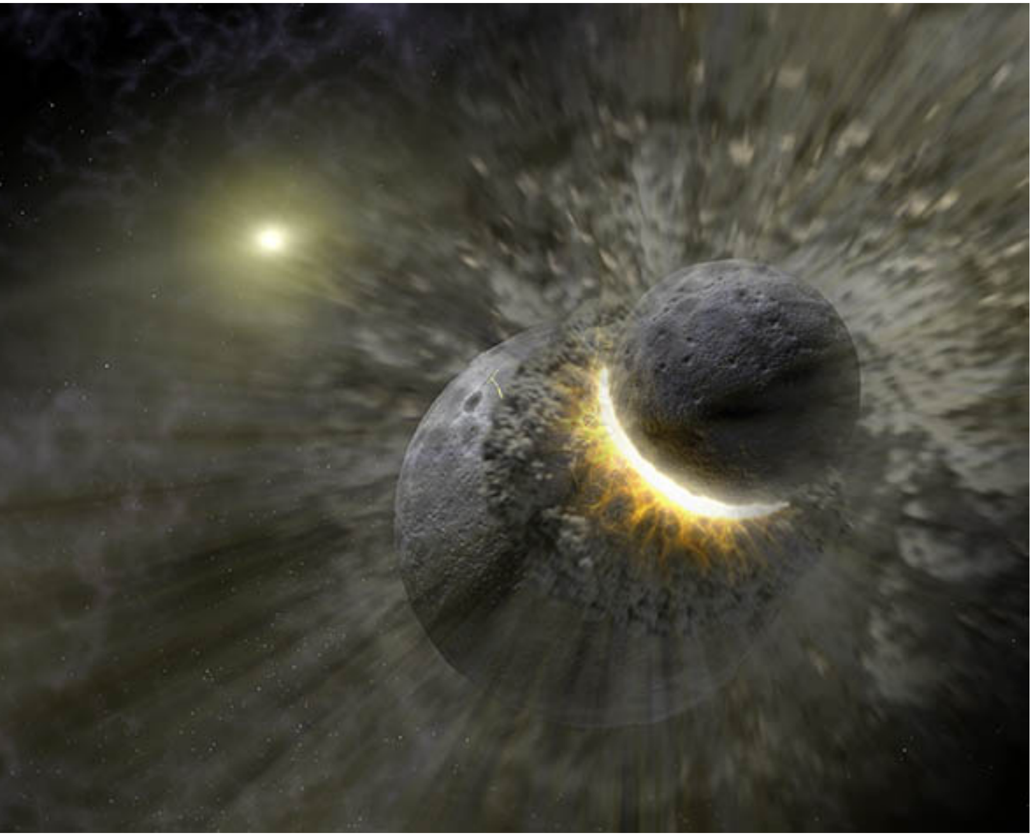


Animation showing the impact of a Mars-size proto-planet with the young Earth. The animation covers only 24 hours, ending with the Earth surrounded by a disk of debris, from which the Moon will coalesce.

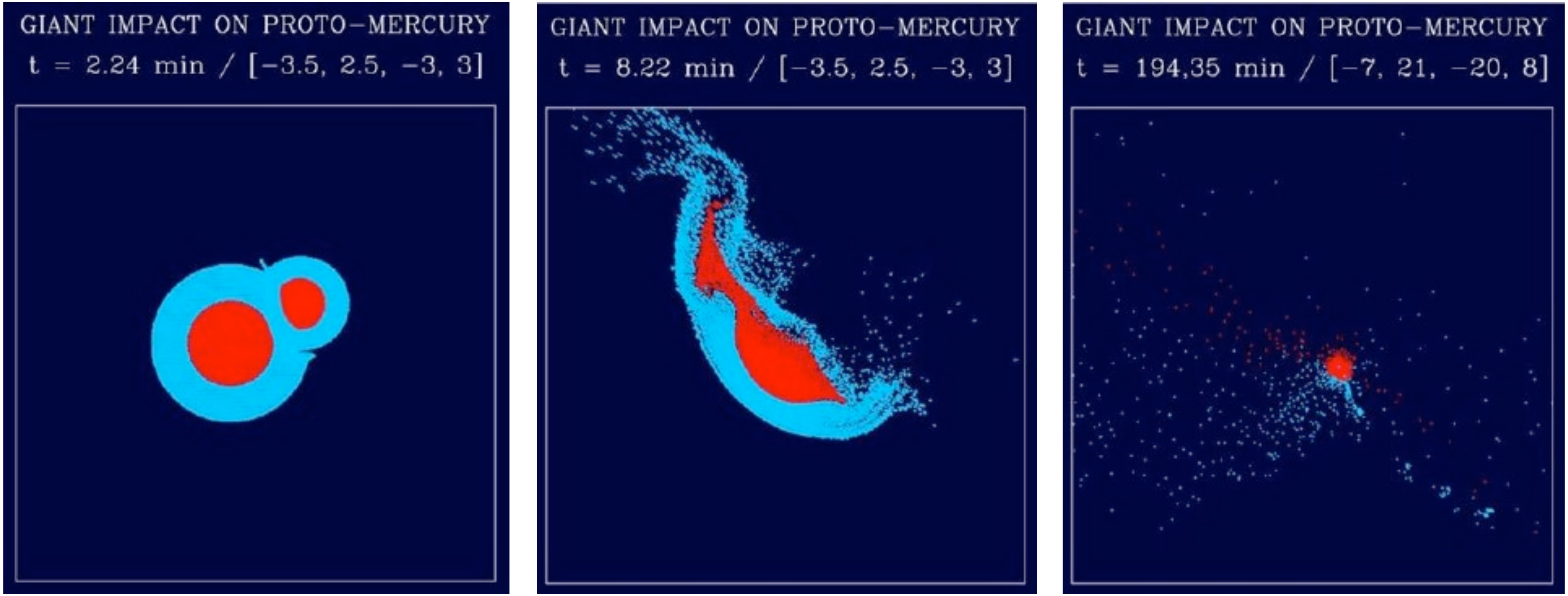
The impact that made the Moon was just the biggest in a whole spectrum of impacts. While the planets were forming, there would have been a continuous distribution of sizes of objects: ten Moons for every Mars-sized object, ten Marses for every Earth, and so on. Smaller impacts will tend to cancel out, but the biggest impact can only come from one direction and one angle, and so can have very different results.

We now think that the following oddities are the result of giant impacts in the very last stages of planet formation.

Charon was probably also formed in a giant impact: it is hard to explain the enormous mass ratio of Pluto/Charon in any other way. This impact probably also tipped Pluto's spin axis all the way over.



Mercury: Mercury's giant iron core may also be the remnant of a giant impact. A "hit and run" collision with a proto-planet of comparable size may have vaporised the silicate-rich mantle of the proto-Mercury, leaving behind an iron-rich core.



Simulation of a glancing impact on a proto-Mercury. Much of the lighter mantle material (blue) is ejected from the inner solar system altogether, leaving a remnant rich in core material.

