
Origins: From the Big Bang to Life
Lecture 3
From stars to planets

Last week, we talked about how about how our Milky Way galaxy formed from the merger of smaller galaxies, and how the birth and death of stars enriched the interstellar gas with heavy elements.

Today, we'll talk about where and how our own Sun was born, and how its planets formed around it.

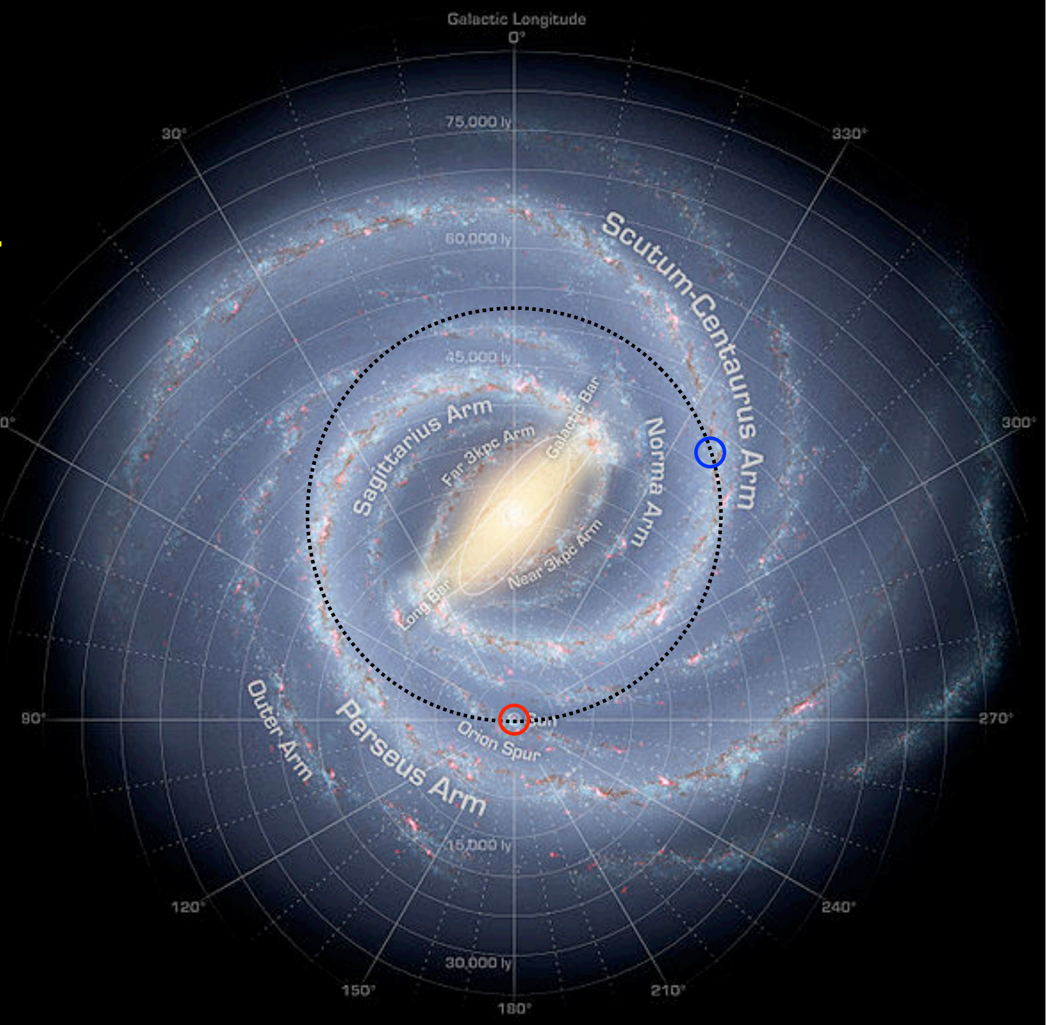
The birth of the Sun

Most stars like the Sun are born in clusters, containing anywhere from a hundred to a million stars. However, such clusters don't last very long, dispersing in only 10 million years and spreading their stars through the Galactic disk.

How then can we find out about the birth region of our Sun?

