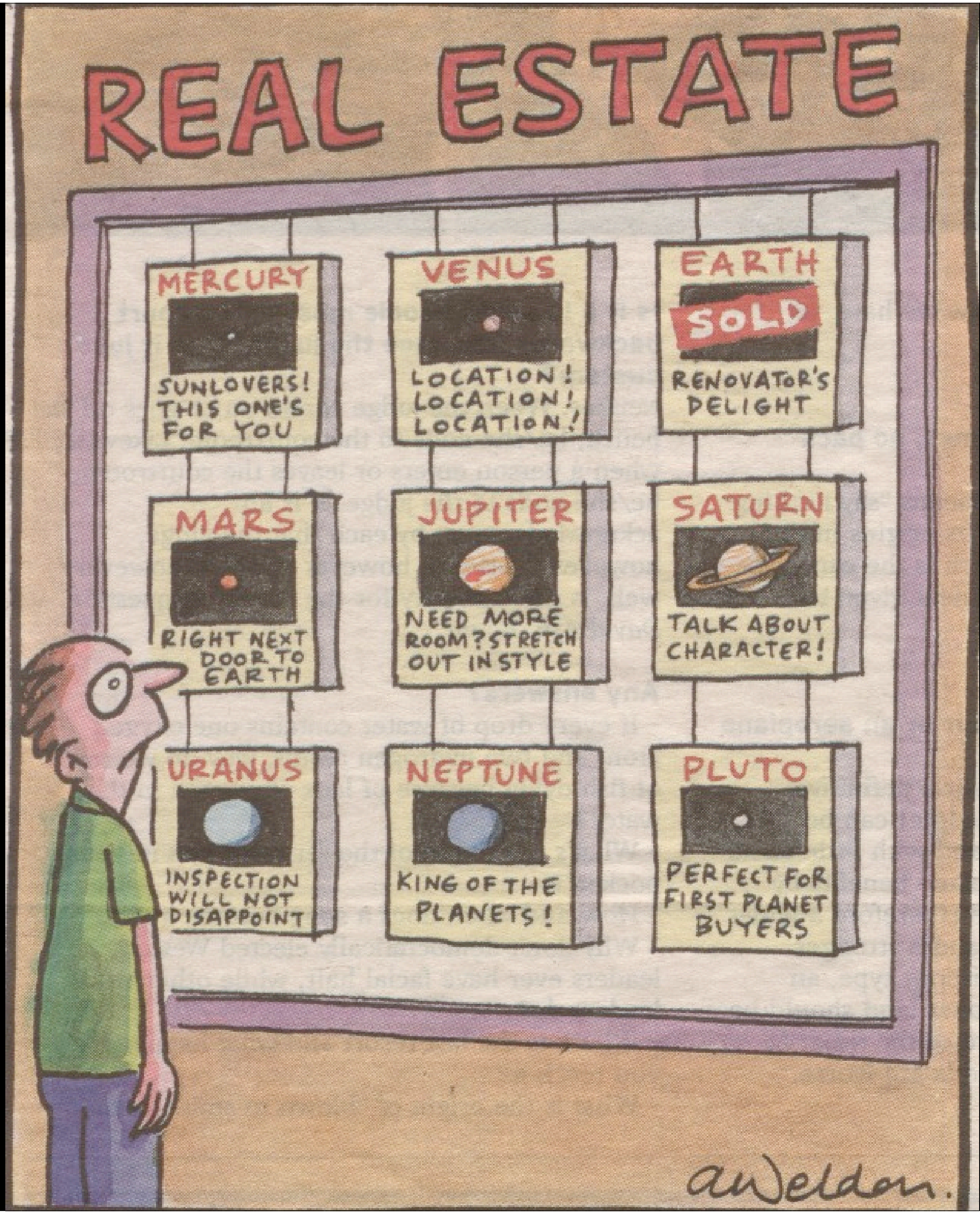
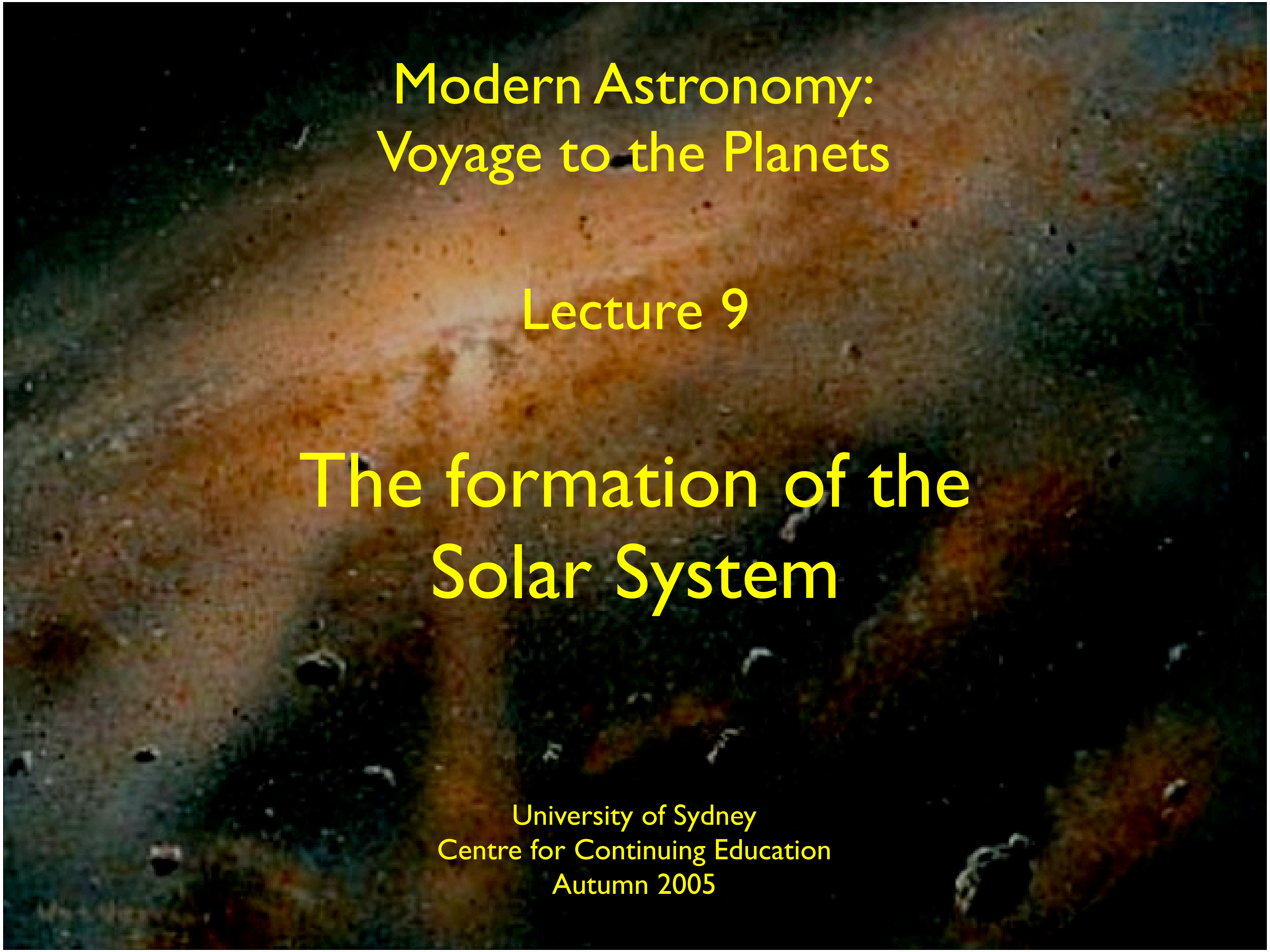
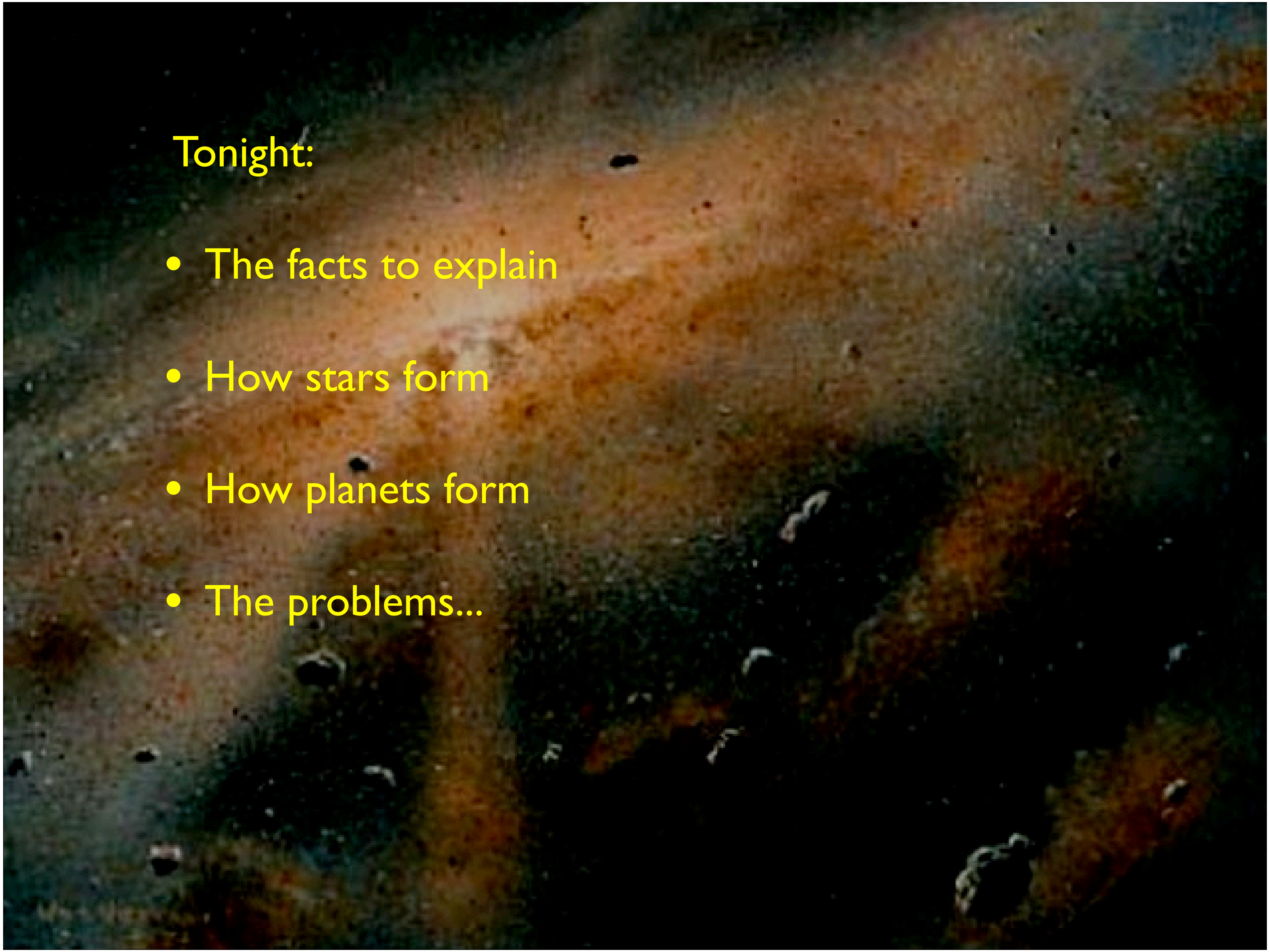

REAL ESTATE
MERCURY
SUNLOVERS! THIS ONE'S FOR YOU
VENUS
LOCATION! LOCATION! LOCATION!
EARTH
SOLD
RENOVATOR'S DELIGHT
MARS
RIGHT NEXT DOOR TO EARTH
JUPITER
NEED MORE ROOM? STRETCH OUT IN STYLE
SATURN
TALK ABOUT CHARACTER!
URANUS
INSPECTION WILL NOT DISAPPOINT
NEPTUNE
KING OF THE PLANETS!
PLUTO
PERFECT FOR FIRST PLANET BUYERS
aWeldon.


Modern Astronomy:
Voyage to the Planets
Lecture 9
The formation of the Solar System
University of Sydney
Centre for Continuing Education
Autumn 2005


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.

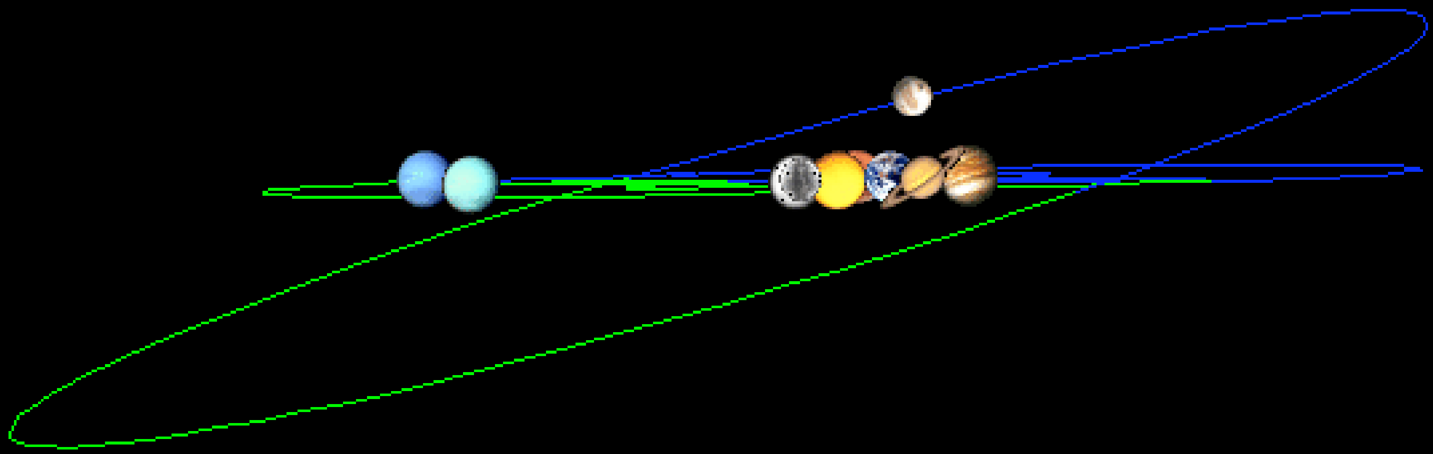
Unfortunately, we only have one planetary system to study in detail, so we have no real idea of the diversity of systems which could arise in other circumstances. Theoretical models have, naturally, concentrated on trying to reproduce the variety of worlds we see in this system. Only recently have we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

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.

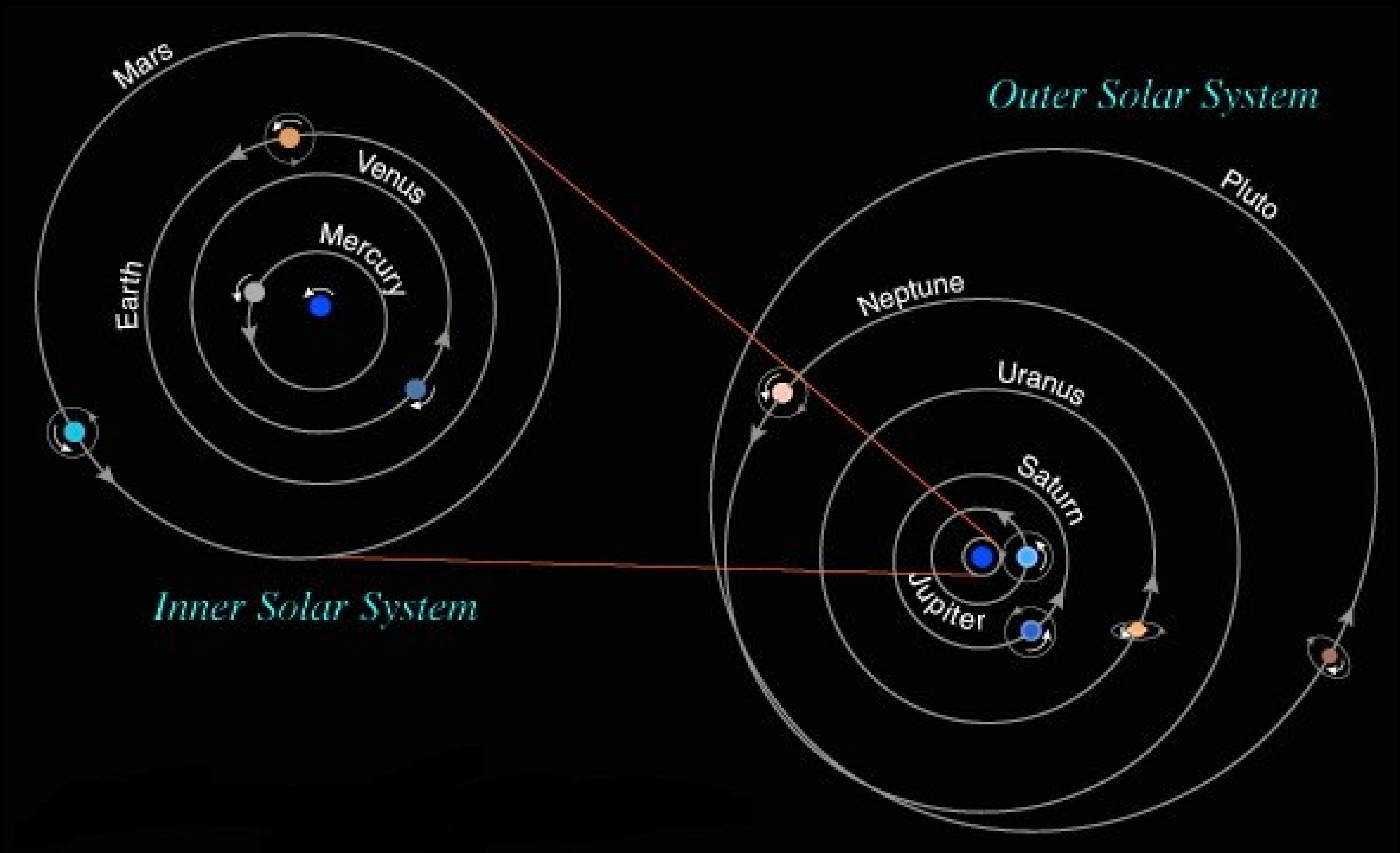
Any theory for the formation of the Solar System must be able to account for the following features.