Mars: The Martian crustal dichotomy could have been formed by a giant impact, if it only struck a glancing blow.

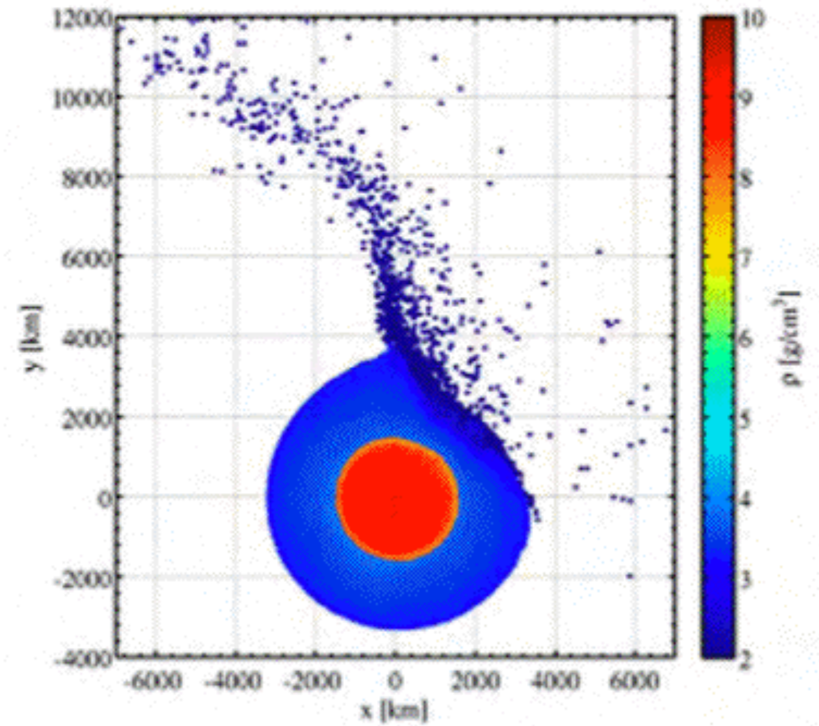
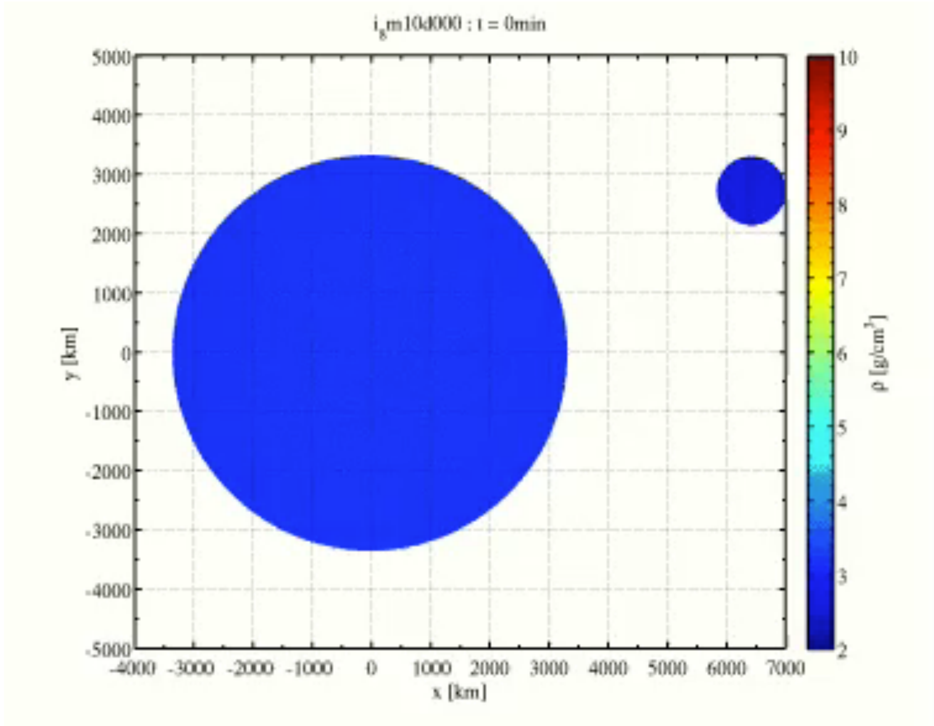
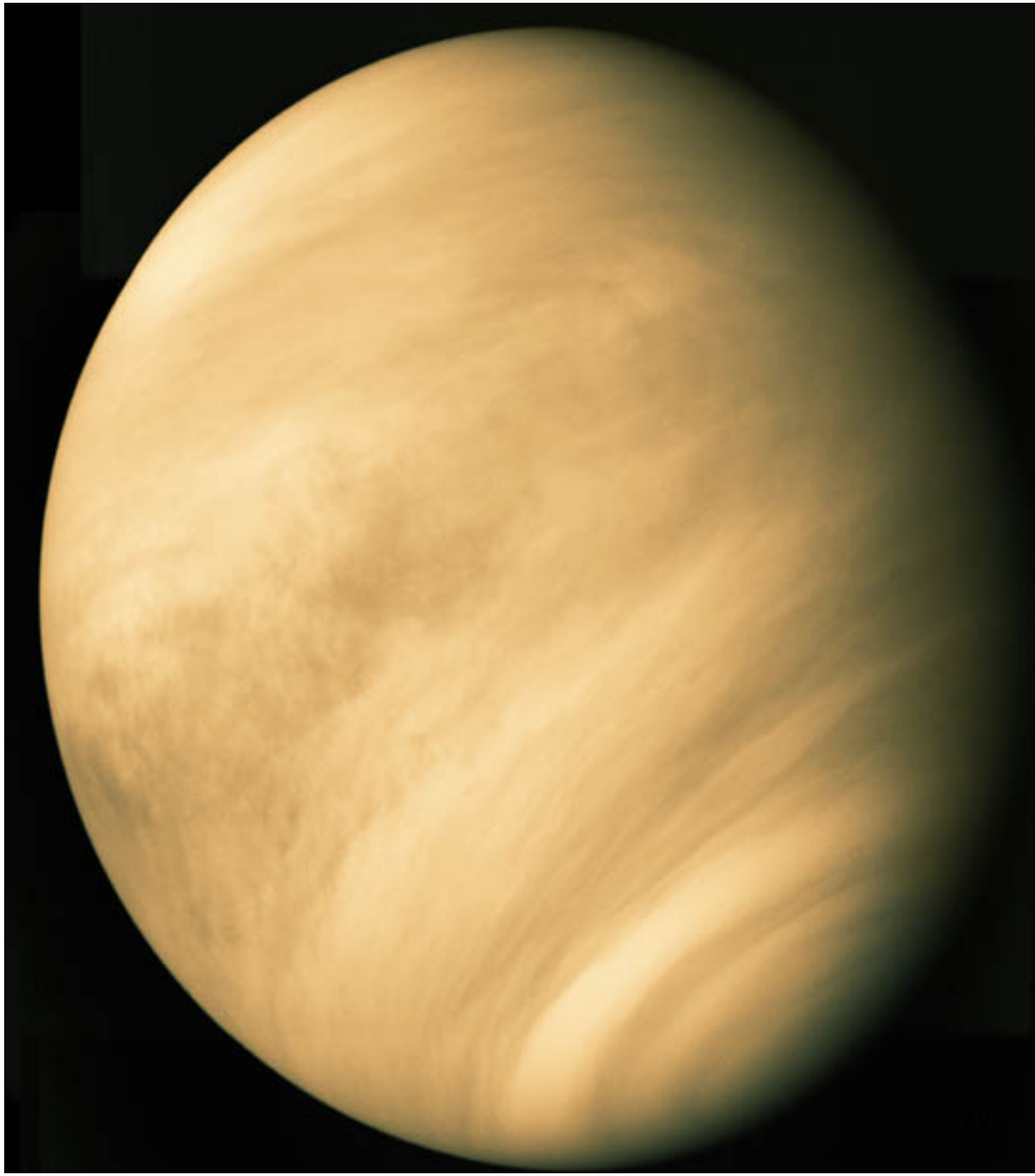