The young star cluster NGC 7129

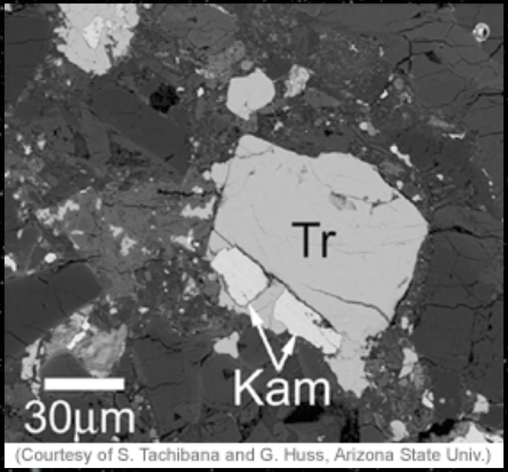
The Sun was born 4.6 billion years ago. It is in an almost circular orbit around the Galactic centre in the plane of the disk, travelling at 235 km/s. This means that since birth it has travelled around the Galaxy some 27 times, travelling more than 3 million light years in that time. The birthplace would have been at about the same Galactic distance in the direction of the Centaurus arm. The Sun's siblings are by now spread all over the Galaxy.



We actually have some clues which allow us to put some surprisingly good constraints on what that birth environment must have been like.

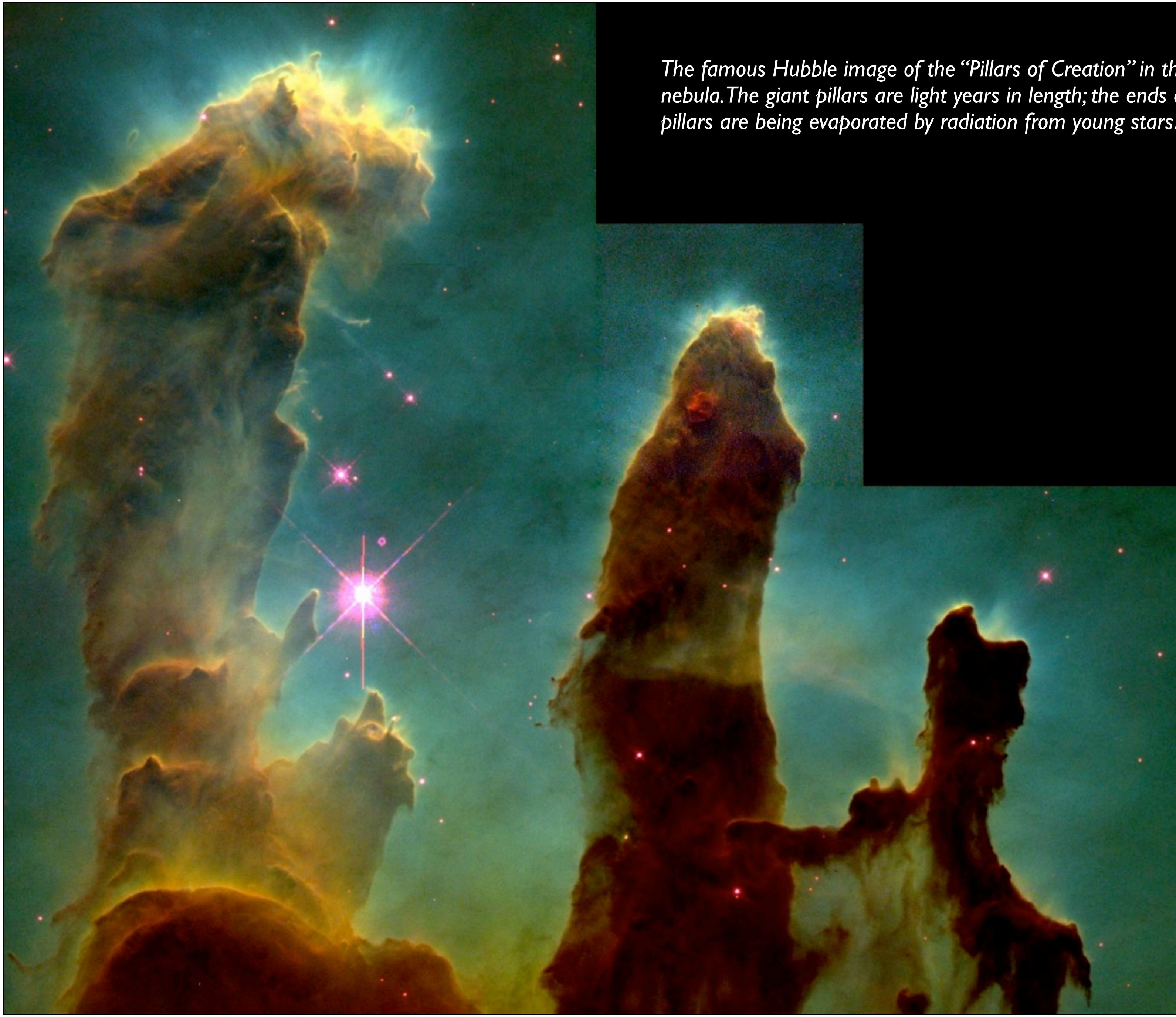
The presence of the decay products of short-lived radioactive isotopes like ^{60}Fe (half-life 1.5 million years) means that the Sun formed in a region where massive stars were ending their lives. A nearby supernova must have seeded the pre-solar nebula with these isotopes, which then condensed into rocks within a few million years.