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

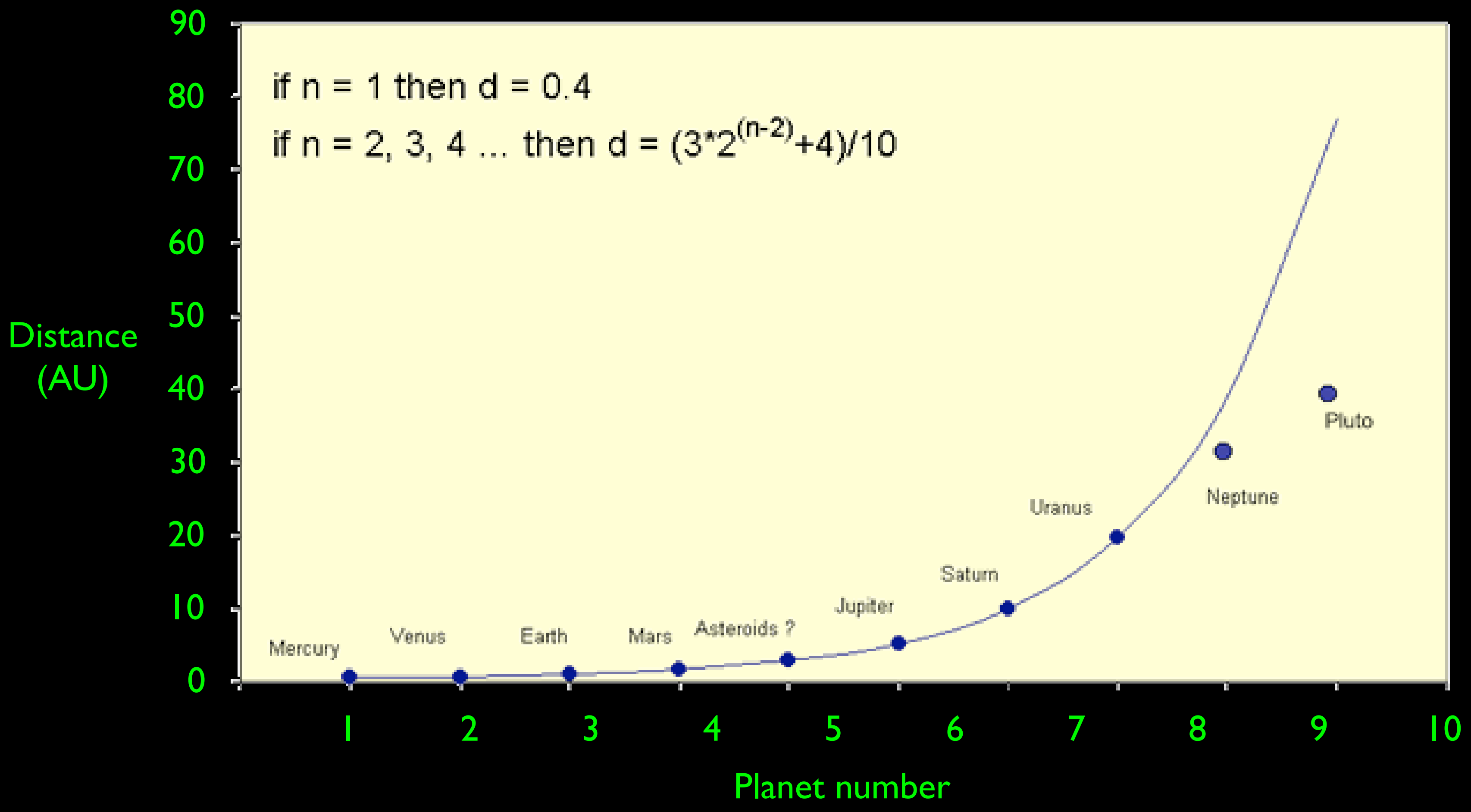


Position of the planets on 1 March 2005

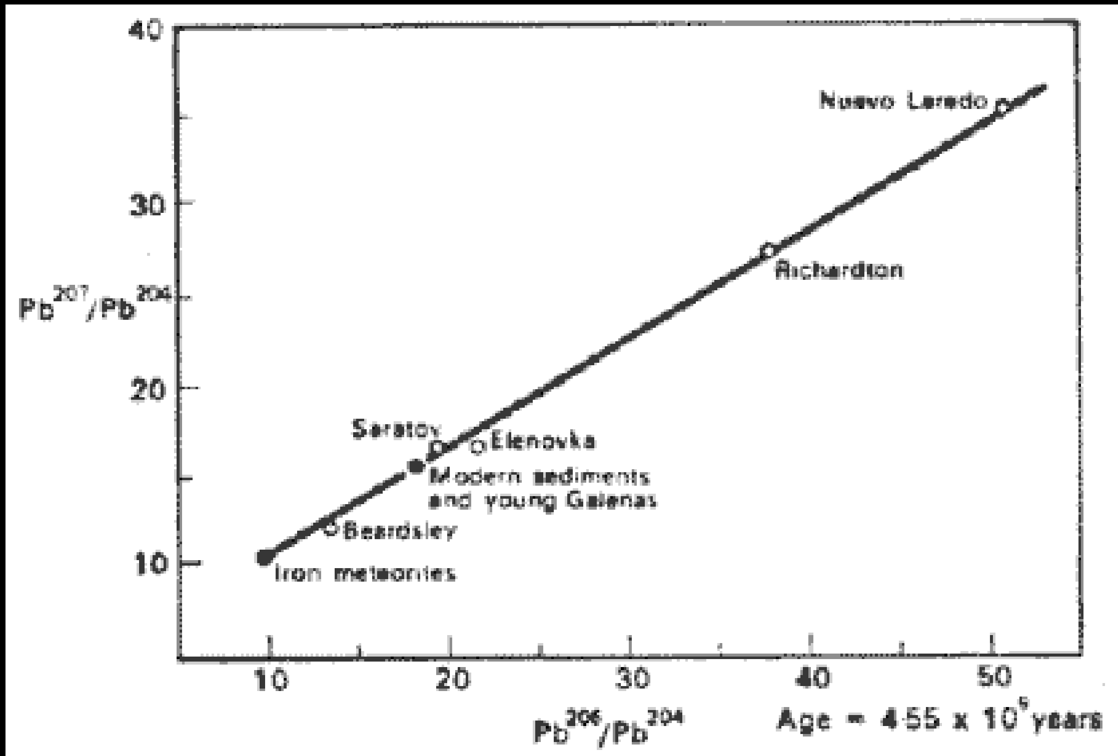
All planets (except Pluto) have orbits which are very close to circular. Most planets rotate in the same direction as the planets revolve.



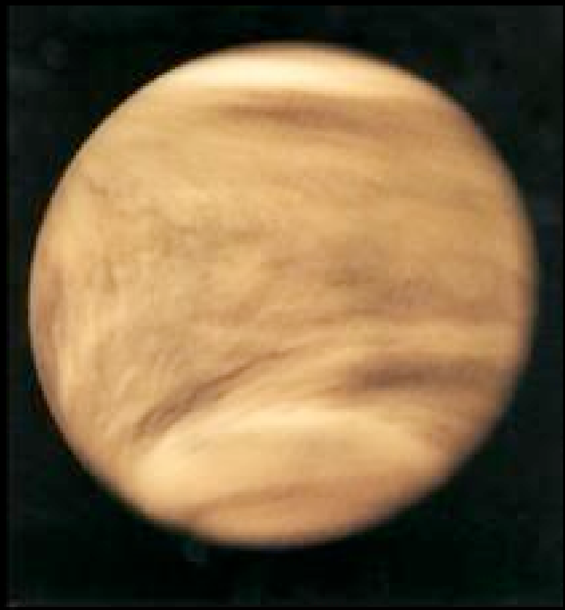
The planets are well separated, with the distance between planets increasing with distance from the Sun. *(Bode's Law?)*. The space between planets, apart from the Asteroid Belt, is almost completely empty.

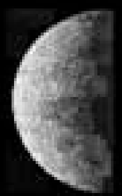


Meteorites have ages of 4.56 billion years. Rocks from the Moon and the Earth are younger, with lunar rocks typically being 3–4.4 billion years old, and terrestrial rocks are less than 3.9 billion years.

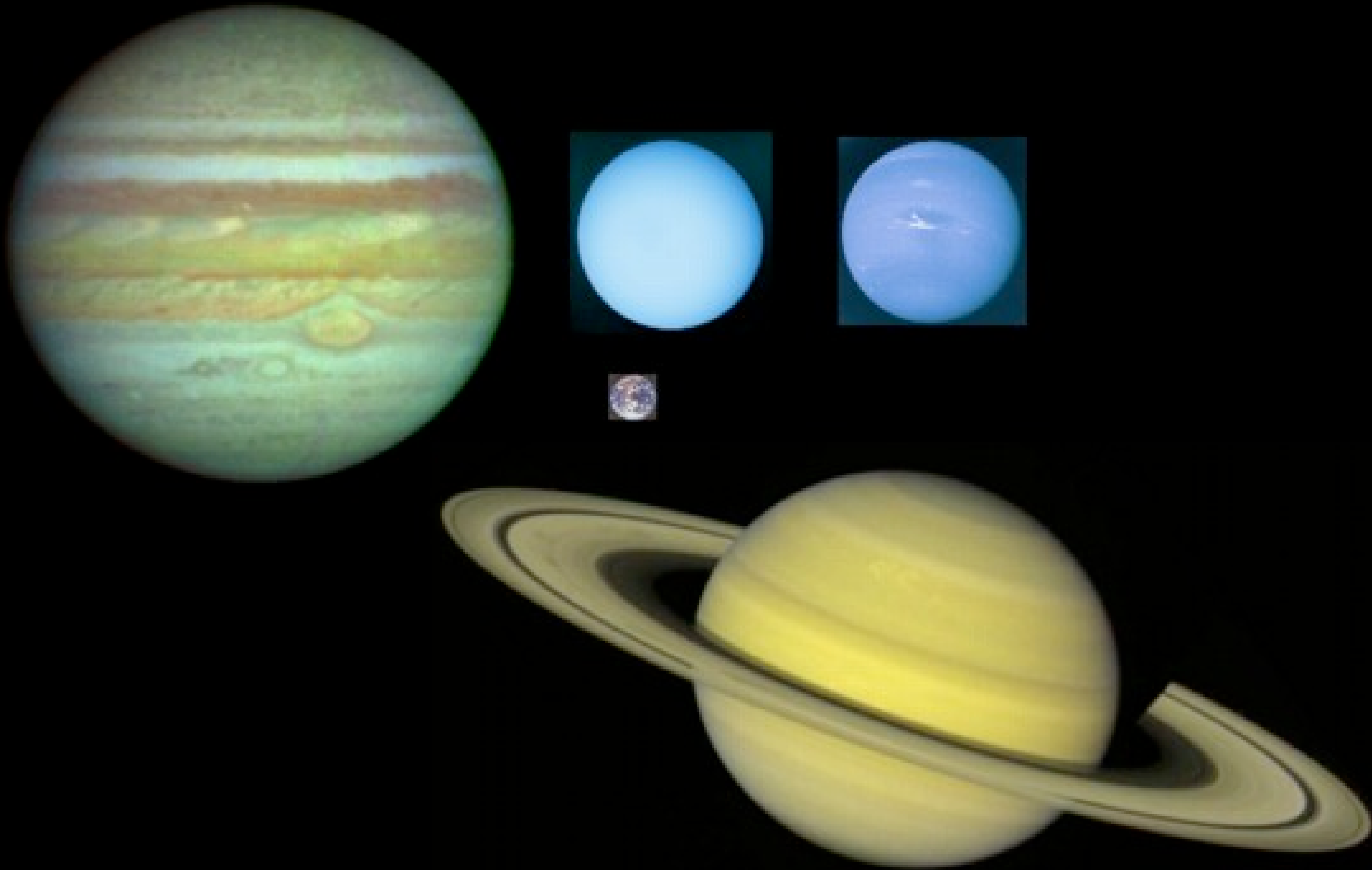


The small rocky terrestrial planets and asteroids lie closer to the Sun. The closer planets are significantly denser than the further ones.

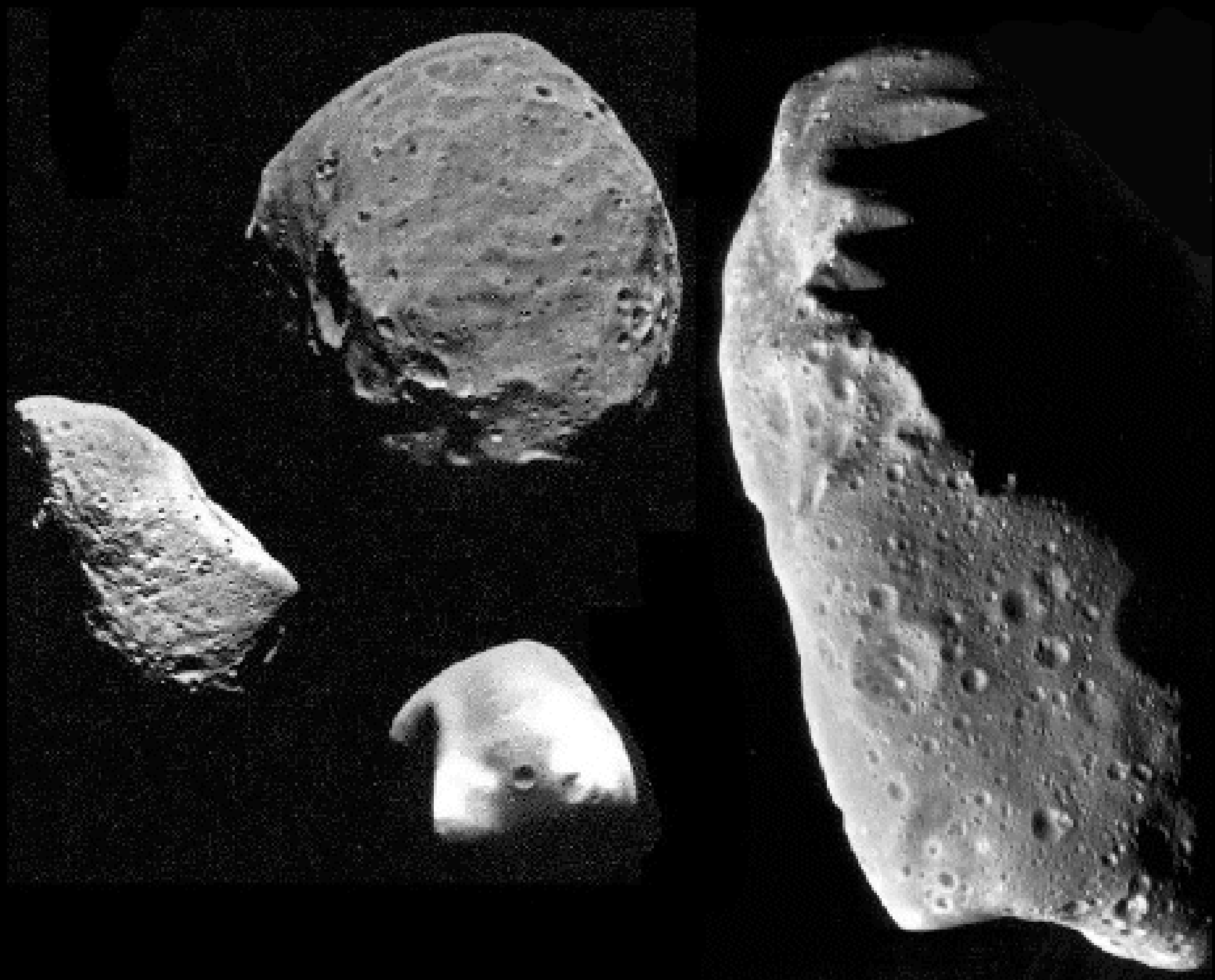




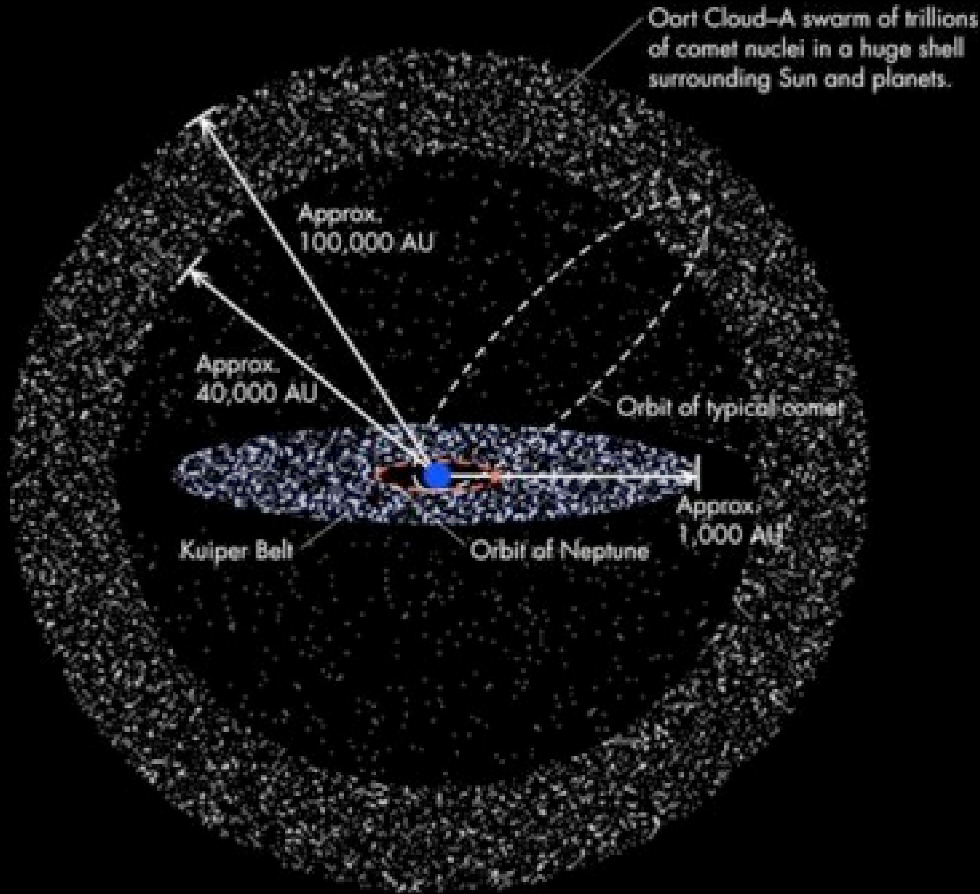
At larger distances, we find the giants Jupiter and Saturn and then the somewhat smaller Uranus and Neptune. Jupiter and Saturn are mainly composed of hydrogen and helium, while Uranus and Neptune contain large amounts of ice and rock.



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.



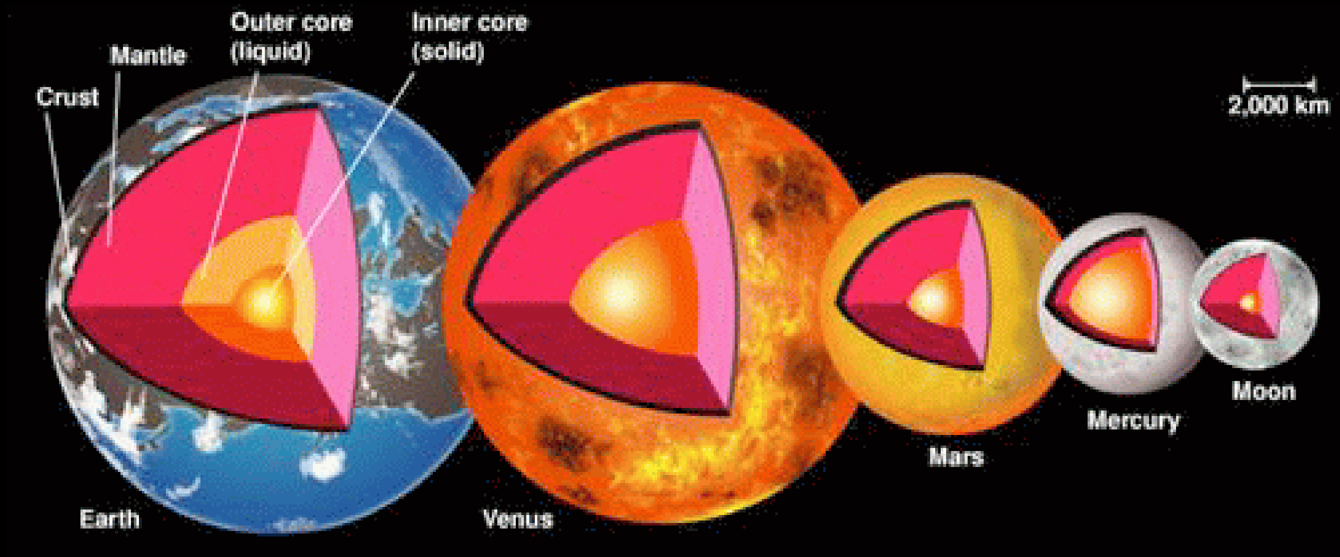
There is a large, roughly spherical collection of icy bodies circling the Sun beyond about 10,000 AU, called the Oort Cloud. Closer in, between 35 and 100 AU, is a flattened disk of similar bodies, known as the Kuiper Belt.



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.

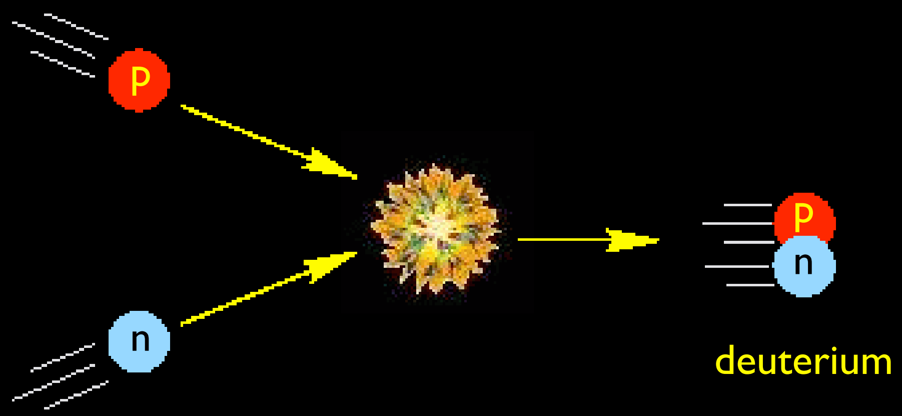
All the major planets and most large moons and asteroids are differentiated, with the heavier metals sunk to the core and the lighter material on the outside. This implies that all these bodies were warm at some stage in the past.



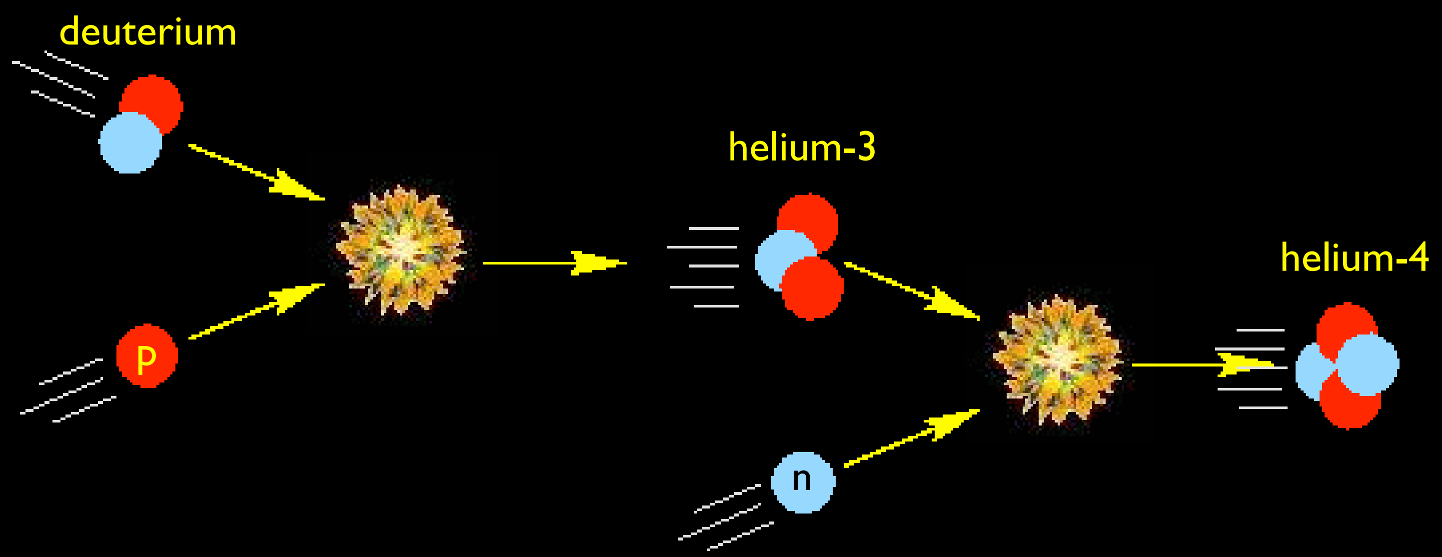
Most planets and satellites show large numbers of impact craters, far more than could be produced over the age of the Solar System at current impact rates.