Figure 1. Snapshot of an impact simulation: t = 25 min after impact. Half-space shown. Impact parameters v = 6 km/s, $D_{impactor}$ = 860 km, 1.45×10^{29} J, $D_{crater} \sim 8000$ km, impact angle = 30 deg.

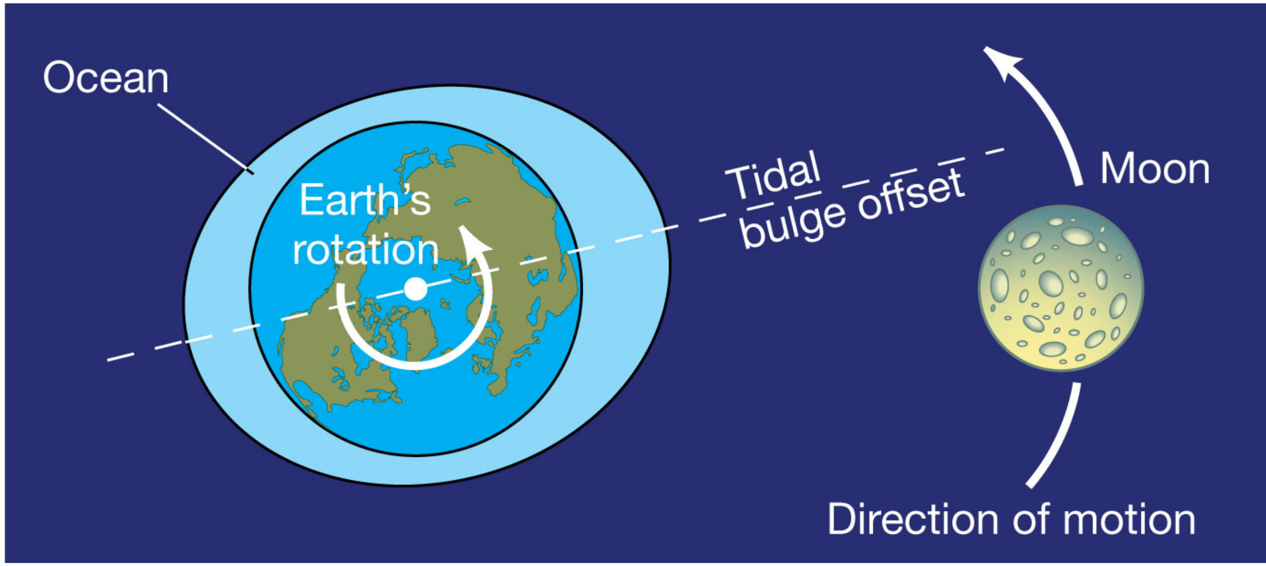


Venus: Venus may have acquired not only its tipped axis but also its slow rotation from a giant impact.



In fact, the spins of most planets are assumed to arise from the accumulation of angular momentum imparted by the various planetesimals which accreted, possibly modified by later tidal forces.

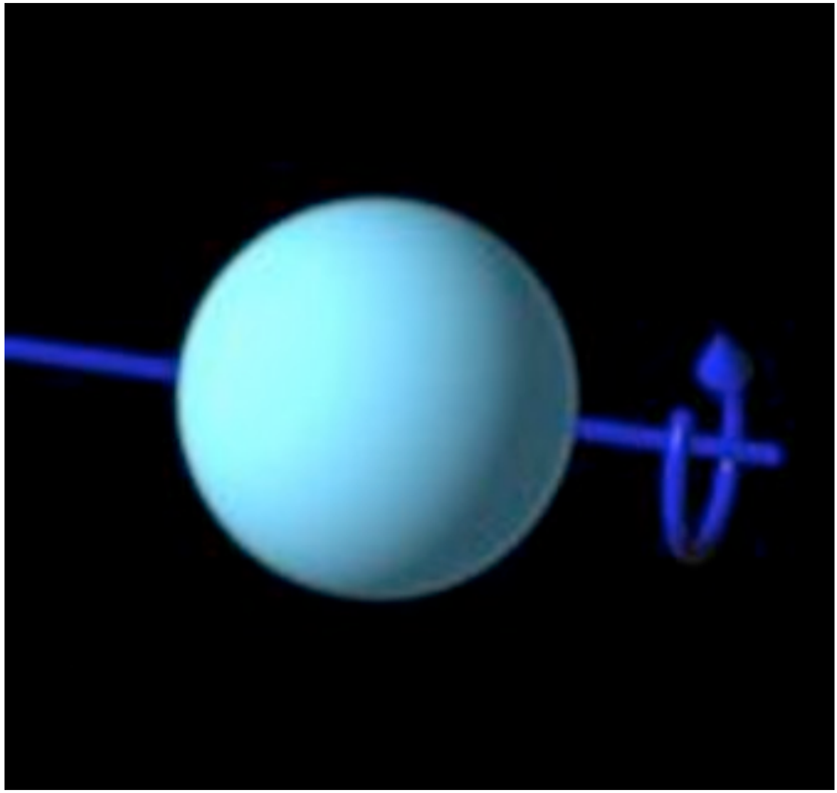
The collision that formed the Moon would have also set Earth spinning faster; it is estimated that a day was only 6 hours long for the early Earth. Since then, friction from the tides have slowed the Earth's rotation and increased the size of the Moon's orbit.