Polished piece of the meteorite Bishunpur. The mineral labelled "Tr" is troilite (FeS), in which the ratio of ^{60}Fe to ^{56}Fe was measured.



This means the Sun must have been born in a region which was producing both low-mass and high-mass stars, like the Eagle nebula

The Eagle nebula, M16, in hydrogen, oxygen and sulfur.

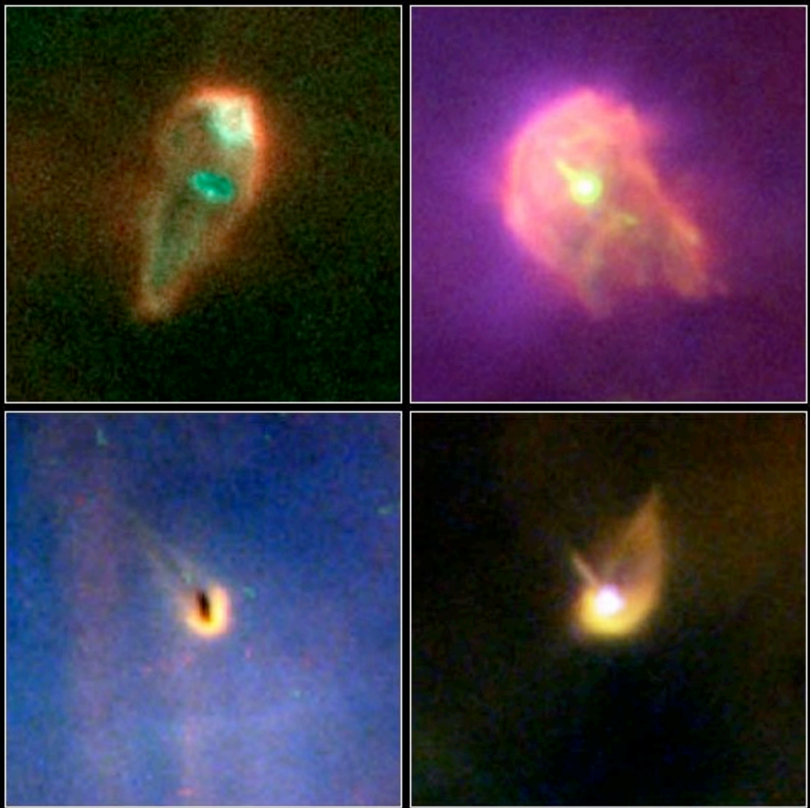


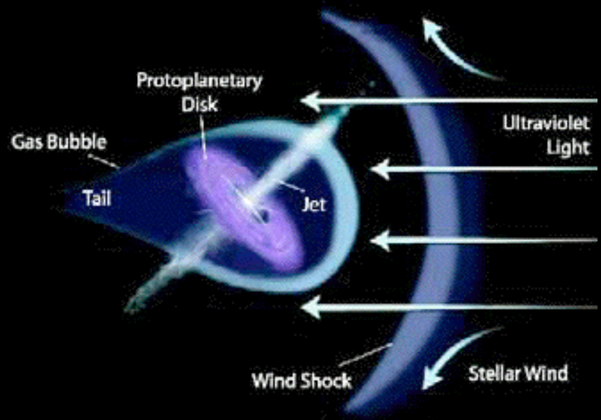
The famous Hubble image of the "Pillars of Creation" in the Eagle nebula. The giant pillars are light years in length; the ends of the pillars are being evaporated by radiation from young stars.

A towering "mountain" of cold hydrogen gas laced with dust is the site of new star formation in the Carina Nebula.The great gas pillar is being eroded by the ultraviolet radiation from the hottest newborn stars in the nebula. The jet is being launched from a newly forming star hidden inside the column.

Bok globule known as the "Caterpillar", in the Carina nebula. These dusty cocoons are sites of star formation.