The Moon, Mercury and Ganymede

About 3 minutes after the Big Bang, the temperature of the Universe had cooled from 100 billion degrees to about 1 billion degrees. As the temperature dropped, protons and neutrons began combining to form a deuterium nucleus: prior to this they had too much energy, and didn't "stick".

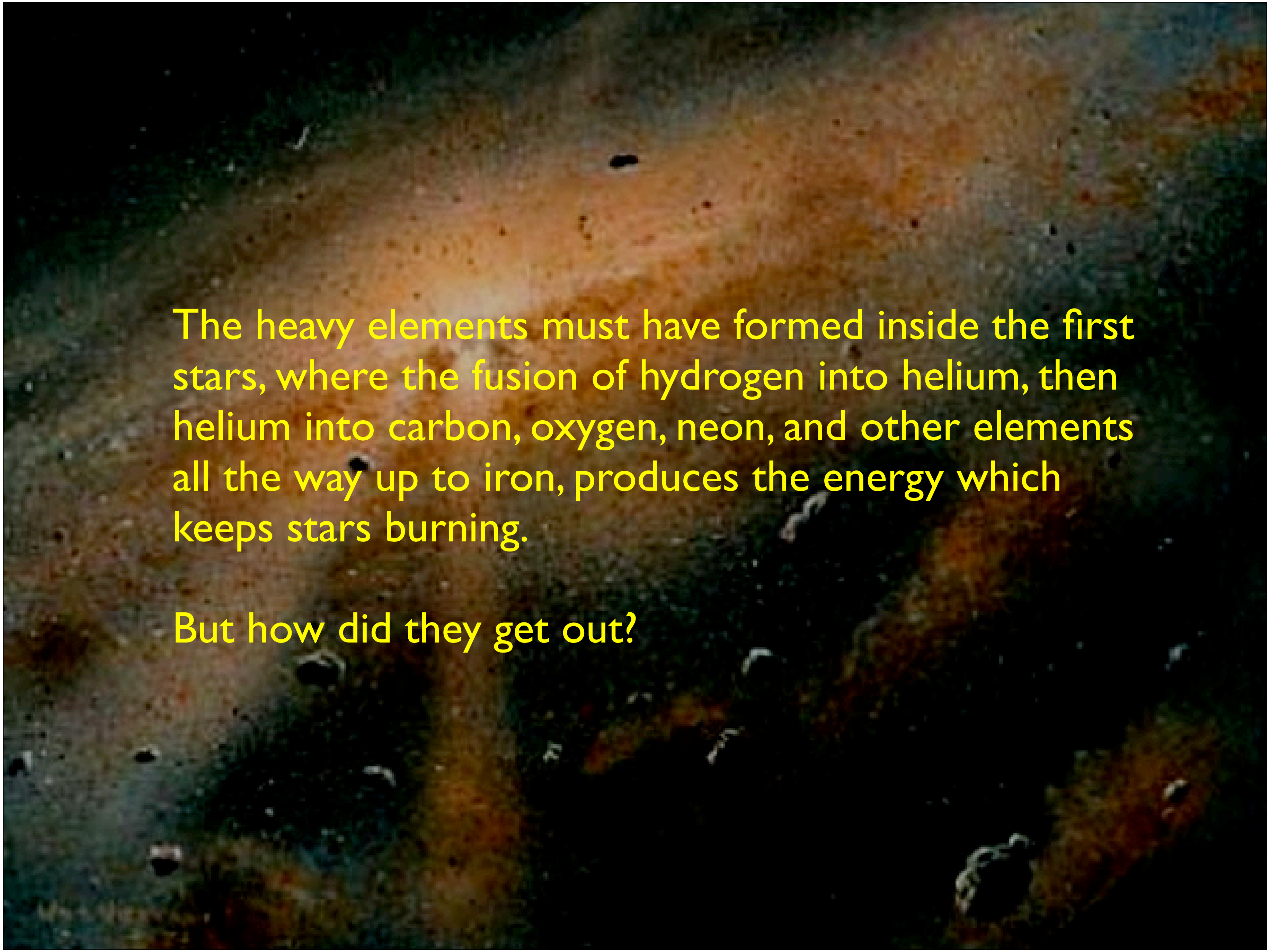


Nearly all the nuclei with a few protons and neutrons are unstable or easily destroyed. Helium-4 is the only really stable one, so lots of Helium-4 was formed in the next few seconds. But apart from tiny amounts of Lithium-7, no other element can be easily formed. So when the era of fusion ended, about 3½ minutes after the Big Bang, the universe consisted of lots of hydrogen, some helium, tiny amounts of deuterium and lithium-7, and not much else.



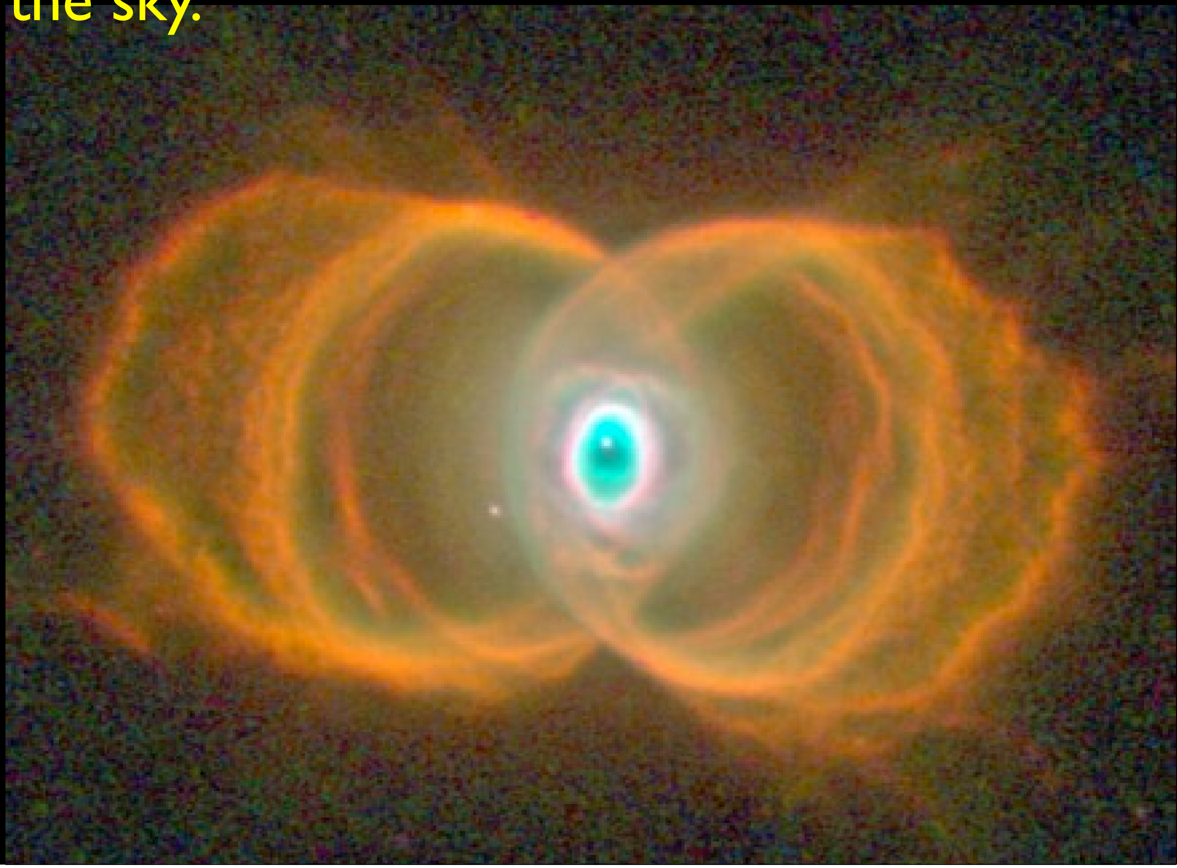
The first stars to form in the universe would have been very different from our own Sun: they had no heavy elements. With no heavy elements, there can have been no rocky planets (no silicon, carbon, etc.), and any gas giants which formed would have looked very different, without that 1% heavy elements to give them their brilliant colours.

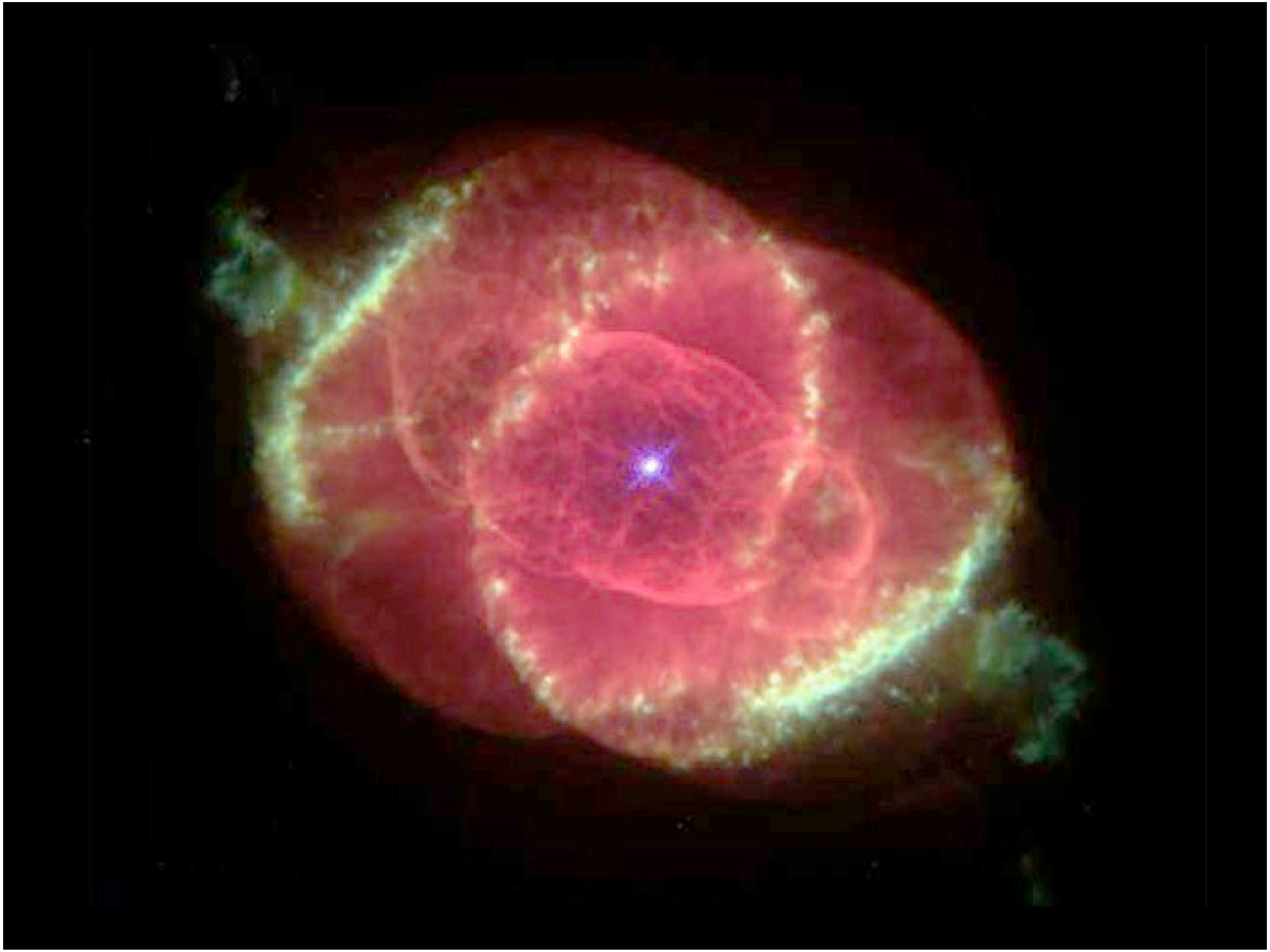
So where did the heavy elements come from?


The heavy elements must have formed inside the first stars, where the fusion of hydrogen into helium, then helium into carbon, oxygen, neon, and other elements all the way up to iron, produces the energy which keeps stars burning.
But how did they get out?

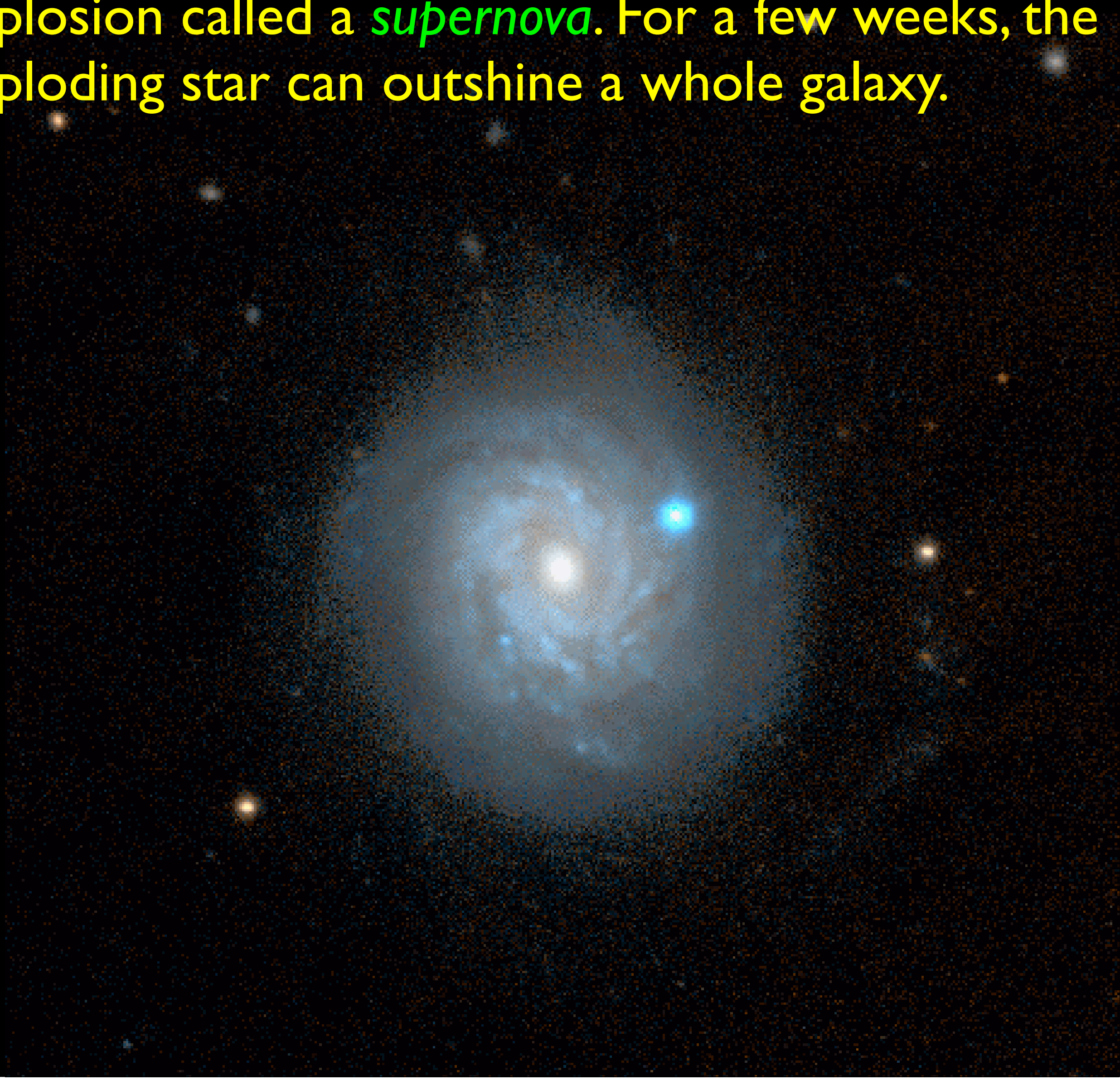
The Death of Stars

When stars die, they often die messily. Sometimes they blow large amounts of their outer layers into space, which become visible as *planetary nebulae*, some of the most beautiful objects in the sky.



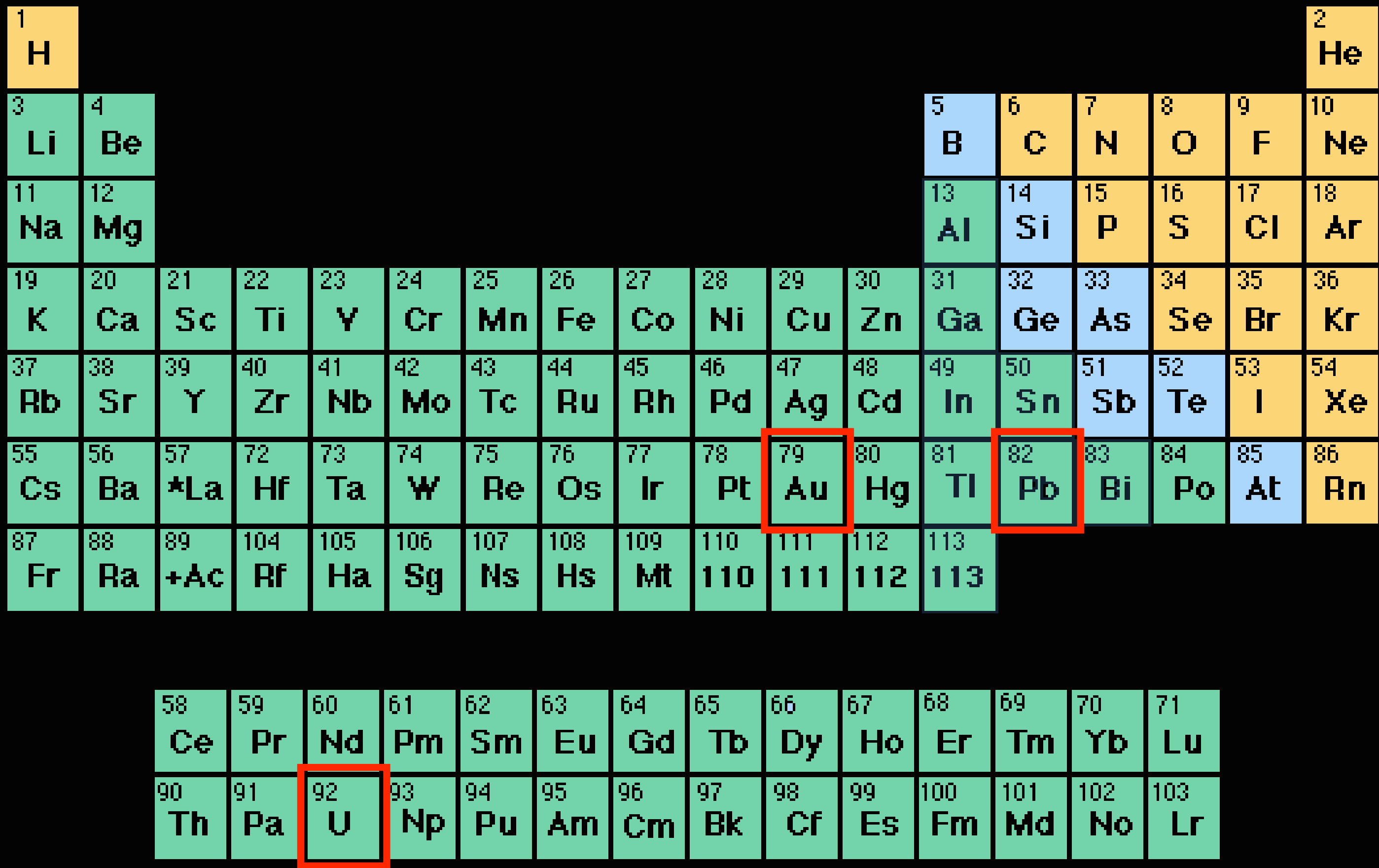


When really massive stars die, they expire in a titanic explosion called a *supernova*. For a few weeks, the exploding star can outshine a whole galaxy.



The star is destroyed in the explosion. The central core collapses to form a neutron star or black hole, but most of the mass of the star is thrown out into space at high speed. As it expands, it becomes visible as a *supernova remnant*, like the Crab Nebula.

In addition, the elements heavier than iron are actually produced during the supernova explosion itself. A flood of neutrons produced by the collapsing core slams into the gas in the stars interior, and produces all the heavy elements, including gold, lead and uranium.