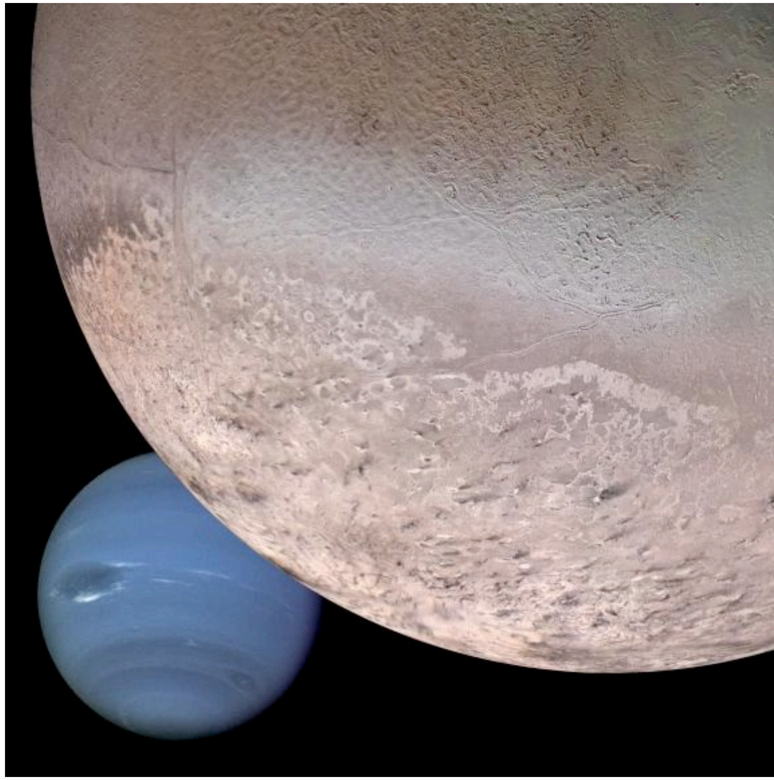
Mars' current spin period is probably close to its primordial period, since its moons are too small for tidal forces to have slowed its rotation at all.

If the planet grew only by accreting lots of little planetesimals, the final rate of spin does not tend to be very fast, as the impacts tend to come from lots of different directions. So Mars' rapid rotation (25 h) probably also arose from one or more giant impacts.

Uranus and Neptune: Uranus' extreme tilt (98°) is thought to have been caused by a giant impact. A body of at least 2 Earth masses hit the proto-Uranus at an oblique angle, tilting the spin axis. A large amount of material spun off the equator left a disk in orbit from which the current system of moons eventually assembled. In contrast, if the final impact on Neptune was nearly straight down, it would heat the planet but not leave a disk, explaining the absence of regular satellites around Neptune.

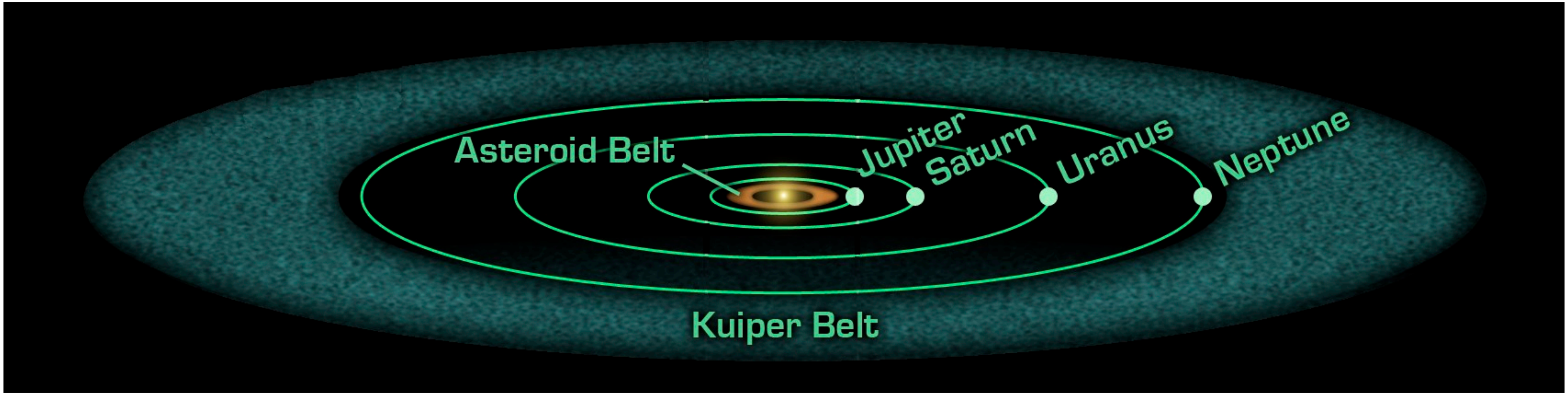


Triton: Triton, with its retrograde and highly inclined orbit about Neptune, is most likely a Kuiper belt object which wandered close to Neptune. There, it was captured into orbit, possibly colliding with (and destroying) one of Neptune's regular satellites. The initial orbit would have been highly eccentric, but tidal interactions with Neptune would have circularised it, taking about a billion years.



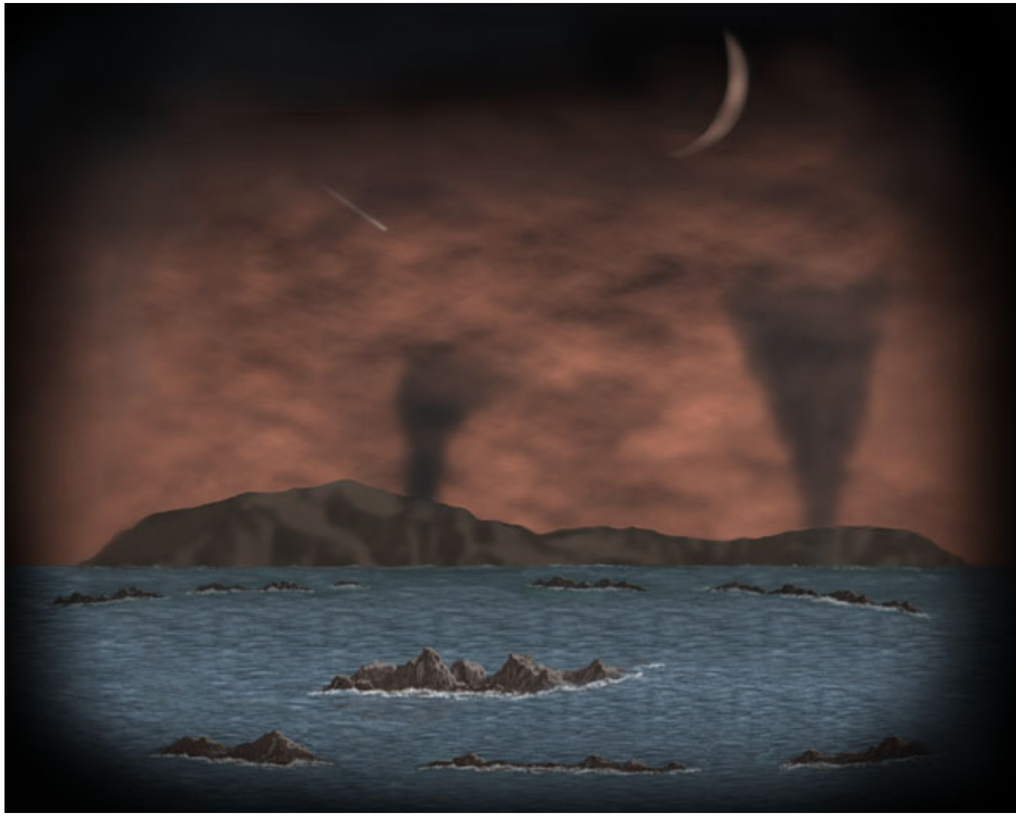
Neptune's original satellite system would have been destroyed by mutual collisions when Triton induced chaotic perturbations in their orbits. Nereid was almost ejected from the system, but not quite.