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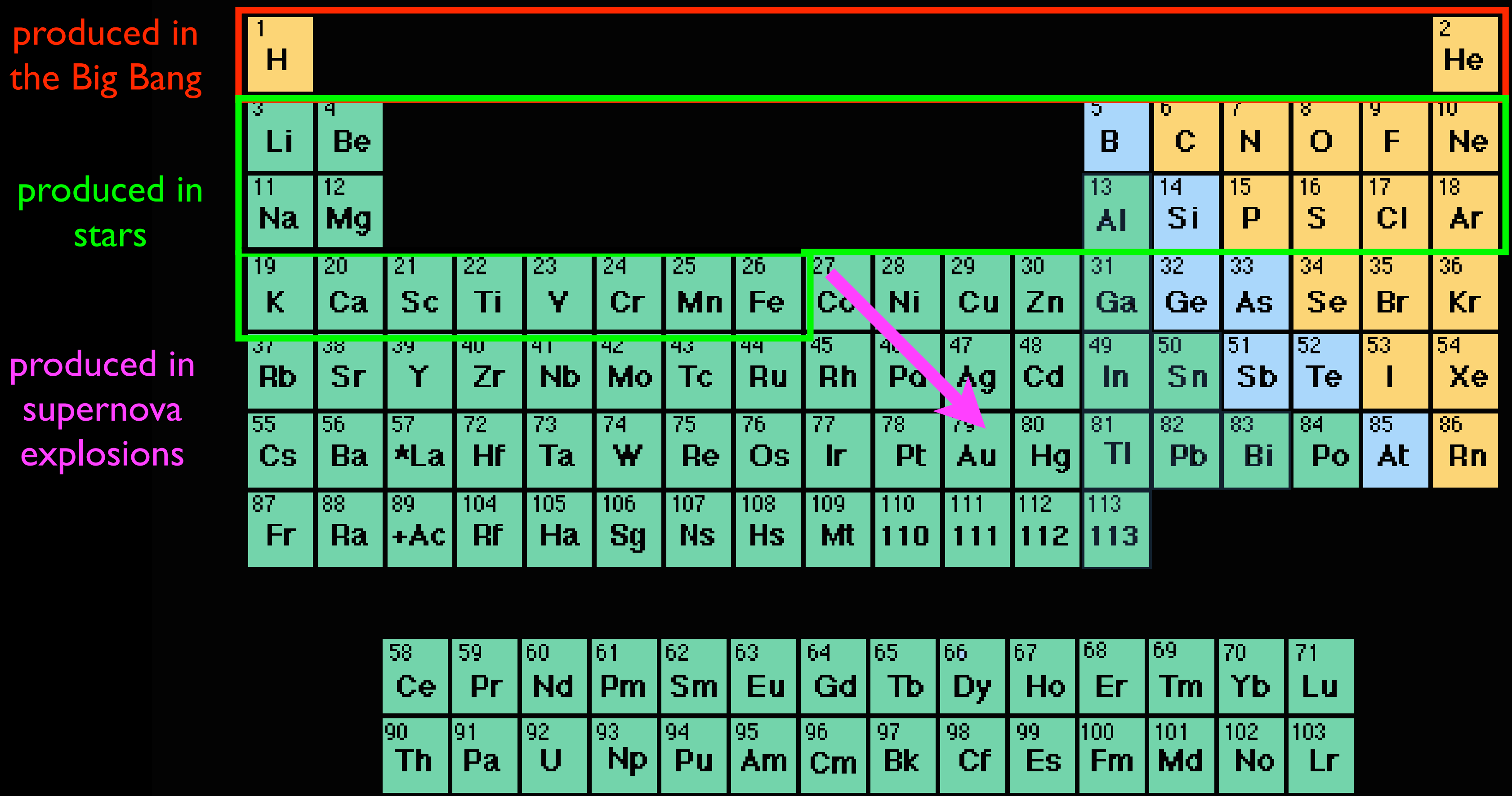
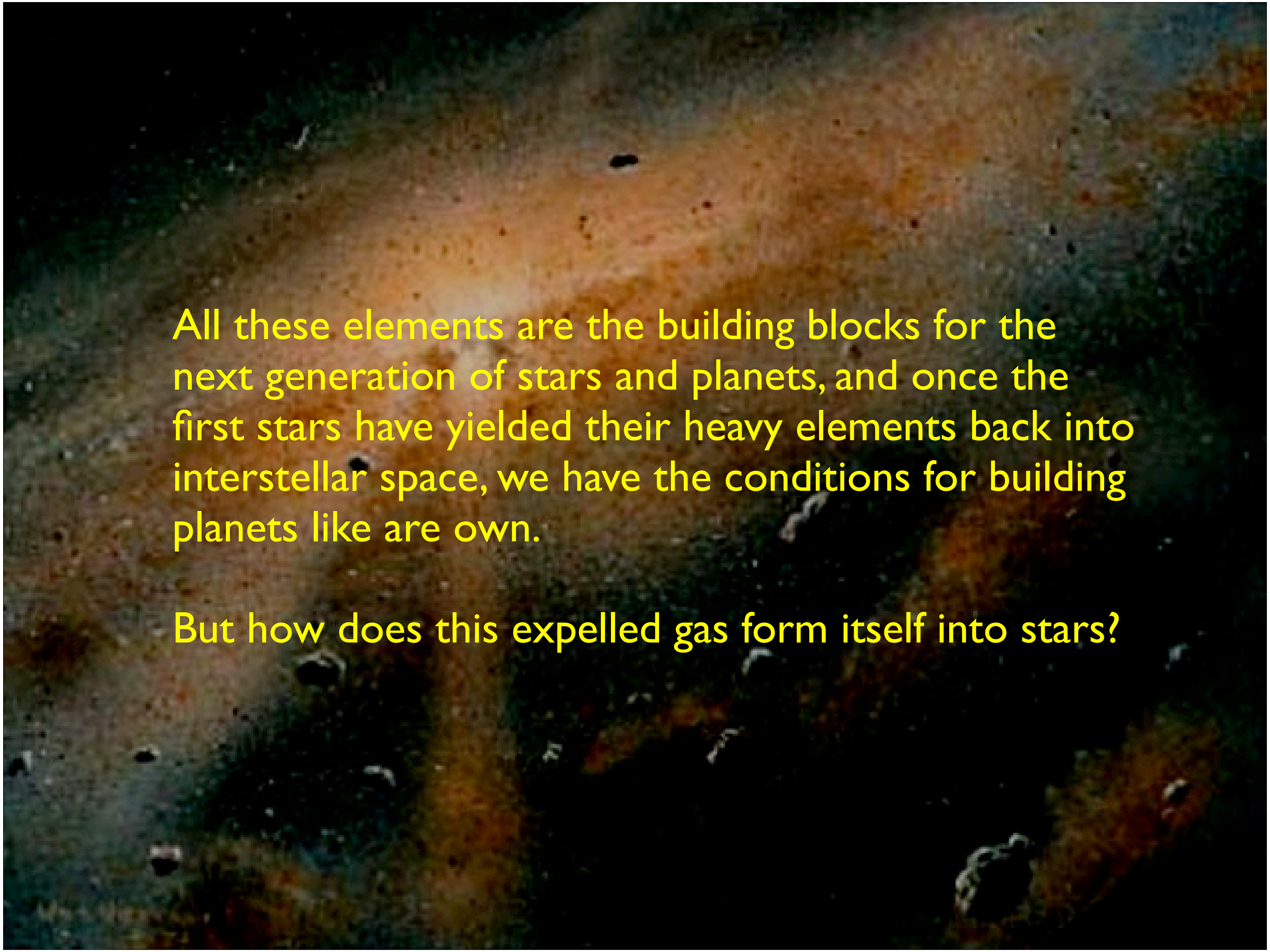




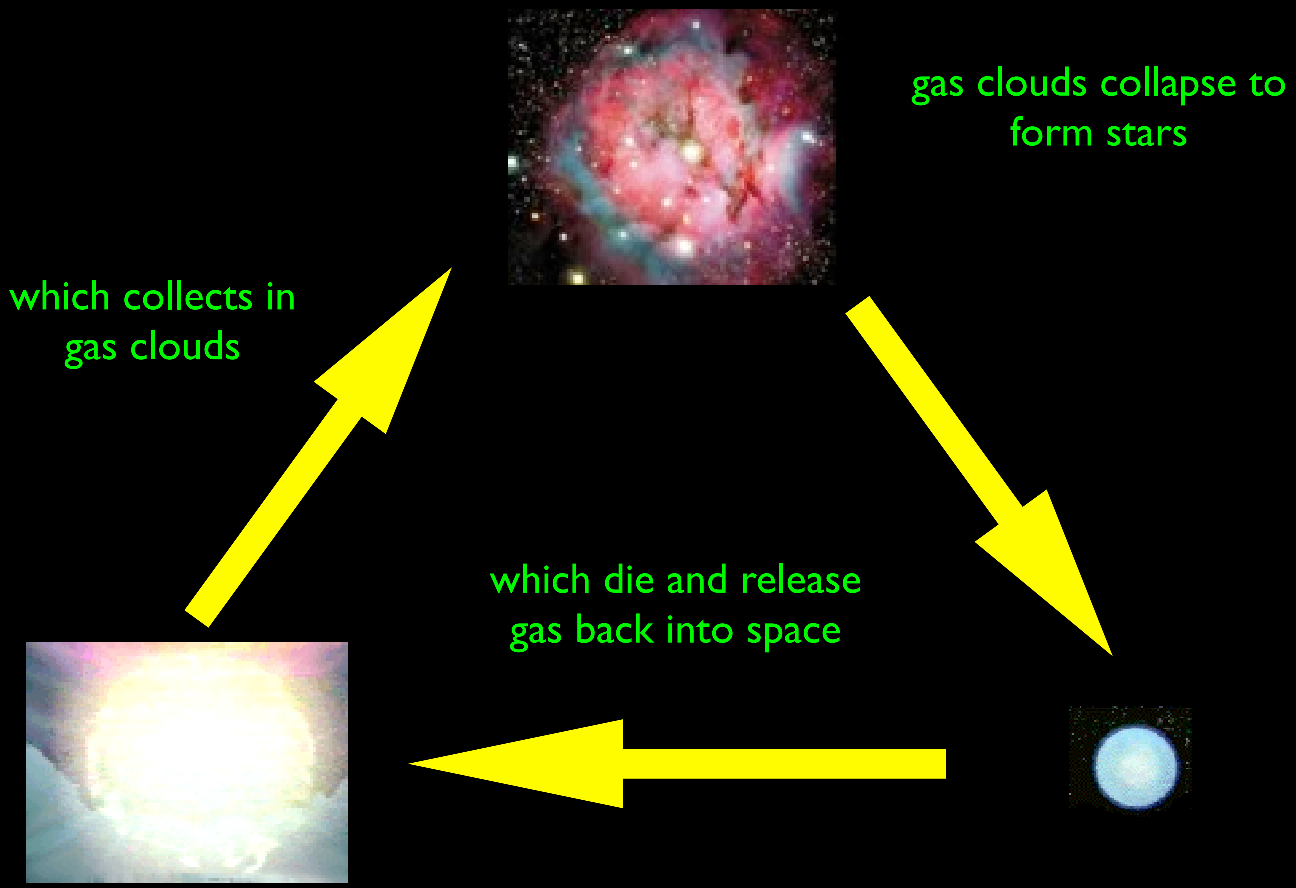
All these elements are the building blocks for the next generation of stars and planets, and once the first stars have yielded their heavy elements back into interstellar space, we have the conditions for building planets like are own.

But how does this expelled gas form itself into stars?

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*.

These clouds are the sites of star formation. Here you can see the new-born stars in NGC 281 lighting up the wispy remnants of the cloud which gave them birth. The dark blobs are *Bok globules*, small sub-clouds which are currently forming stars.

These stars will in their turn age, die, and release their gas back to the interstellar clouds, in a giant cycle of stellar birth and death.



This is how molecular clouds form. How do they collapse to form stars?

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.

It turns out the cloud will only collapse if its mass exceeds a critical mass called the *Jeans mass*, which depends on the density and type of gas. Low density clouds with large mass may collapse to form galaxies, while smaller but denser clouds collapse to form star clusters or single stars.

As the cloud contracts, its speed of rotation increases. The law of *conservation of angular momentum* says that as rotating things get smaller, they rotate faster.

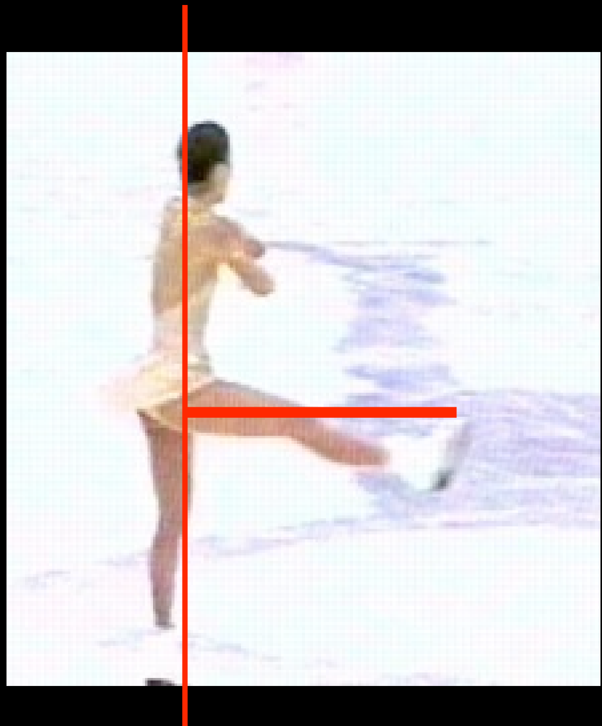
To be precise, angular momentum is equal to

mass x velocity x distance from axis

If no outside forces act on the body, this quantity remains the same, so if the distance gets smaller, the velocity must increase.

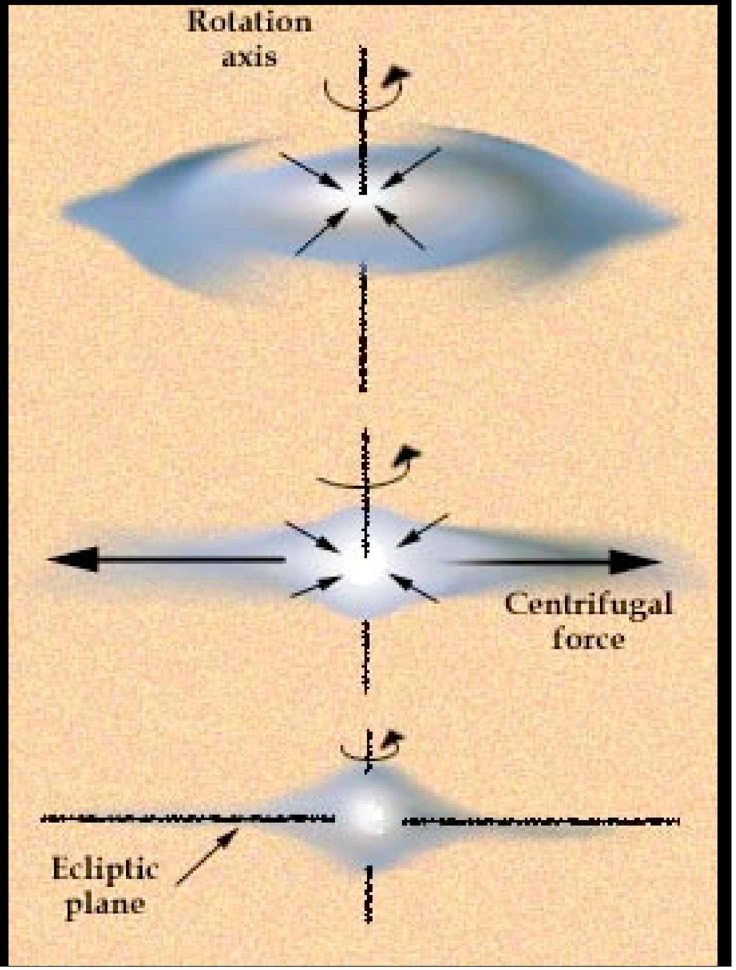
Conservation of angular momentum is what ice skaters use when they speed up a spin.

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.

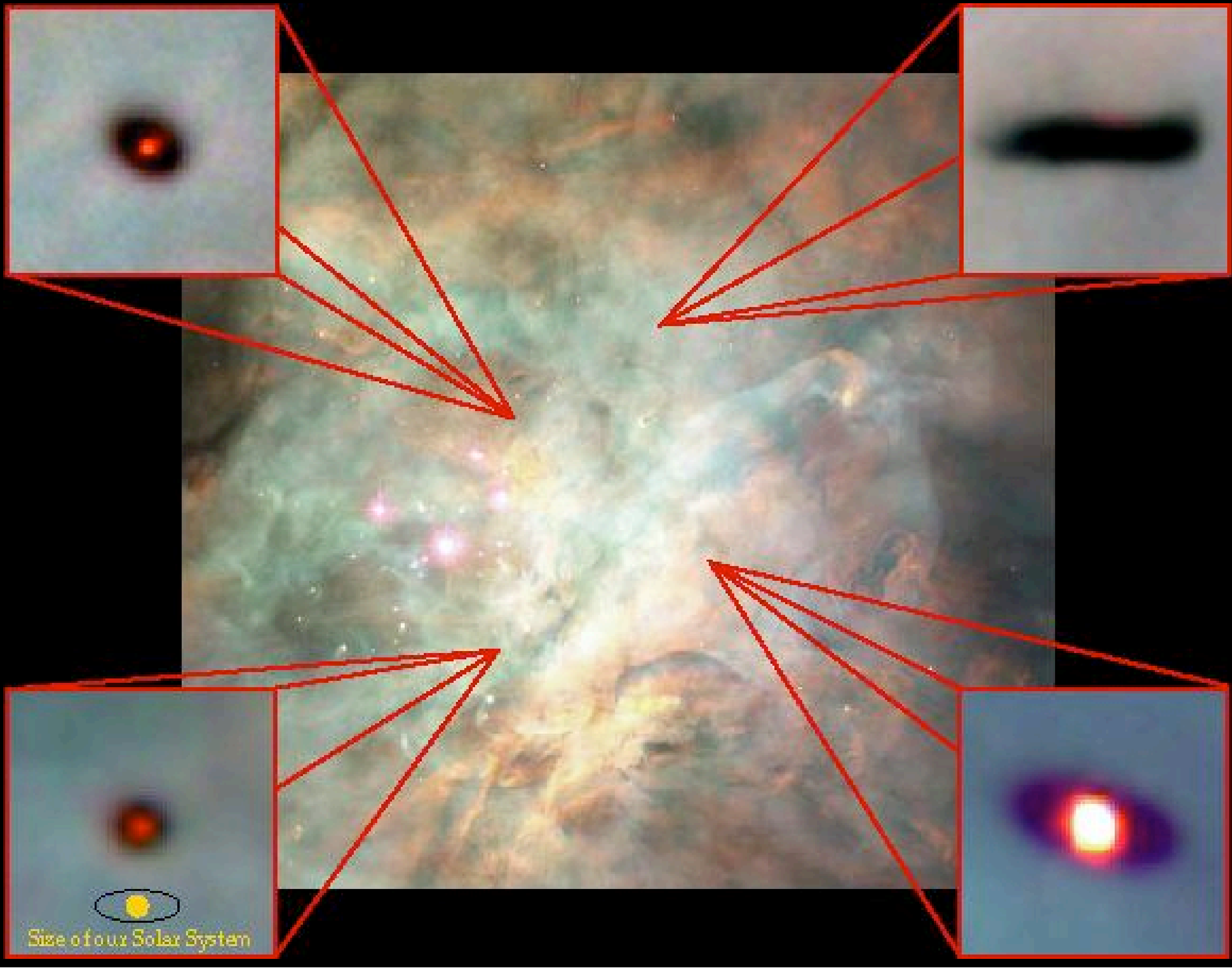


The collapsing cloud will be rotating slightly, even if only due to Galactic rotation. The cloud shrinks by a factor of 10,000 or more, so any slight rotation is greatly amplified and the cloud will end up rotating rapidly.

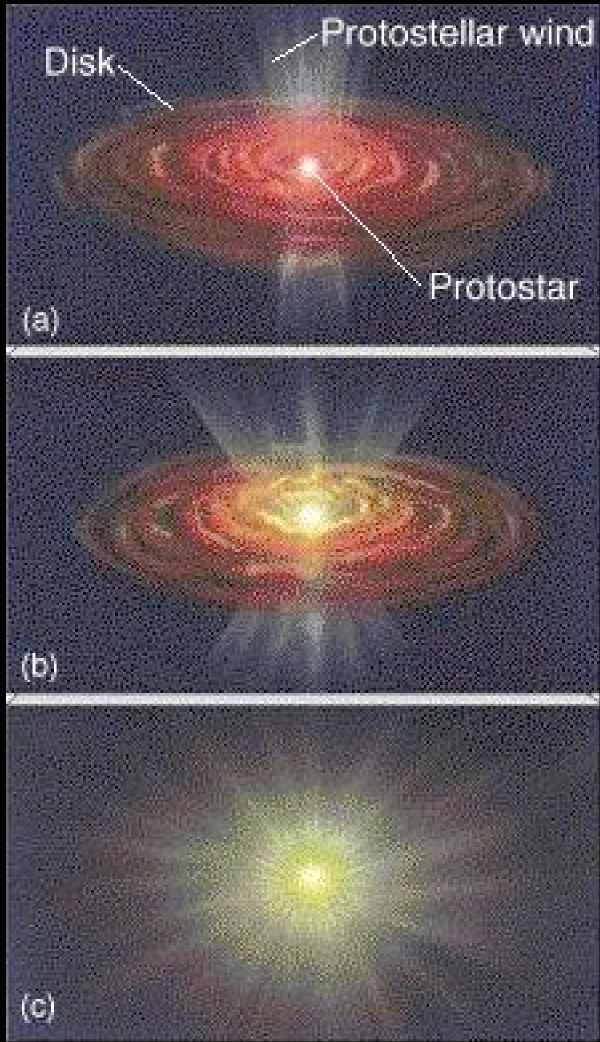
What's more, it will end up as a *disk*, because while angular momentum makes it hard to collapse to the centre, there is nothing to stop the gravitational collapse to the plane.



We can actually see these disks around newborn stars.



The cloud collapses from the inside out, with the interior caving in more quickly than the outer regions. This collapse raises the temperature of the gas, as the gravitational kinetic energy is converted into heat. For a while, this thermal energy can be radiated away, and the collapse can continue, but as the density increases, the heat gets trapped, and the temperature of the central core rises until it reaches 1 million degrees, when hydrogen can begin fusing into helium. This produces enough energy to stop the collapse: a star has been born.




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 Orion Nebula, another famous star-forming region, shows these strange objects called "proplyds", which appear to be infant solar systems in the process of forming.

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?

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.

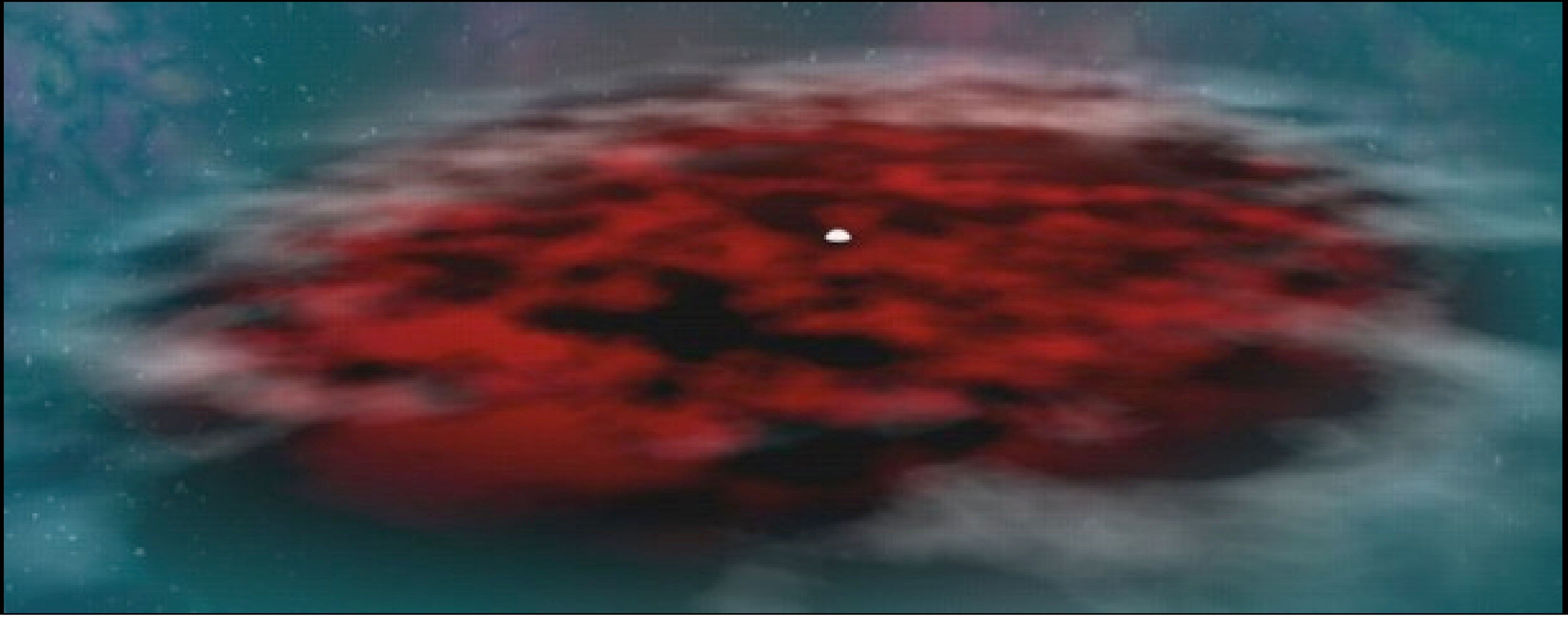
The giant planets must have formed within 10 million years, before the new Sun swept away the gas.

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.

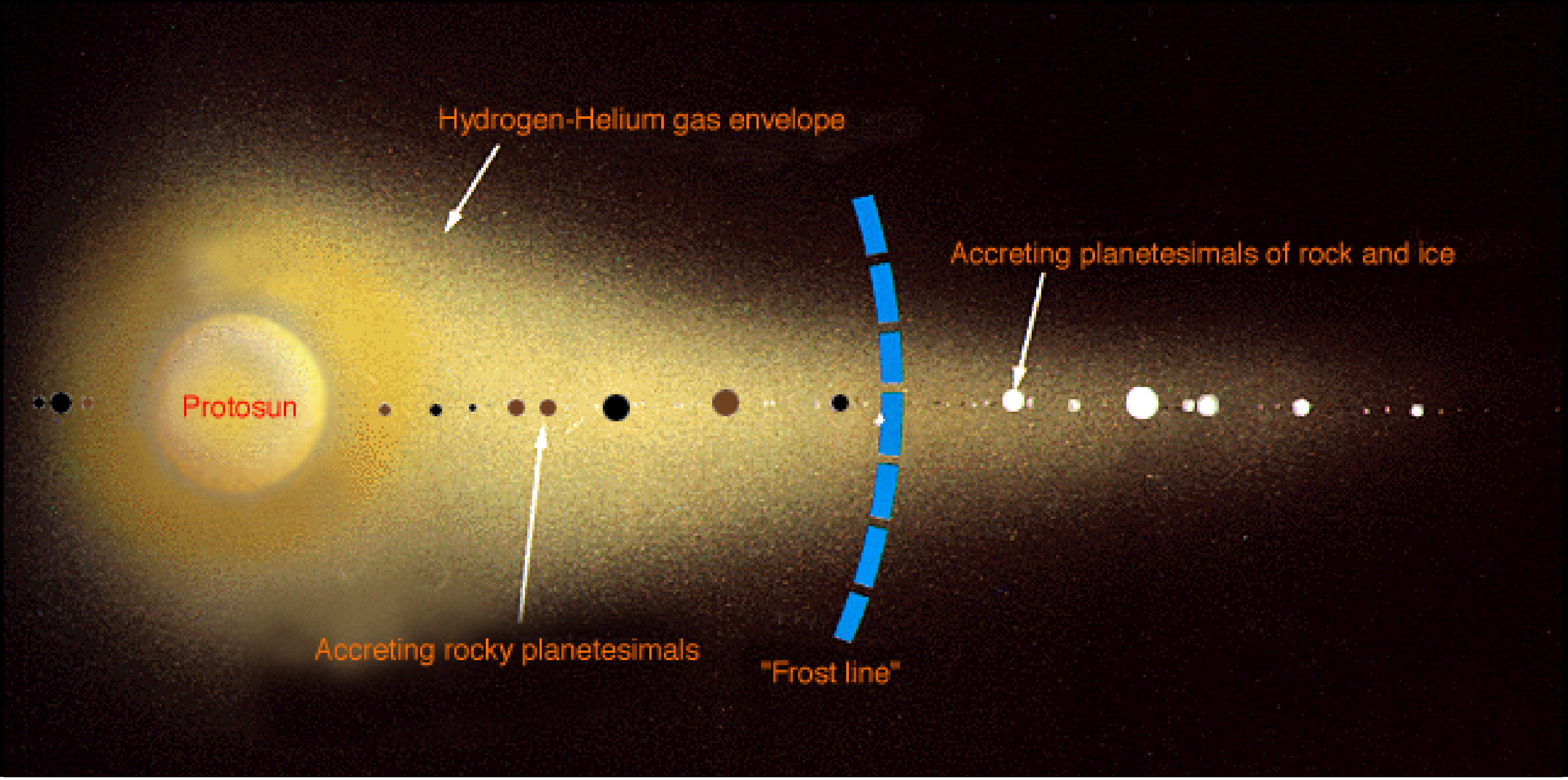


The disk is hotter near the centre, close to the protostar, so different materials condense out at different radii.

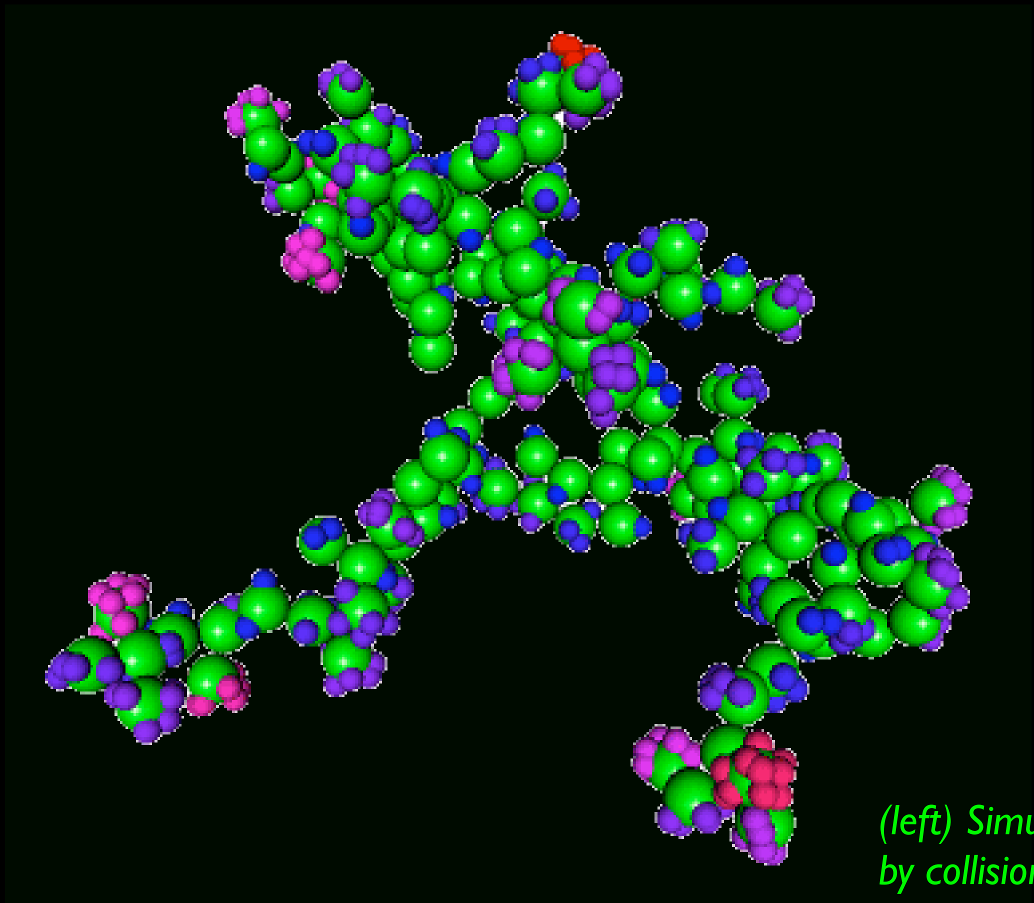
At high temperatures (< 2000K) rocky minerals and metals like iron condense.

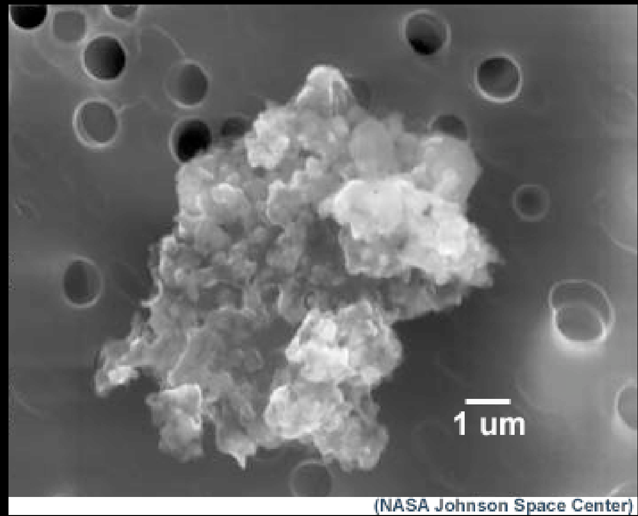
Below about 270 K water ice condenses, as well as ammonia and methane.

The distance at which water can freeze out is called the *ice line*. Beyond that distance there is much more mass available.

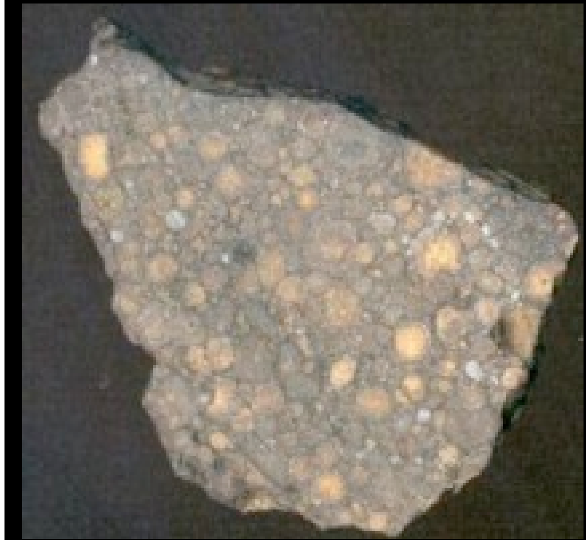


The condensing materials stick together by colliding and sticking together using normal chemical forces. They form loose fractal aggregates, described as “fluffy dustballs”.



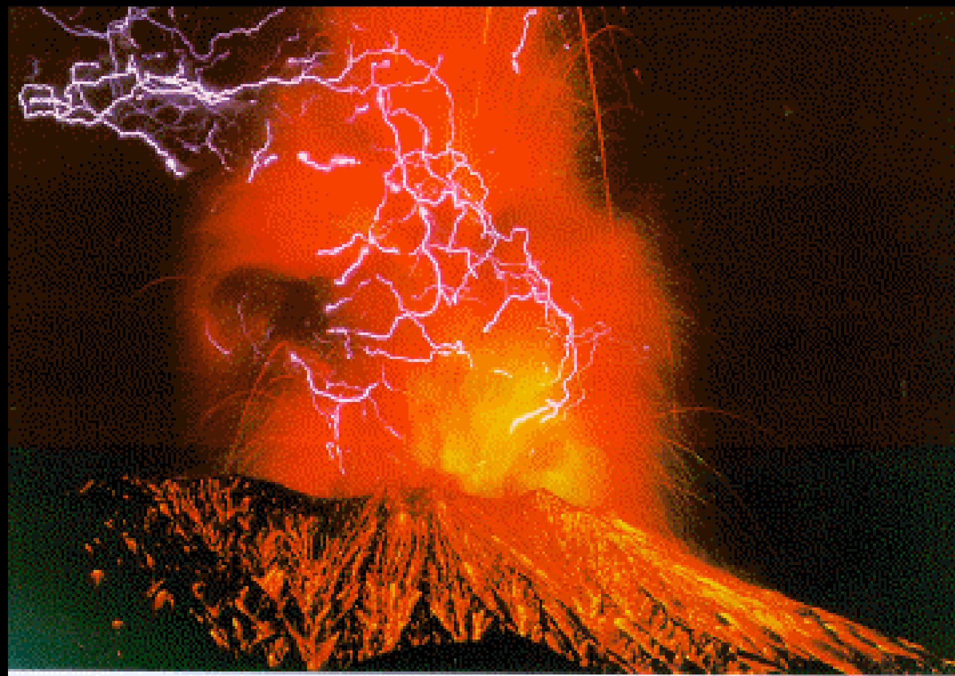


(left) Simulation of a molecular aggregate formed by collisions; (above) Electron microscope image of a typical cosmic dust particle



Recall that 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.

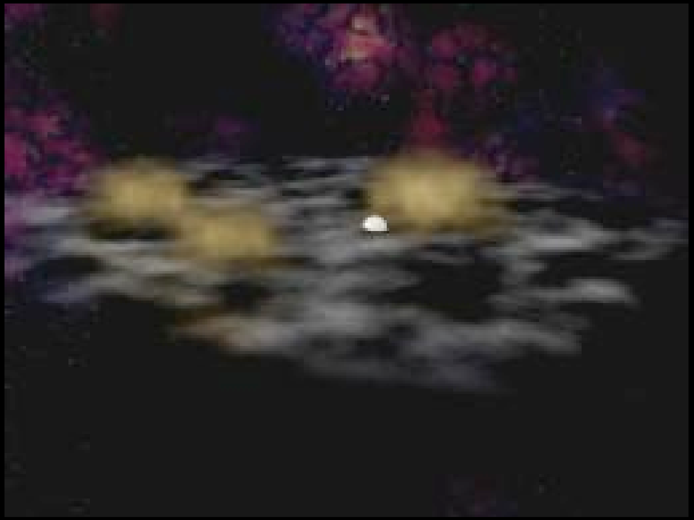
But how were they melted? No-one knows for sure: perhaps passage through shocks in the disk, or lightning in the disk (seen in volcano plumes)

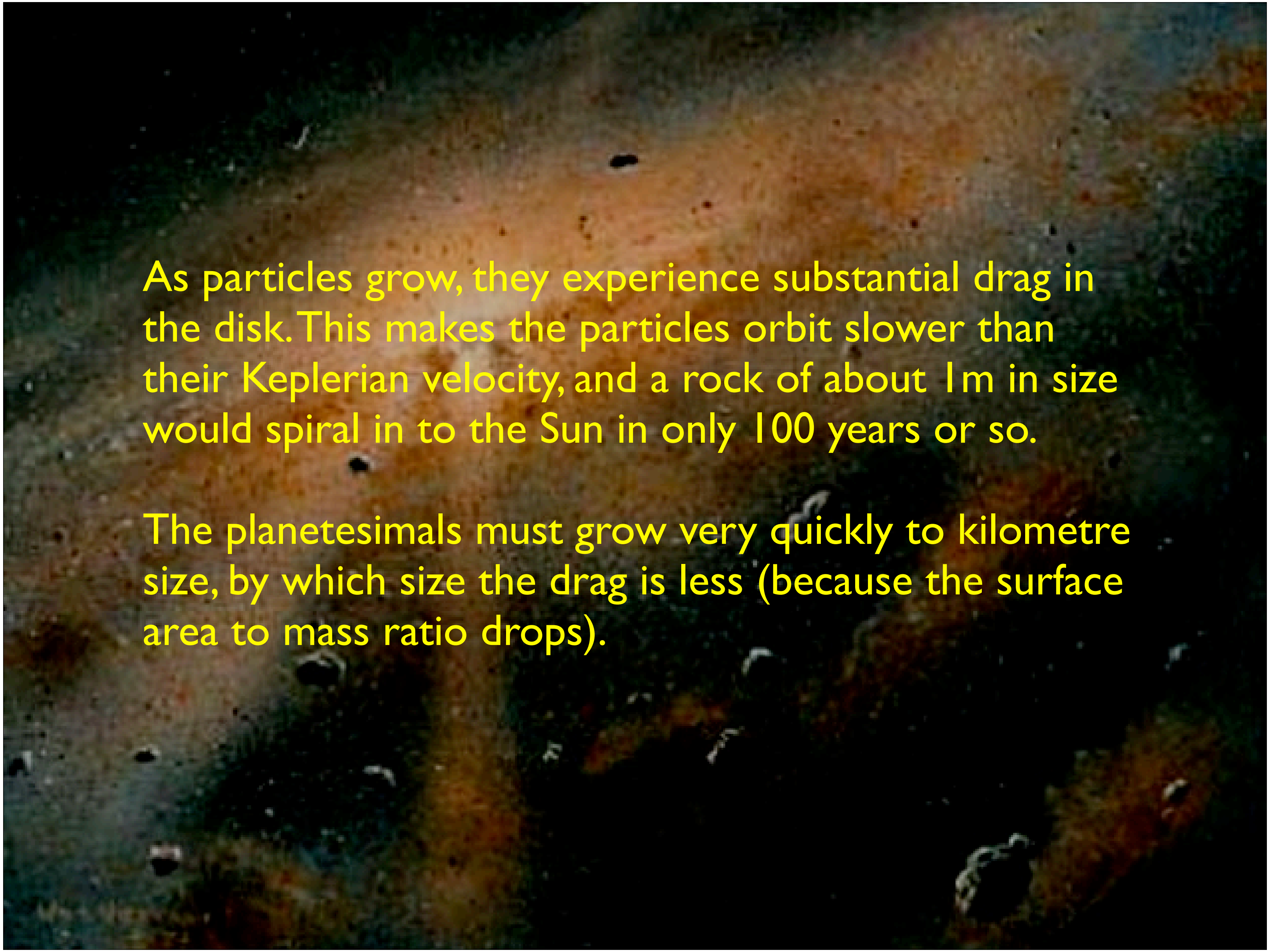


Phase 2: Accretion

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 collisions 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 orbit slower than their Keplerian velocity, and a rock of about 1m in size would spiral in to the Sun in only 100 years or so.