Meanwhile, the outer parts of the proto-stellar disk never coalesce into planets. Outside the orbits of the planets, the Sun is left with a disk of icy bodies beyond Neptune: the *Kuiper Belt*.

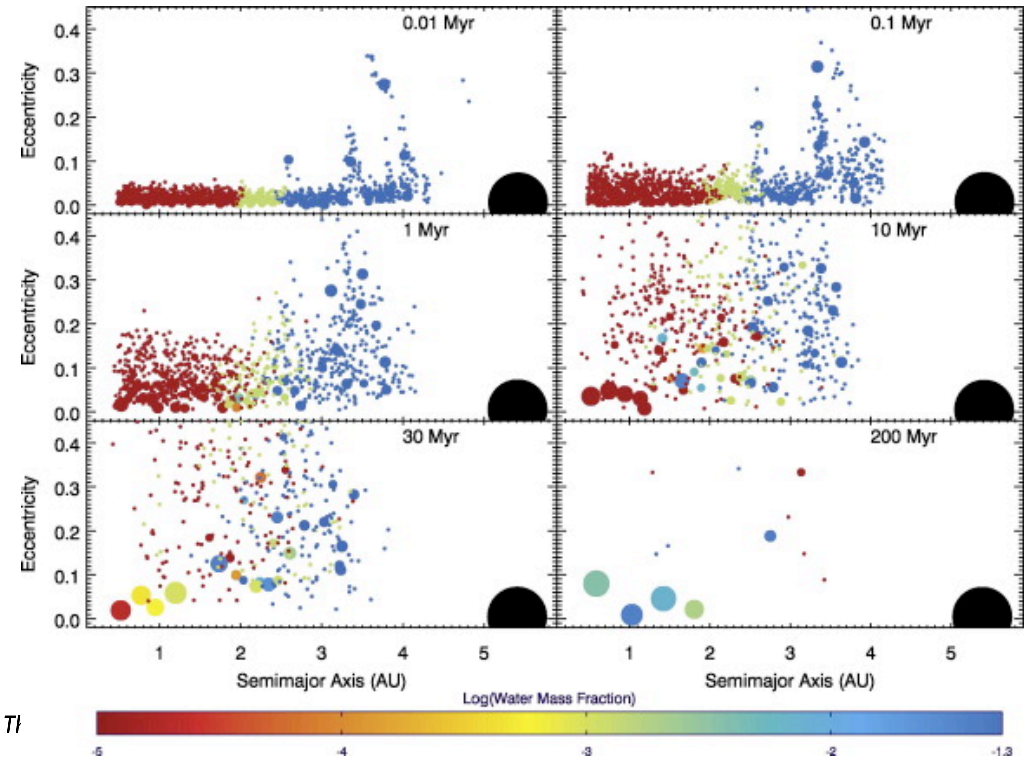


What about atmospheres? The giant planets acquired their atmospheres during their formation. The much smaller terrestrial planets, however, couldn't hold on to much gas during their formation, and what atmosphere they had was probably lost during the major bombardment.

As the impact rate dropped and the planets started to cool, atmospheres accumulated around Venus, Earth and Mars, from volcanic outgassing and comet impacts. Icy bodies from the Kuiper Belt and Oort cloud could have delivered enough volatiles to Earth and the other terrestrial planets to make atmospheres and oceans.



Here is a computer model of the accumulation of the terrestrial planets. As the protoplanets perturb each others orbits and collide, they also mix up, so that planetary embryos which were born far from the Sun can end up in the inner solar system. This is probably where the water in the inner planets came from.



Six snapshots in time for a computer simulation of terrestrial planet formation by Raymond et al (2009). The size of each body is proportional to its mass, while the colour corresponds to the water content by mass, going from red (dry) to blue (5% water). The large black circle represents Jupiter.

One problem is that it is very hard to account for Uranus and Neptune. Neither planet would have had enough time to grow as big as they did in the thin outer regions of the Solar System: they do not accrete planetesimals fast enough to grow.

We will be discussing planets in other solar systems next week; but their discovery quickly led to a radical idea: planets might not stay put where they were formed. In other words, planets might *migrate*.

Planetary migration can happen in a number of ways. In the early Solar System, it mostly took place due to gravitational interactions between planets and the disk of planetesimals. The combined interactions can slowly change the size and shape of the planet orbits, as the icy bodies are slingshotted from one planet to the next.

When researchers incorporated this suggestion into their models, several long-standing problems could be explained.

The *Nice Model* suggests that giant planets migrated from an initial compact configuration, much closer to the Sun than their present positions. Comets were slung from one planet to the next, which gradually caused Uranus, Neptune, Saturn and the belt to migrate outwards. In other words, Uranus and Neptune formed much closer in, where material was more abundant, and migrated outwards due to interactions with Jupiter and Saturn.

The following is a simulation of such a process. The cores of the four giants formed at similar distances from the Sun, about 15–20 AU. Beyond them was a large, dense disk of planetesimals.

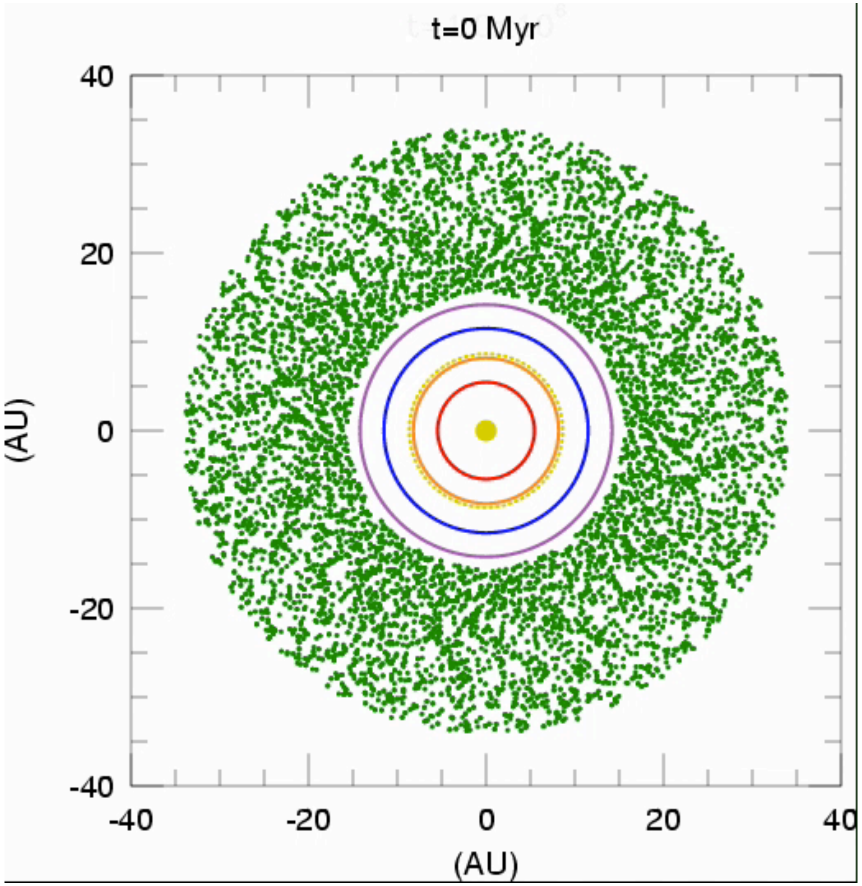
The orbits of the giant planets slowly expand, until after about 700 My, Saturn comes into 1:2 resonance with Jupiter. This makes the orbits of Uranus and Neptune unstable, and their orbits scatter into the disk. This sends a large amount of material into the inner Solar System, producing the late heavy bombardment of the Earth and Moon, and possibly contributes to the atmospheres of the terrestrial planets.