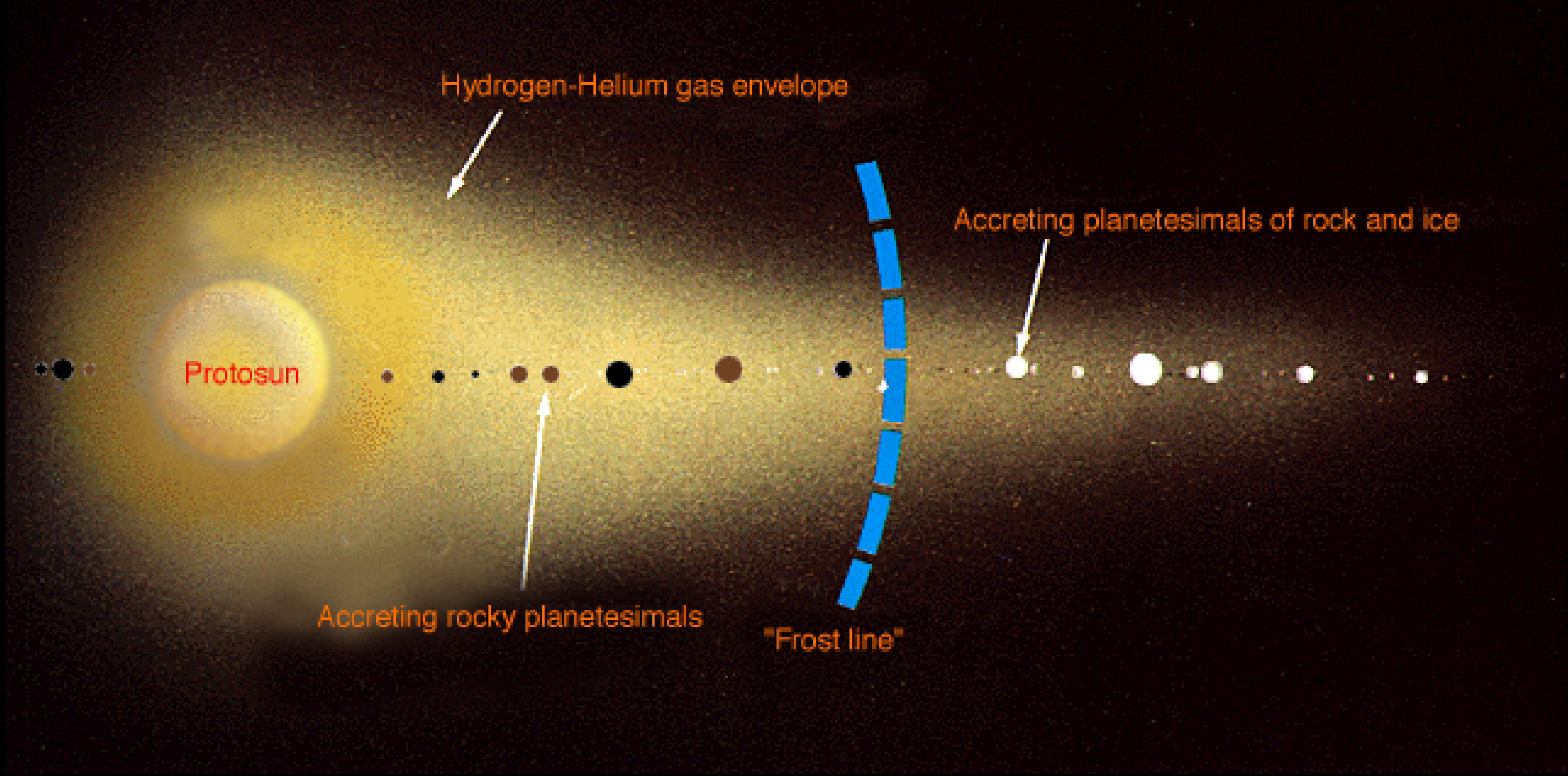
The planetesimals must grow very quickly to kilometre size, by which size the drag is less (because the surface area to mass ratio drops).

Phase 3: Runaway growth

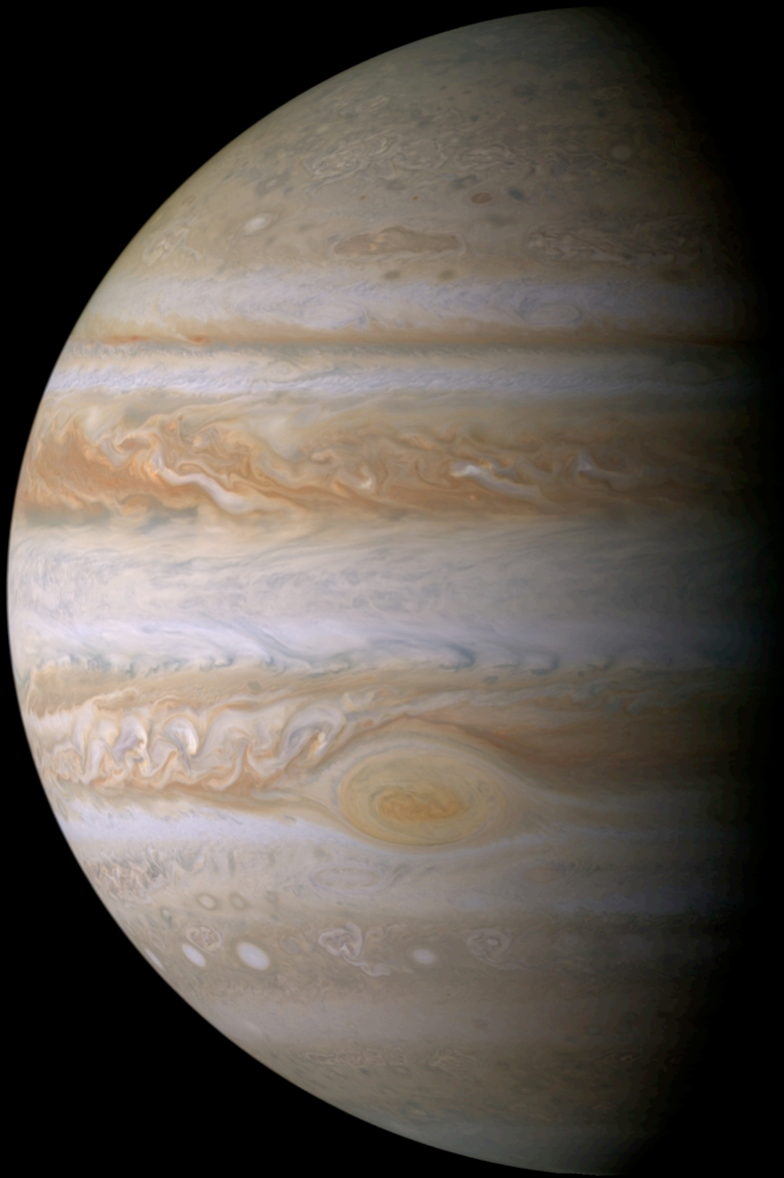
Once the particles reach about 1 km in size, gravity starts becoming important. The larger planetesimals can sweep up more material, so the biggest bodies grow much faster than smaller ones – a process known as *runaway growth*.

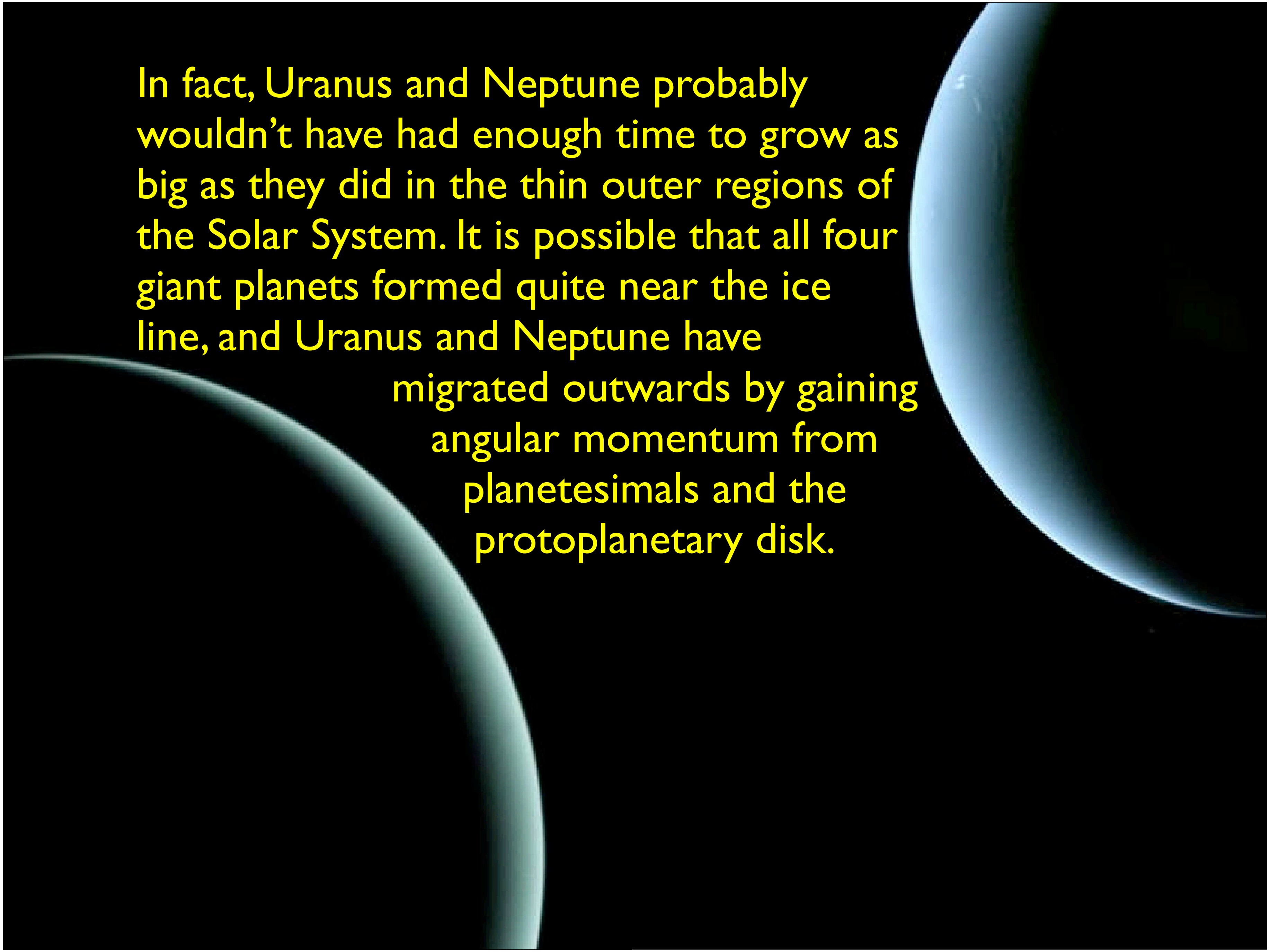
Runaway growth ends when the planetesimal (now called a *planetary embryo*) has consumed nearly everything within its reach.

The runaway growth phase ends with massive protoplanets fairly well spaced, since each has accreted everything within its gravitational sphere of influence.



The giant planets appear to have formed by first accreting a core of several Earth masses. This core was more massive than the proto-planets in the inner Solar System because the proto-Jovian planets were beyond the ice line. Once this solid mass had accumulated, the planet starts accreting gas more and more efficiently, in a runaway gas accretion phase. Jupiter and Saturn grew much larger because they formed further in, where the disk was thicker.





In fact, Uranus and Neptune probably wouldn't have had enough time to grow as big as they did in the thin outer regions of the Solar System. It is possible that all four giant planets formed quite near the ice line, and Uranus and Neptune have migrated outwards by gaining angular momentum from planetesimals and the protoplanetary disk.

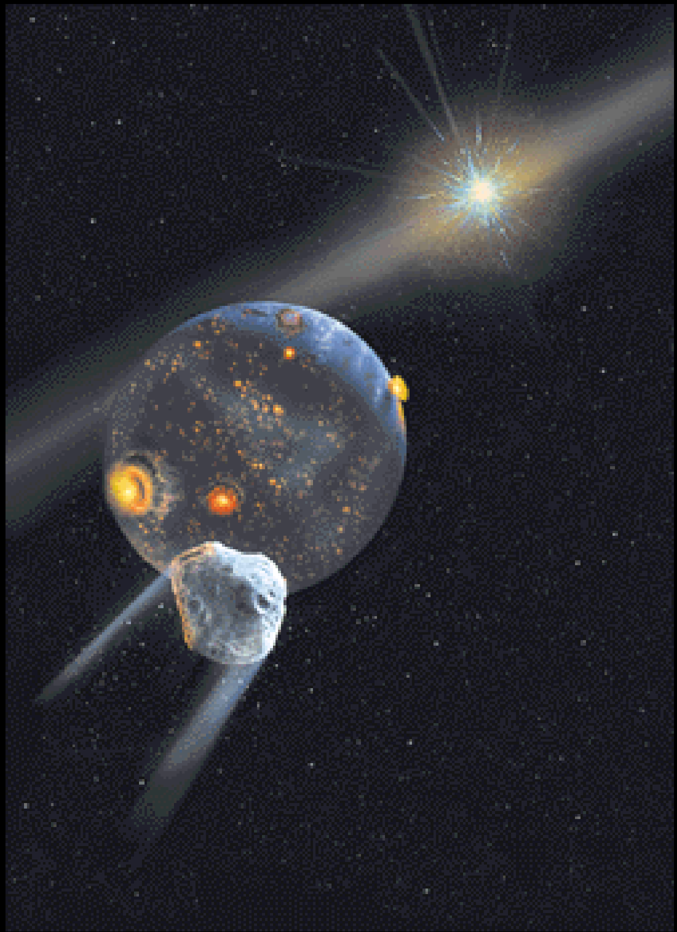
Satellites must have formed from a disk around their primary, just like miniature planetary systems. This disk was heated by the forming planet, leading to gradients of composition just like those we see in the planets.

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

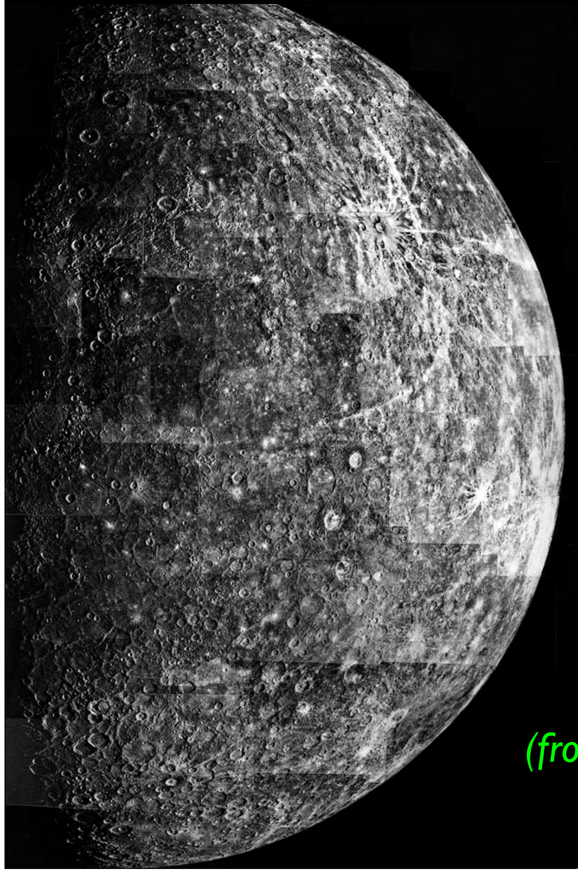
The Earth's moon and Charon have a different origin.

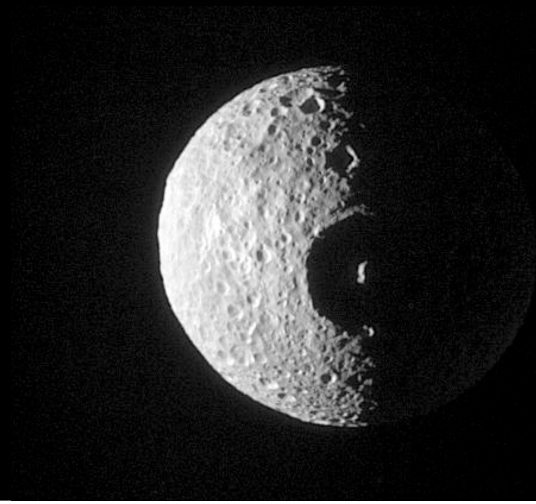
Phase 4: The era of carnage

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.





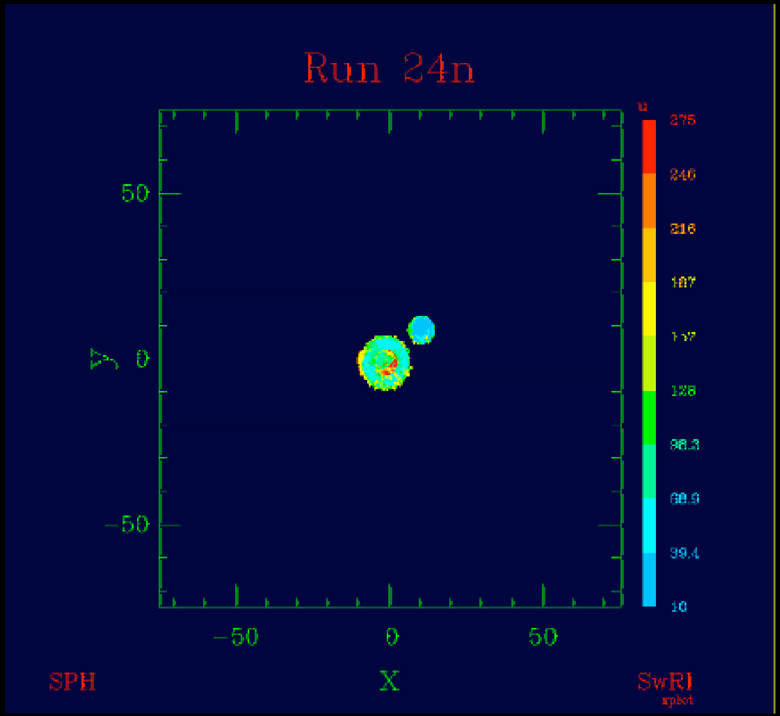
(from left) Mercury, Mathilde, Callisto and Mimas

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.

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

The Moon: it is thought that the Moon was formed when a protoplanet the size of Mars struck the proto-Earth. A large amount of debris was blown off, and a fraction entered Earth orbit and coalesced into the Moon. This explains the lack of heavy elements in the Moon (the Earth was already differentiated so only mantle material was ejected) and the lack of volatiles (they were vaporised and escaped into space), as well as the evidence that the moon's surface was molten at some stage.

Here is an animation showing a computer simulation of a Mars-sized object striking the proto-Earth. This animation covers only 24 hours, ending with the Earth surrounded by a disk of debris, from which the Moon will coalesce.



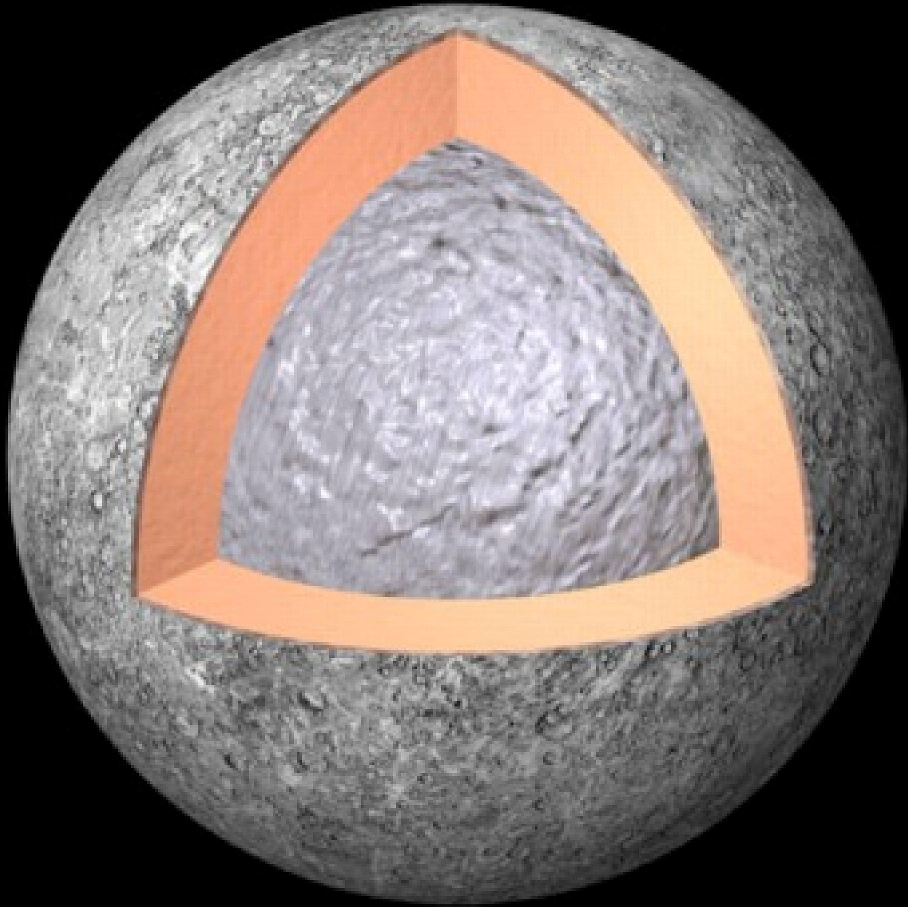
The impactor must have struck at quite a low (relative) velocity, and have formed at a similar distance from the Sun.

A recent suggestion is that the impactor formed at one of Earth's Lagrange points, and then drifted into a chaotic orbit that would impact the Earth
with a suitably low velocity.

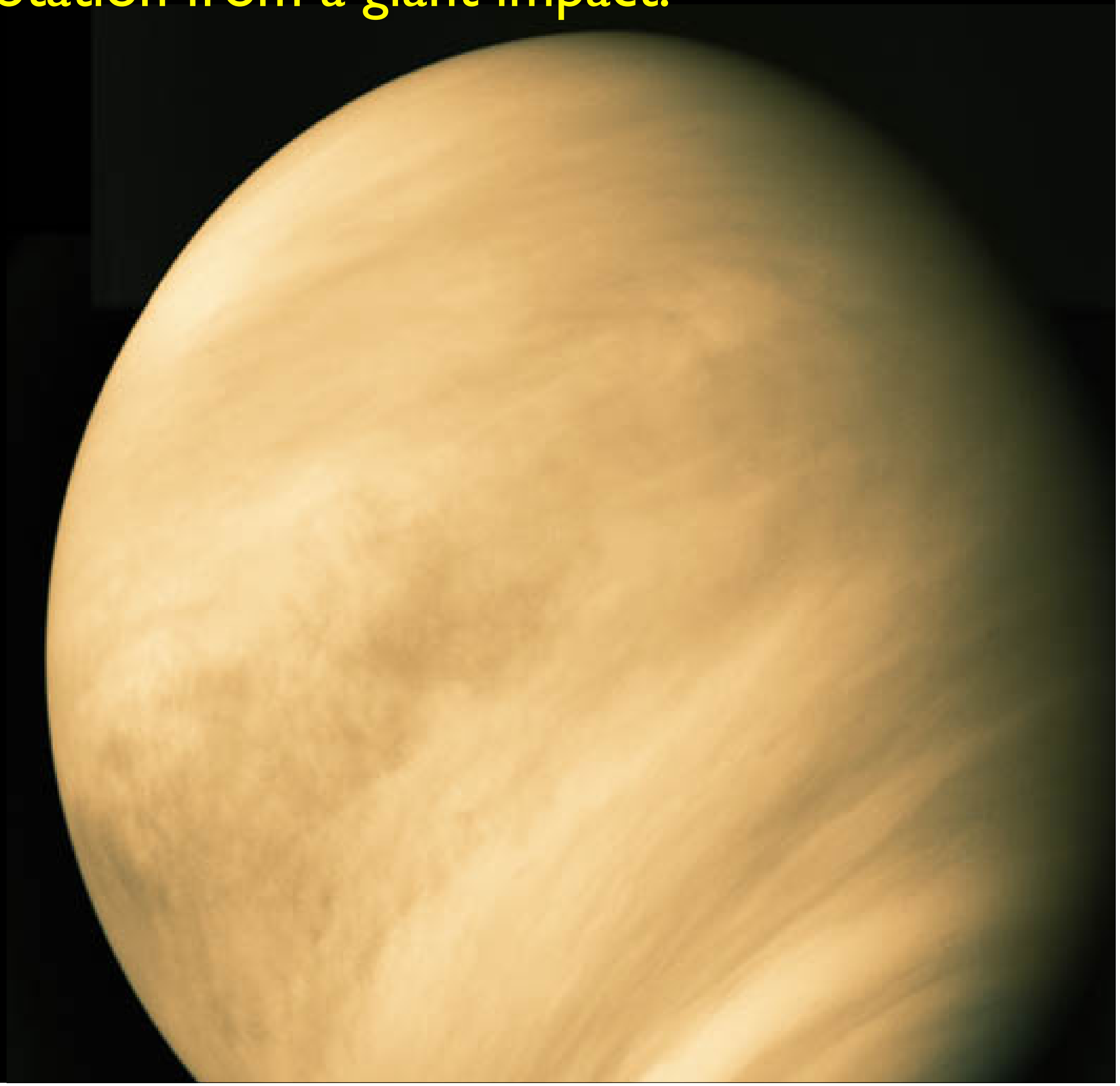
Animation of the impactor forming in Earth's L_4 point, and then drifting into impact.

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.

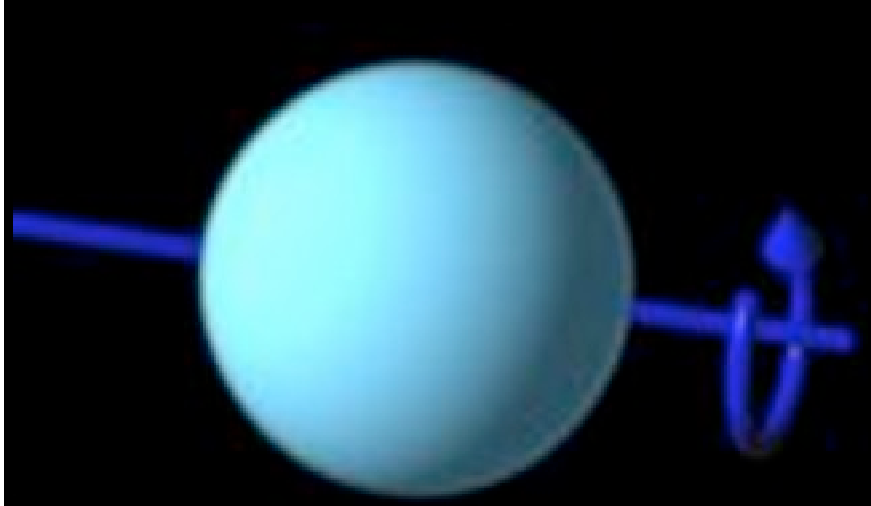
Mercury: Mercury's giant iron core may also be the remnant of a giant impact. An off-axis collision with a proto-planet of comparable size may have vaporised the silicate-rich mantle of the proto-Mercury, leaving behind an iron-rich core.

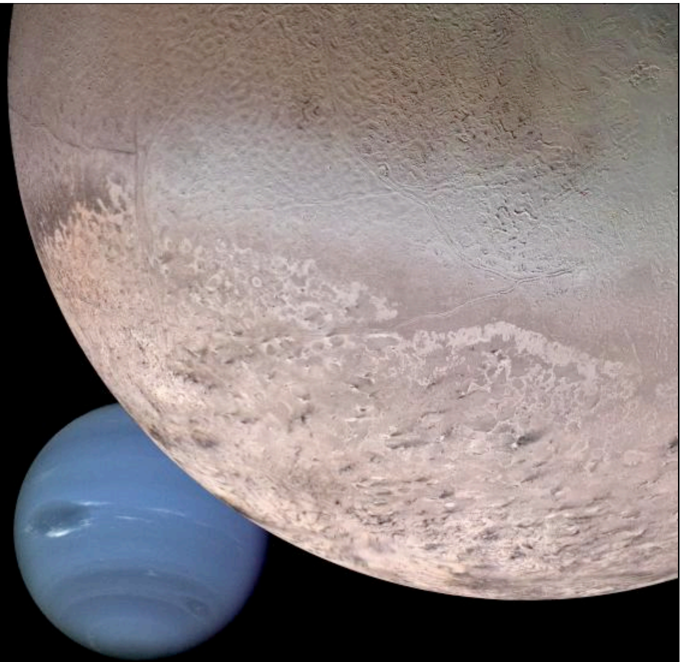


Venus: Venus may have acquired not only its tipped axis but also its slow rotation from a giant impact.



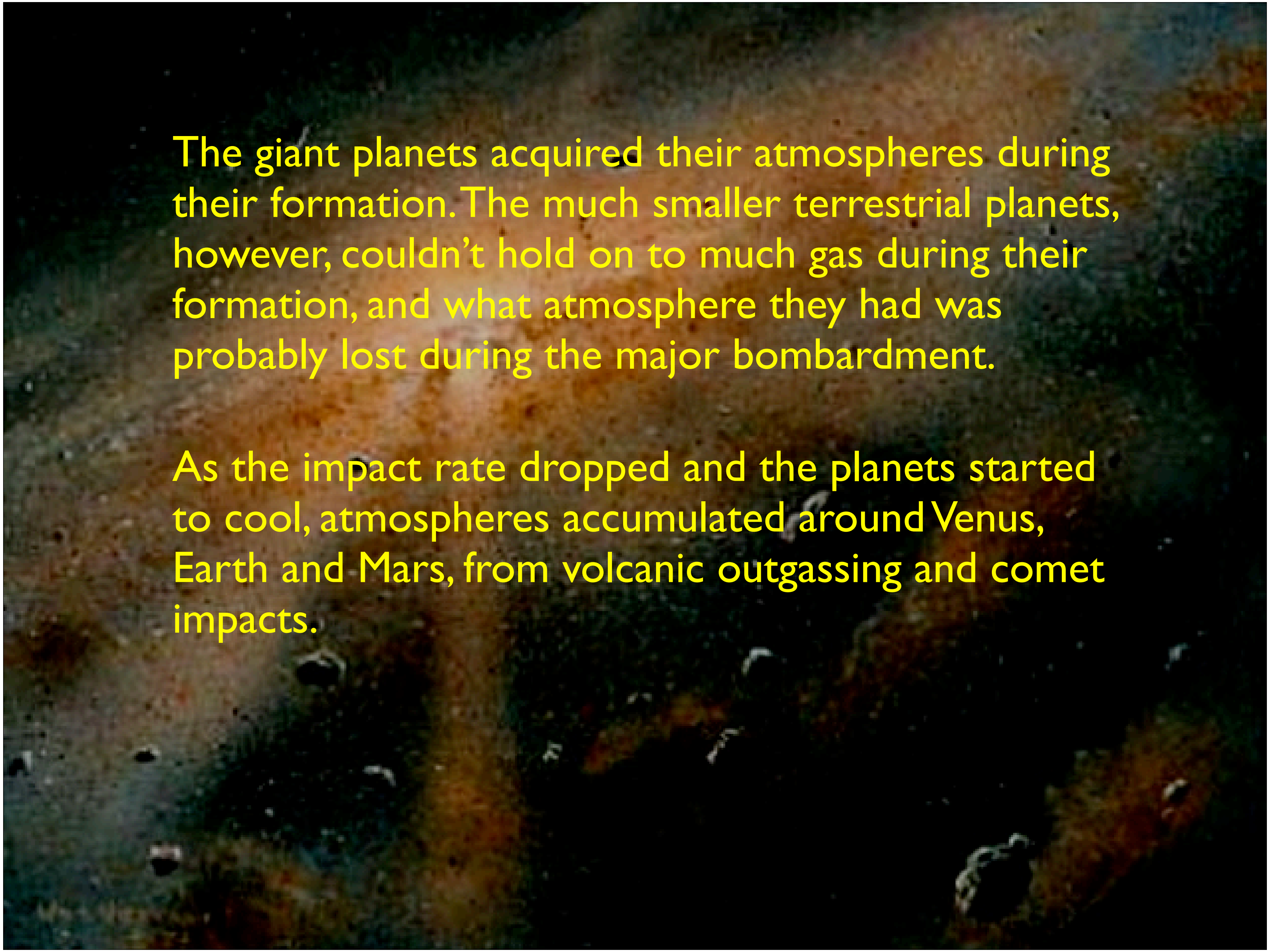
Uranus: Uranus' extreme tilt (98°) is thought to have been caused by a giant impact. A body of at least 2 Earth masses hit the proto-Uranus at an oblique angle, tilting the spin axis. A large amount of material spun off the equator left a disk in orbit from which the current system of moons eventually 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.





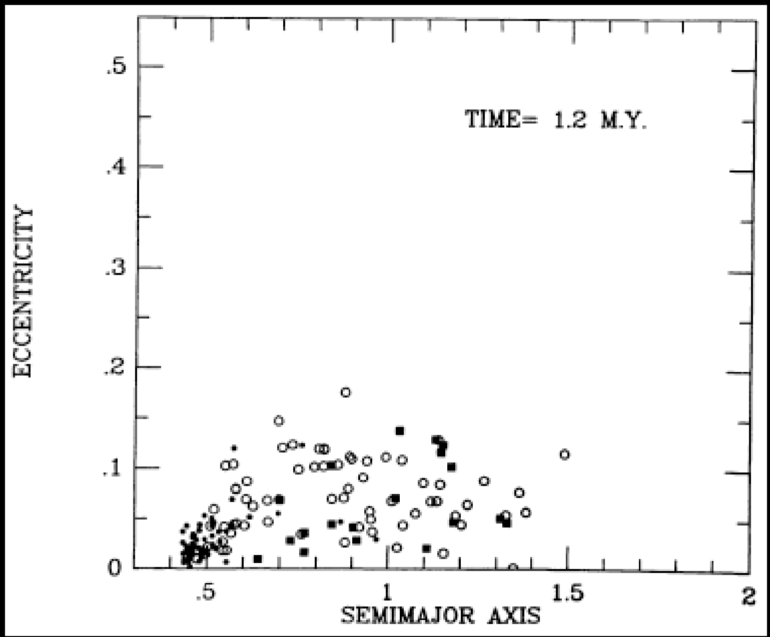
Triton: Triton, with its retrograde and highly inclined orbit about Neptune, is most likely a Kuiper belt object which wandered close to Neptune. There, it was captured into orbit, possibly colliding with (and destroying) one of Neptune's regular satellites. The initial orbit would have been highly eccentric,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

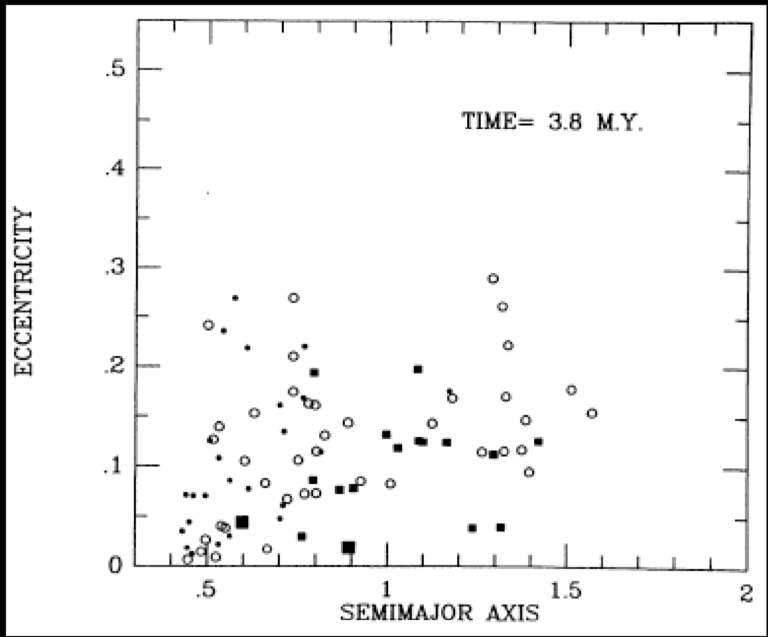
Neptune's original satellite system would have been destroyed by mutual collisions when Triton induced chaotic perturbations in their orbits. *Nereid* was almost ejected from the system, but not quite.


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.

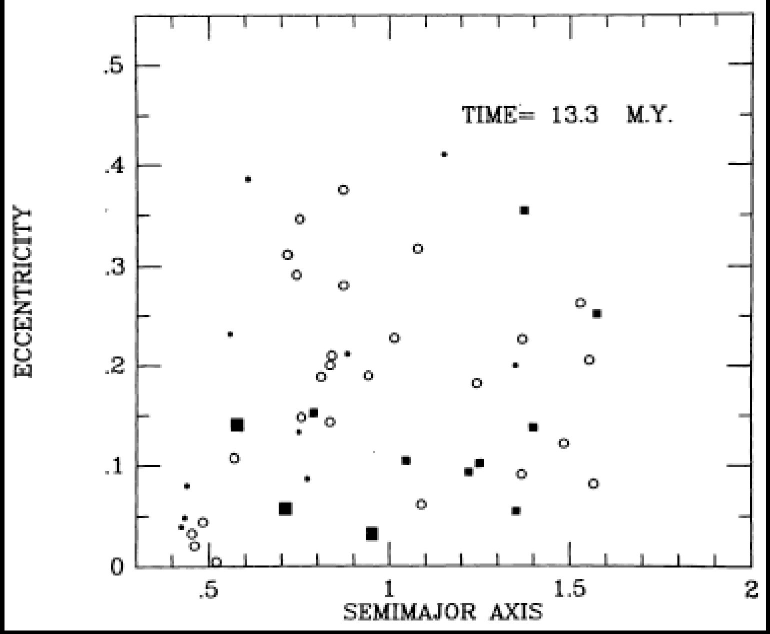
As the impact rate dropped and the planets started to cool, atmospheres accumulated around Venus, Earth and Mars, from volcanic outgassing and comet impacts.

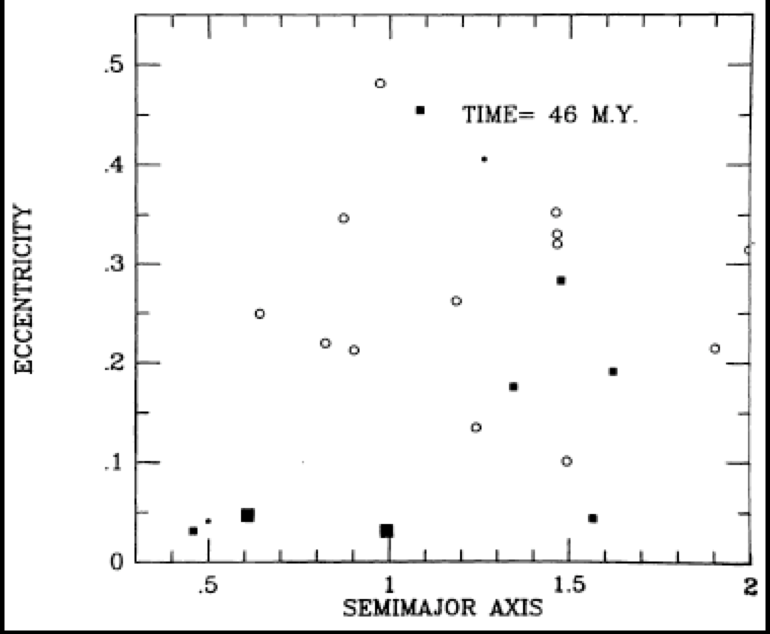
Here is a numerical model of the accumulation of the terrestrial planets. Planetary embryos in orbits which started out circular collide and perturb each other so the orbits become much more eccentric.



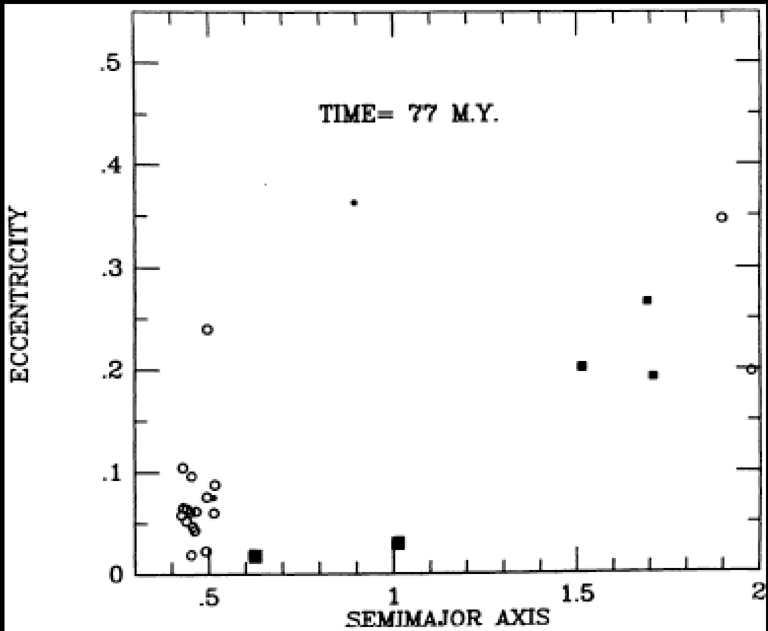


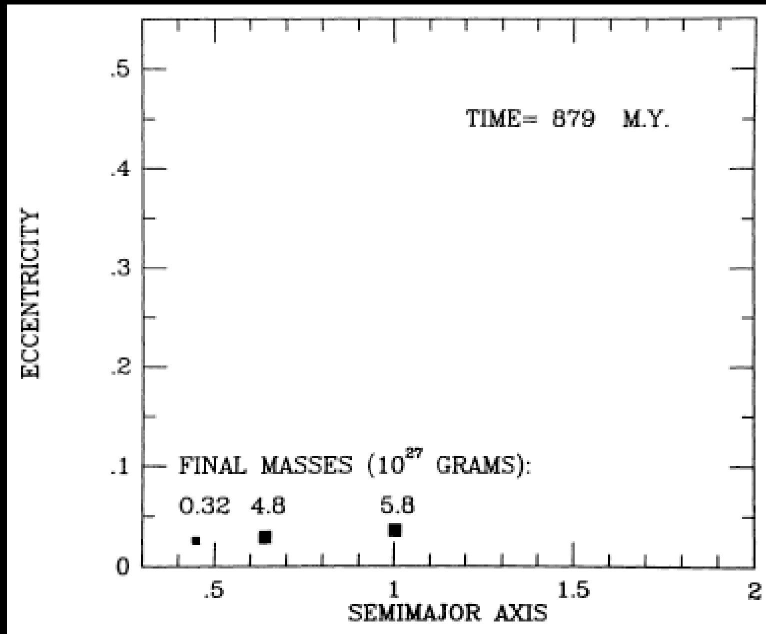
As accumulation continues, the largest bodies get larger and smaller ones disappear, being gobbled up or flung out of the system.