Jupiter

Saturn

Uranus

Neptune



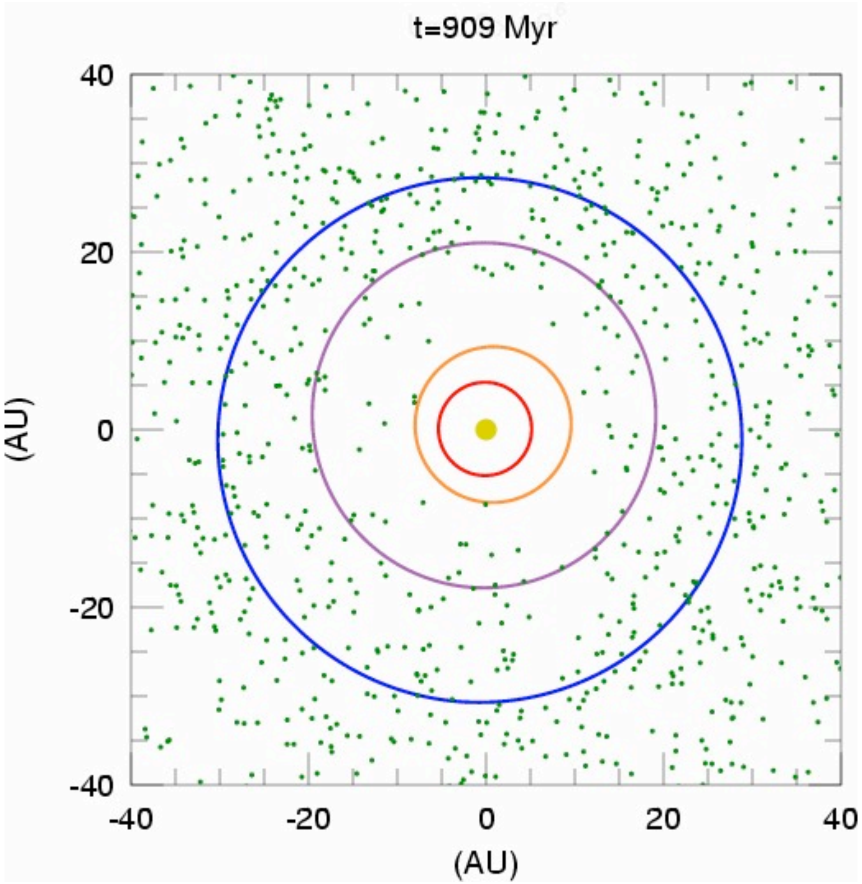
A bit more slowly:

Jupiter

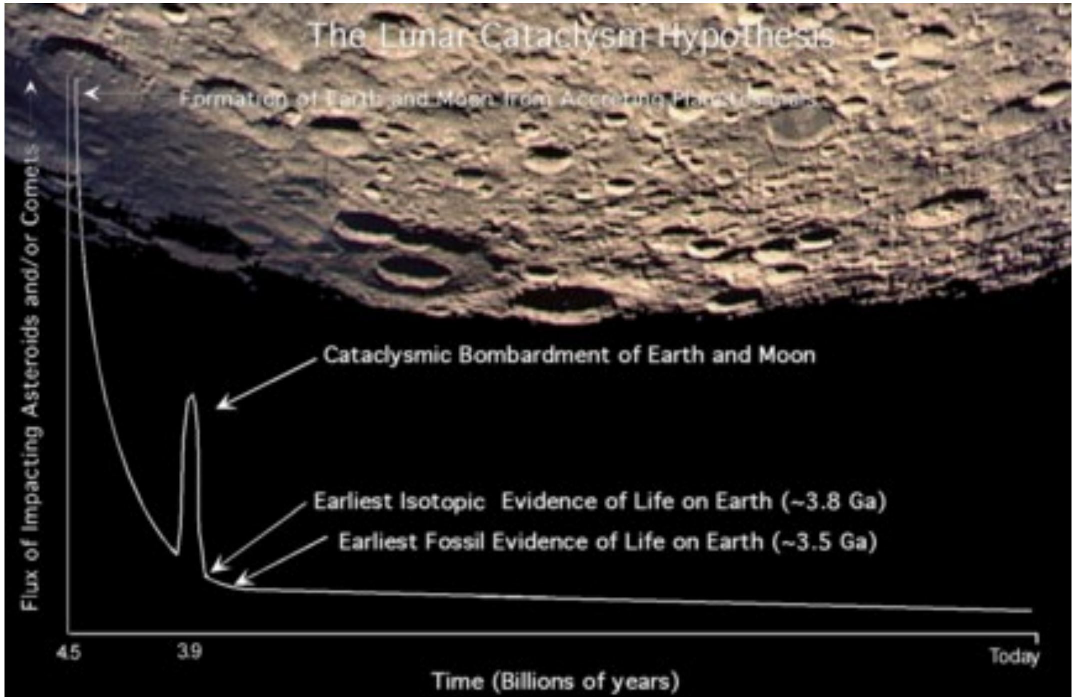
Saturn

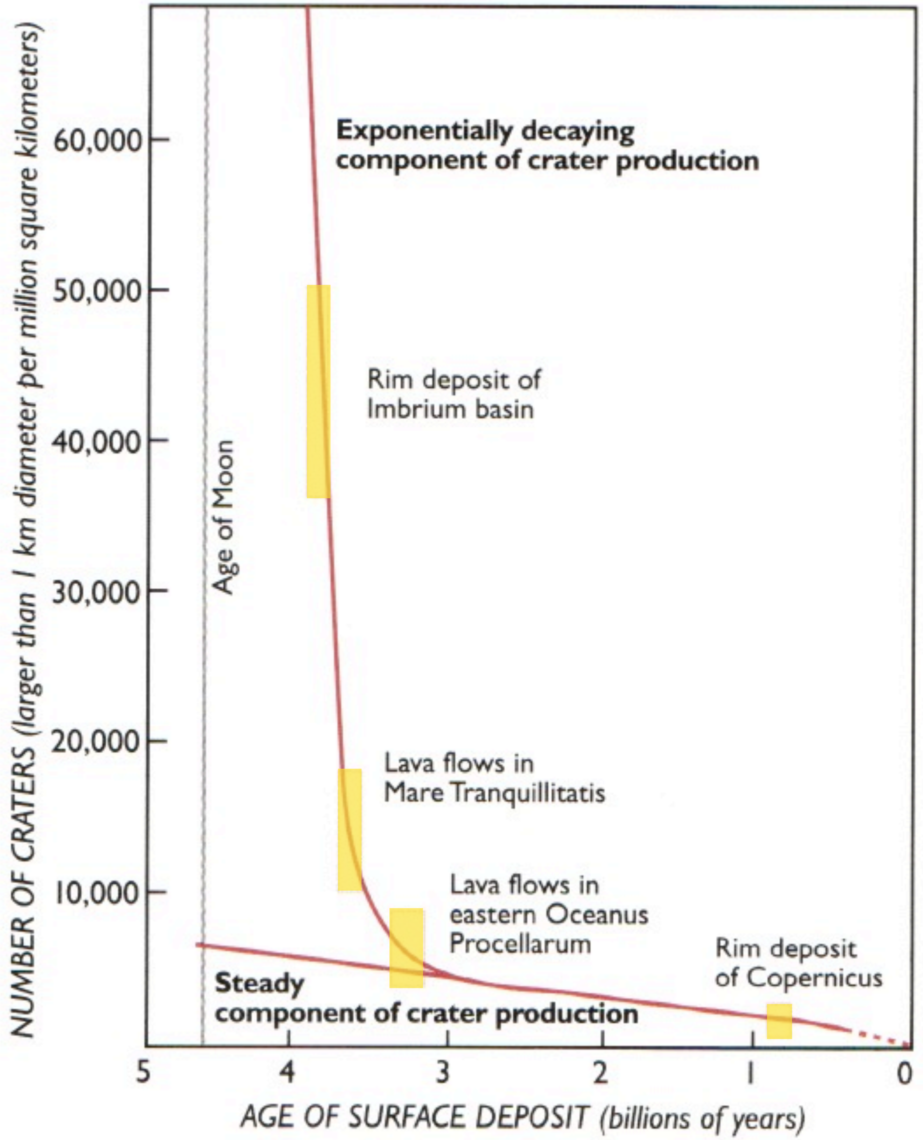
Uranus

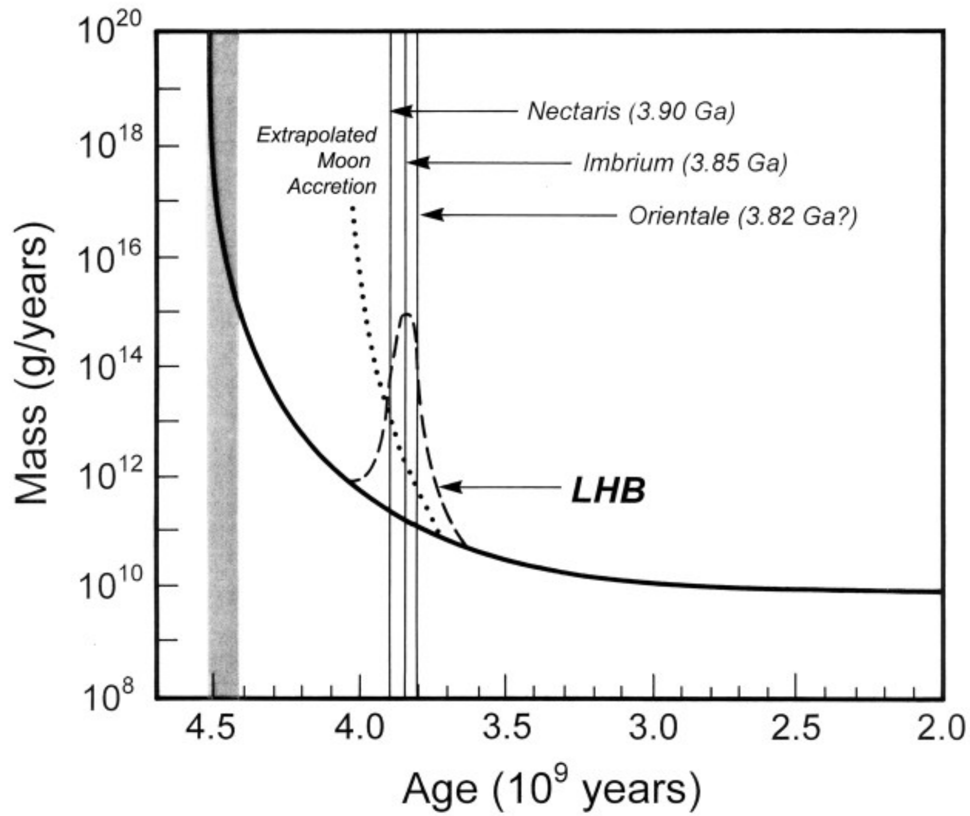
Neptune



There is evidence that the Earth and the Moon underwent a brief but cataclysmic episode of bombardment about 3.9 billion years ago: the *late heavy bombardment*. These were the impacts which produced the great basins on the Moon, and may also be related to the emergence of life on Earth.