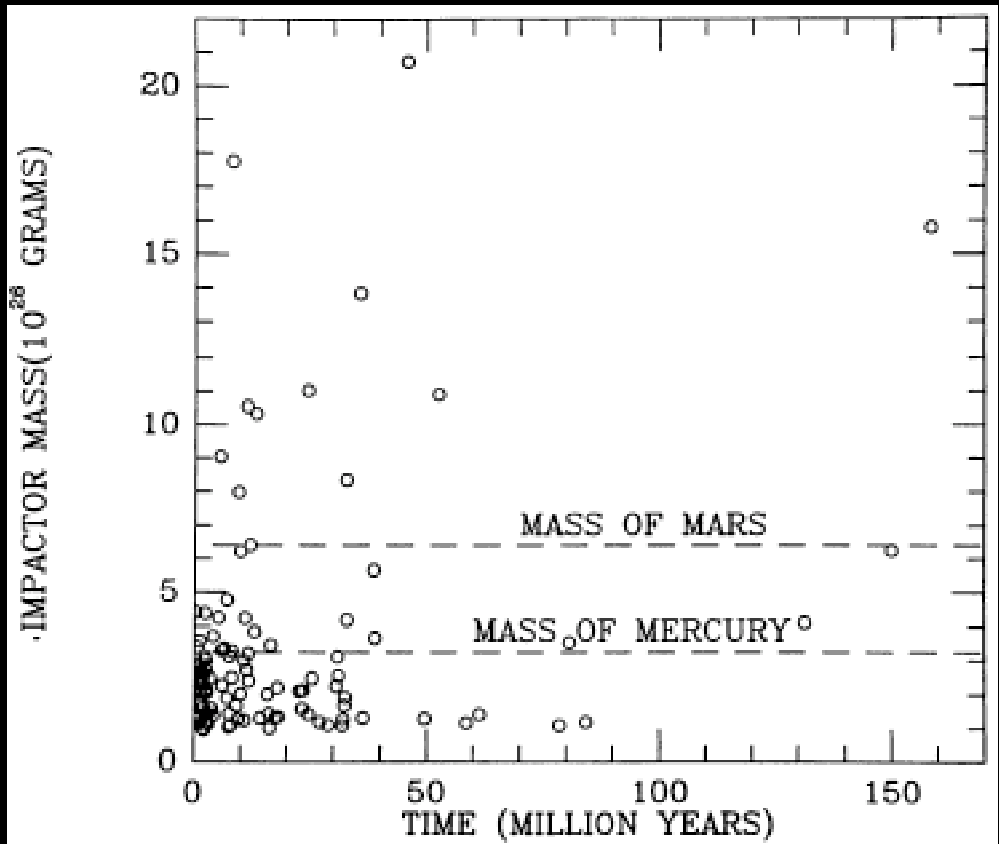


The final swarm of moderate-sized bodies finally coalesces to form "Mercury". Of the three potential "Mars" objects, none survive: two were ejected and one collided with "Venus".

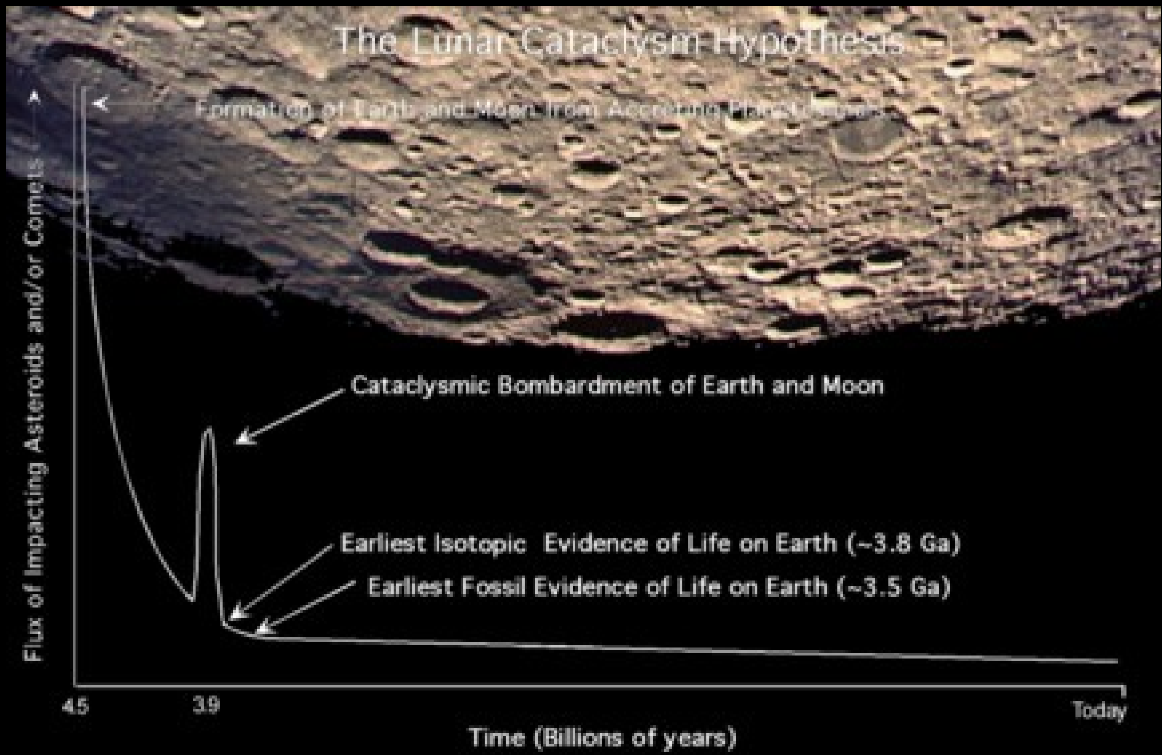




The distribution in size of the last few impacts on "Earth" for ten different simulations. On average, one object more massive than Mars impacts, and two more massive than Mercury.



Earth: 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.



One suggestion is that this period of "late heavy bombardment" was related to the formation of Uranus and Neptune.

The standard model of planetary formation has great difficulty in forming Uranus and Neptune in a reasonable amount of time: they do not accrete planetesimals fast enough to grow.

Recent work suggests Uranus and Neptune formed much closer in, 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 disk of planetesimals.

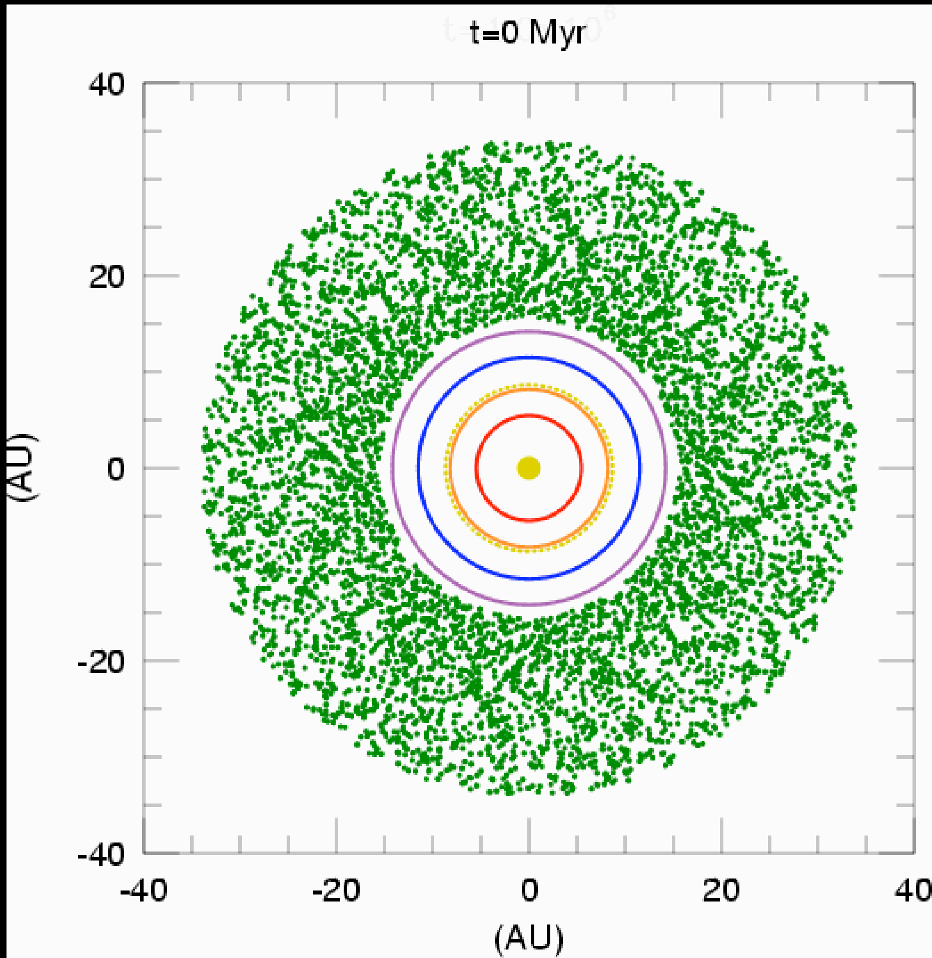
The orbits of the giant planets slowly expand, until after about 700 My Saturn comes into 1:2 resonance with Jupiter. This makes the orbits of Uranus and Neptune unstable, and their orbits scatter into the disk. This sends a large amount of material into the inner Solar System, producing the late heavy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

Jupiter

Saturn

Uranus

Neptune



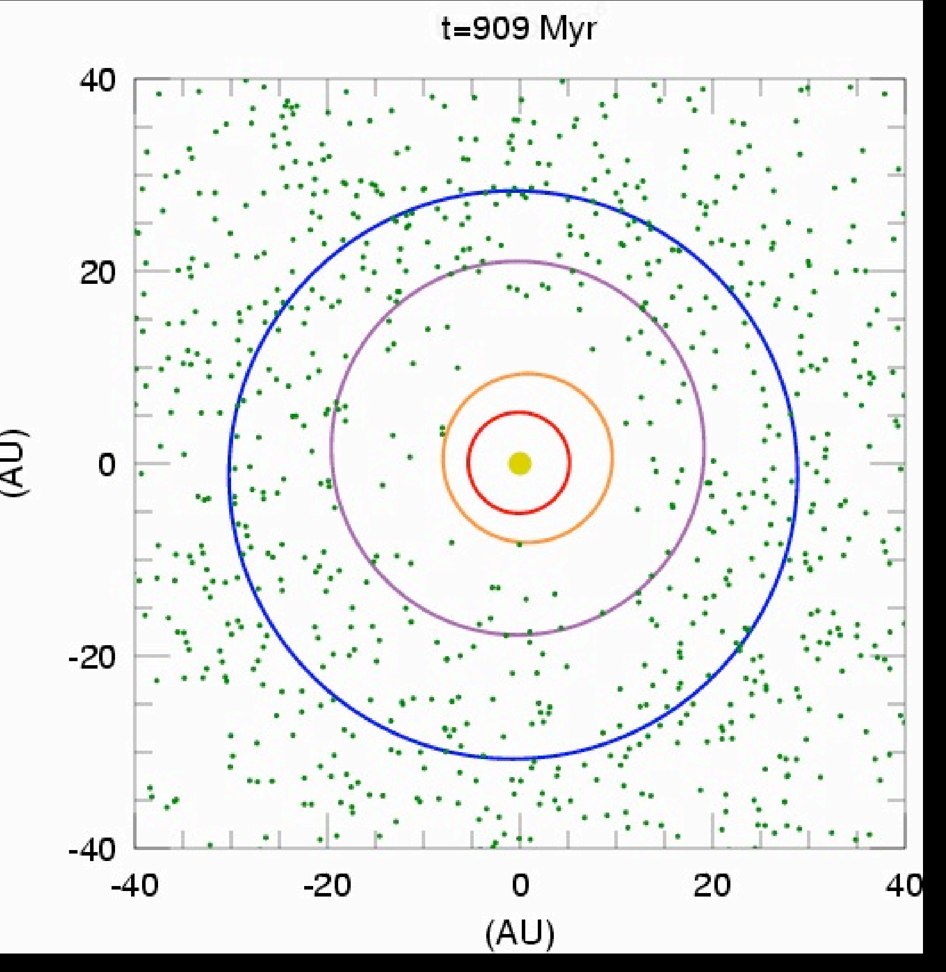
A bit more slowly:

Jupiter

Saturn

Uranus

Neptune

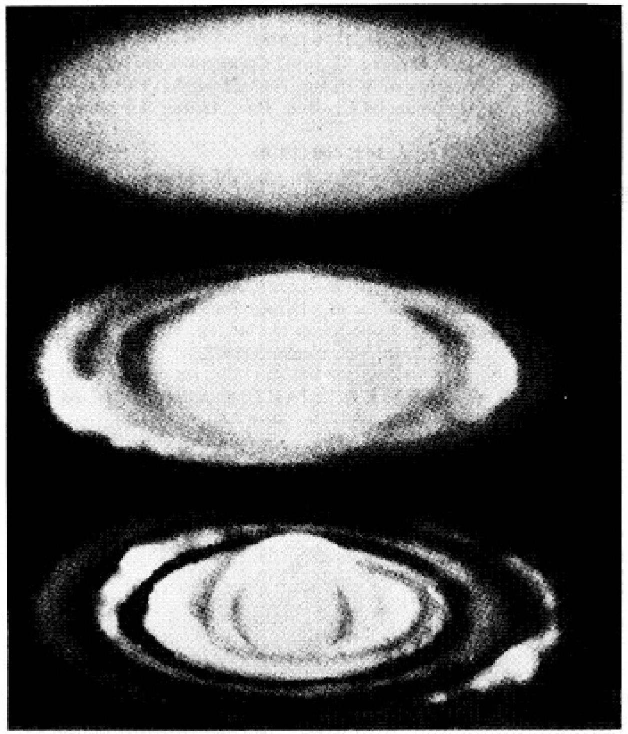


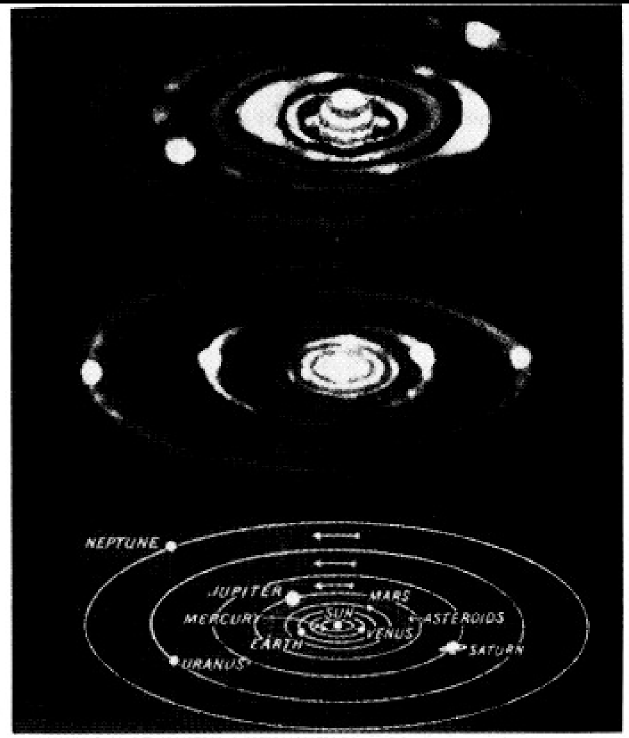
So we believe we have a general understanding of the formation of the Solar System. The planetesimal hypothesis explains the composition of the planets, their relative sizes, the shapes and directions of their orbits, and their satellite systems.

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

Not well....

Andrew Prentice and the "Modern Laplacian Theory"





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.
- 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/
- 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

Sources for images used:

- Background image: from "Astronomical Artwork of William K. Hartmann Pictorial Catalog", 100: Solar System Origin http://www.psi.edu/hartmann/pic-cat/index.html
- Co-planar orbits: generated by "Solar System Live" by John Walker, http://fourmilab.to/solar/solar.html
- Circular orbits: from "The Cosmic Perspective" by Bennett, Donahue, Schneider and Voit, (Benjamin Cummings, 2000), http://dosxx.colorado.edu/Pluto/orbits.jpg
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- Asteroids: from "The Nine Planets: A Multimedia Tour of the Solar System" by Bill Arnett http://seds.lpl.arizona.edu/nineplanets/nineplanets/asteroids.html
- Oort Cloud: from "Explorations: An Introduction to Astronomy!" by Thomas T. Arny, Fig. 7.4 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch07/0704.html
- Jupiter's moons: from NASA Spacelink: Images of Jupiter http://spacelink.nasa.gov/NASA.Projects/Space.Science/Solar.System/Voyager/Images.of.Jupiter/.index.html
- Planetary interiors: from "Planets, Stars and Galaxies" by Todd Adams, www.hep.fsu.edu/~tadams/courses/fall02/ast1002/lectures/Lecture01602.pdf
- The far side of the Moon:from Astronomy: Journey to the Cosmic Frontier by John D. Fix, http://www.mhhe.com/physsci/astronomy/fix/student/chapter9/09f19.html
- Mercury: from The Nine Planets: A Multimedia Tour of the Solar System by Bill Arnetts: Mercury http://seds.lpl.arizona.edu/nineplanets/nineplanets/mercury.html
- Ganymede: from Views of the Solar System by Calvin J. Hamilton http://www.solarviews.com/cap/jup/PIA01666.htm
- Big Bang: from "Faith and Reason": The Big Bang http://www.pbs.org/faithandreason/media/bbang-body.html
- Big Bang nucleosynthesis: redrawn from Formation of the Elements by Kipp Penovich http://aether.lbl.gov/WWW/tour/elements/early/early_a.html
- Planetary nebulae: MyCn18, from Astronomy Picture of the Day 2002 June 15, http://antwrp.gsfc.nasa.gov/apod/ap020615.html

- The Cat's Eye nebula, from Astronomy Picture of the Day 2002 March 24 http://antwrp.gsfc.nasa.gov/apod/ap020324.html
- Supernova 1998aq in NGC 3982: from STARS AND GALAXIES A Hypertext Course by Richard McCray http://cosmos.colorado.edu/cw2/courses/astr1120/text/chapter6/lesson6.html
- Crab Nebula: from Astronomy Picture of the Day 2002 July 14 http://antwrp.gsfc.nasa.gov/apod/ap020714.html
- Periodic table: from Windows on the Universe http://www.windows.ucar.edu/tour/link=/earth/geology/periodic_table.html
- Molecular cloud: Barnard 68, from Astronomy Picture of the Day 2003 February 2 http://antwrp.gsfc.nasa.gov/apod/ap030202.html
- NGC 281: from Astronomy Picture of the Day 2003 April 7 http://antwrp.gsfc.nasa.gov/apod/ap030407.html
- Rotation and collapse: from STARS AND GALAXIES A Hypertext Course by Richard McCray http://cosmos.colorado.edu/cw2/courses/astr1120/text/chapter9/l9S3.htm
- Eagle Nebula: from Astronomy Picture of the Day 2001 August 12 http://antwrp.gsfc.nasa.gov/apod/ap010812.html
- Larger view: CFHT picture, from Astronomy Picture of the Day 2003 February 13 http://antwrp.gsfc.nasa.gov/apod/ap030213.html
- Proplyd: from Astronomy Picture of the Day 1996 October 17, http://antwrp.gsfc.nasa.gov/apod/ap961017.html
- Protostellar disk: from "MIRLIN Star/Planet Formation Page" http://cougar.jpl.nasa.gov/HR4796/anim.html
- Ice line: from Windows to the Universe http://www.windows.ucar.edu/tour/link=/jupiter/atmosphere/J_evolution_3.html
- Fractal aggregates: from Random Walk Visualization by Robert Lipman http://cic.nist.gov/lipman/sciviz/random.html
- Cosmic dust particle: from "A new type of stardust", http://www.psrd.hawaii.edu/Aug03/stardust.html
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- Newly formed Neptune: by Don Dixon, from Scientific American, September 1999 issue http://www.sciam.com/article.cfm?articleID=00050729-BAAC-1C73-9B81809EC588EF21
- Moon origin paintings: from Astronomical Artwork of William K. Hartmann Pictorial Catalog http://www.psi.edu/hartmann/pic-cat/index.html

- Stages in the formation of the Moon: painting by Mark Garlick, http://www.space-art.co.uk/markgarlick/articles/f_articles2.htm?an_moon
- Moon formation animation: from "SwRI, UCSC researchers identify the Moon-forming impact", http://www.swri.edu/press/impact.htm
- Formation of the impactor in the Lagrangian point: From Wikipedia: Giant impact theory, http://en.wikipedia.org/wiki/Giant_impact_theory
- Mercury: from Views of the Solar System by Calvin J. Hamilton http://www.solarviews.com/cap/index/mercury1.html
- Lunar cataclysm: from The Lunar Cataclysm Hypothesis, http://www.lpl.arizona.edu/SIC/impact_cratering/lunar_cataclysm/Lunar_Cataclysm_Page
- Scattering of Uranus and Neptune: from "The Early Dynamical Evolution of the Outer Solar System: A Fairy Tale" by Hal Levinson, http://www.boulder.swri.edu/~hal/talks.html
- Extrasolar image: artist's impression of the Tau Gruis system, by David A. Hardy http://www.hardyart.demon.co.uk/html/p-extra1.html