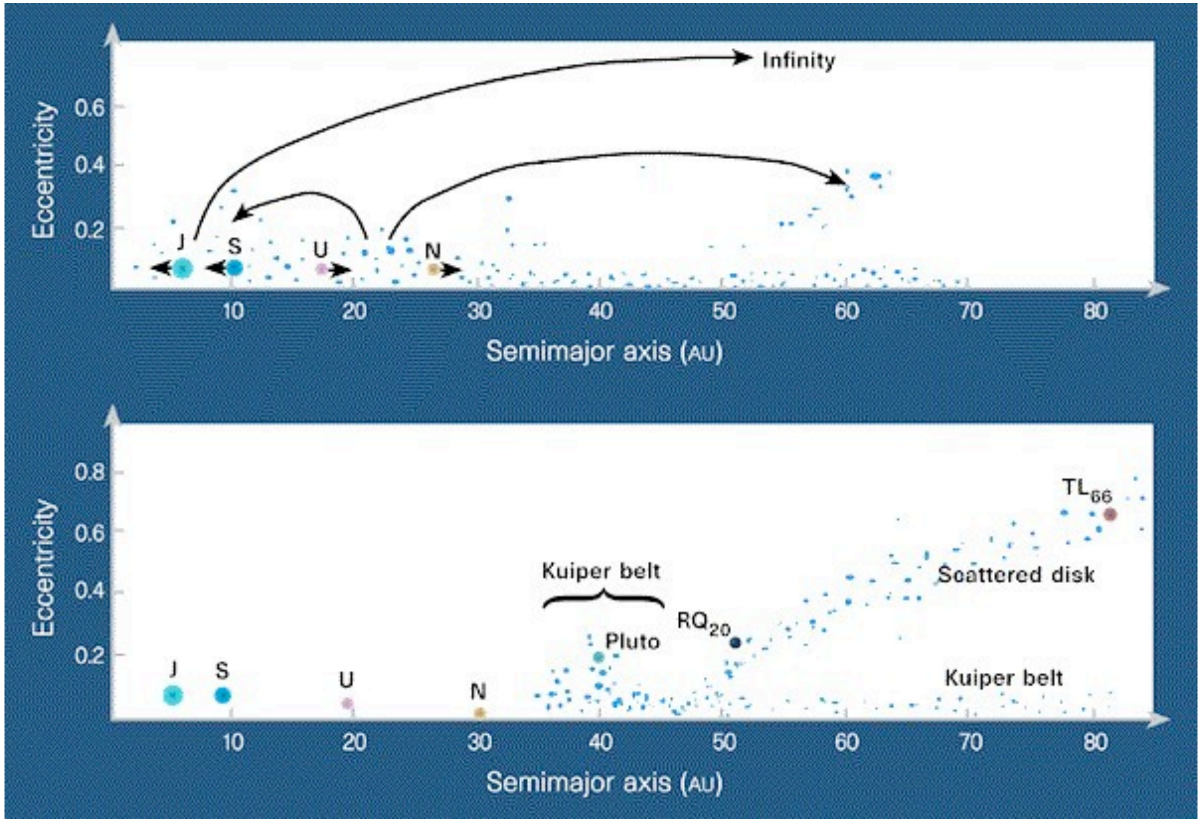




Dating of rocks from Apollo landing sites compared with crater densities show that the rapid cratering rate during the late heavy bombardment fell off dramatically between 3.9 and 3.3 billion years ago, giving way to a slower, steady rate of crater production.
(From Shoemaker 1999).

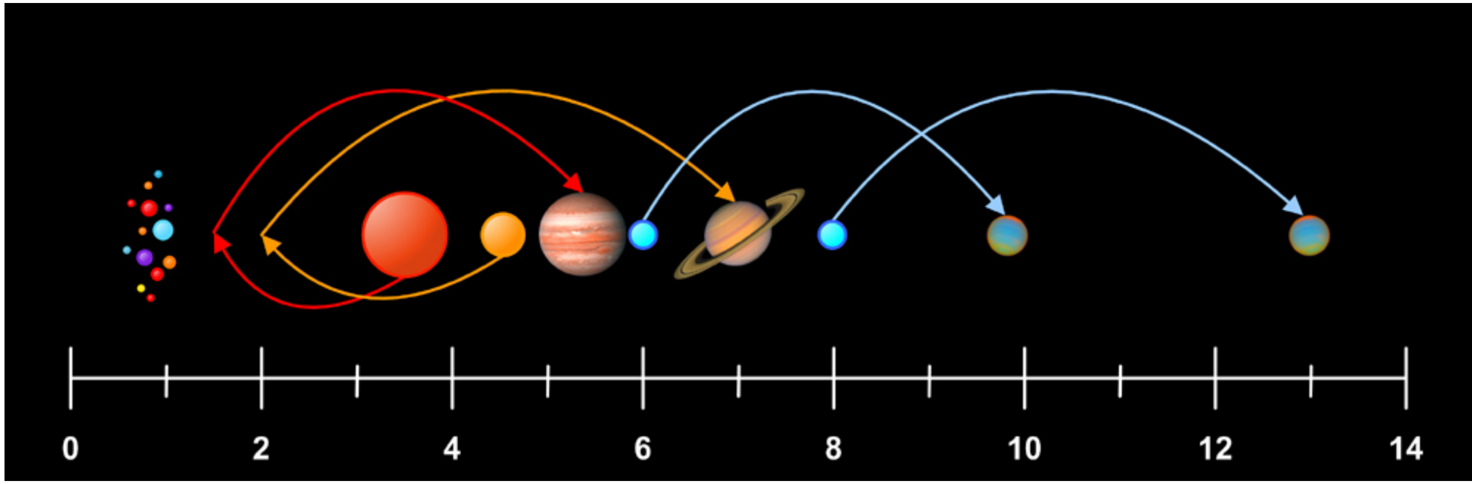
During the late heavy bombardment, the whole inner Solar System was pummelled. The Earth would have been hit by an impact similar to the one that killed the dinosaurs every twenty years.

The *scattered disk* of the Kuiper Belt consists of object deflected out of Uranus' and Neptune's formation zones. Other bodies were scattered inwards towards Jupiter and Saturn, which, being more massive, can scatter them right out of the Solar System.



The *Grand Tack* theory suggests that Jupiter might have already migrated more than once by this time. The theory suggests that Jupiter formed first and migrated inwards through the protoplanetary disk, until a resonance with Saturn reversed it, causing it to move back across the asteroid belt to its current location.

This migration would have wreaked havoc with this region of the disk, depleting both Mars and the asteroid belt of material. This would explain both Mars' small size and the great variety of icy and rocky objects in the asteroid belt.



So we believe we have a general understanding of the formation of the Solar System. The planetesimal hypothesis explains the composition of the planets, their relative sizes, the shapes and directions of their orbits, and their satellite systems

How does this theory stack up when confronted with the new evidence reaching us about extra-solar planets?

Not well....

Next week

… we're going to look at all the planets which have been found around other stars

Further reading

Most books about planets, including the ones I've recommended to you so far, discuss the formation of planets in greater or lesser detail.

- I found one lovely book I haven't told you about yet: "**The Story of the Solar System**" by Mark Garlick (Cambridge, 2002) is by that rarest of creatures, an artist who is also a scientist. The book itself is at a reasonably elementary level, describing the birth, life and death of the Solar System, but the paintings he has done to go with each page are wonderful.
- **"The Big Splat: or How our moon came to be"** by Dana Mackenzie (John Wiley & Sons, 2003) is a very readable book about theories of the origin of the moon, and how we arrived at the current consensus. An extremely enjoyable read.
- There's a terrific new book out called "**From Dust to Life: The origin and evolution of our Solar System**" by John Chambers and Jacqueline Mitton (Princeton UP, 2014). Really up-to-date description of what we know, though it starts all the way back with ancient cosmology, which I didn't really think was necessary.
- There's a beautiful illustrated timeline of the Solar System at The Lunar and Planetary Institute's "Evolution of Our Solar System: A Journey through Time" at http://www.lpi.usra.edu/education/timeline/
- The Planetary Science Institute has a nice page about the origin of the Moon at http://www.psi.edu/epo/moon/moon.html
- The "Grand Tack" theory is described at https://solarsystem.nasa.gov/scitech/display.cfm?ST_ID=2429
- There's a nice article about the possible connection between the formation of Uranus and Neptune and the bombardment of the Moon at PSRD Discoveries: "Uranus, Neptune and the Mountains of the Moon", http://www.psrd.hawaii.edu/Aug01/bombardment.html, and another one called "Gas Giants and Lunar Bombardment" at http://www.psrd.hawaii.edu/Aug06/cataclysmDynamics.html

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