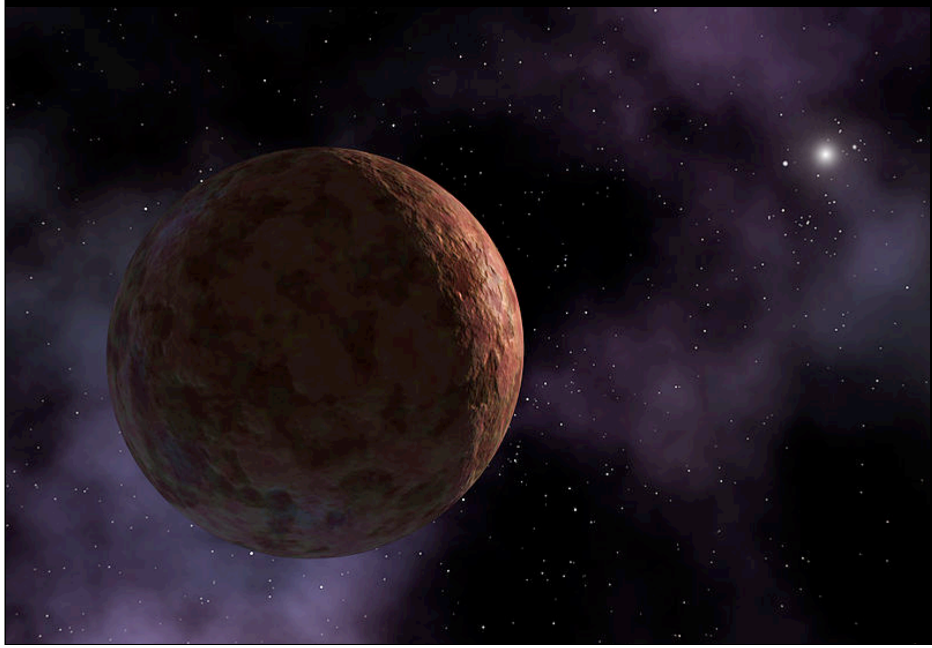
On the other hand, the young Solar System cannot have been *too* close to hot, massive stars, or the disk would have been evaporated away at its outer edge by the fierce ultraviolet radiation.

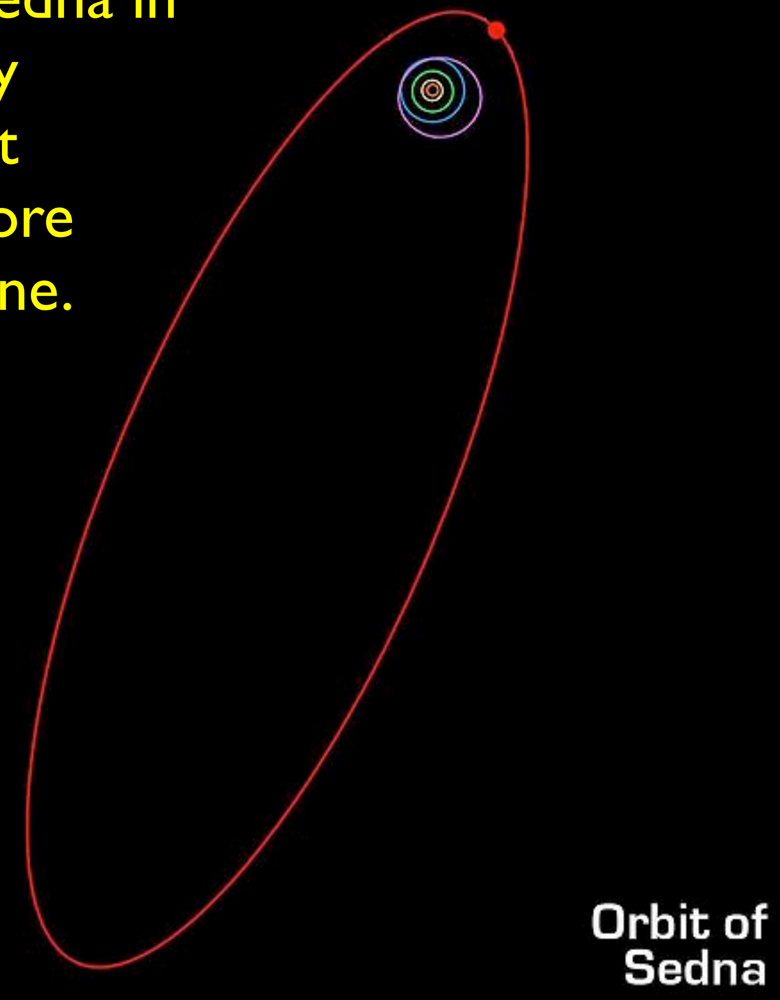




HST images show dust disks around embryonic stars in the Orion Nebula being "blowtorched" by a blistering flood of ultraviolet radiation from the region's brightest star.

The orbits of some of the trans-Neptunian objects discovered in the last decade suggest that the Sun had a close encounter with another star, presumably while it was in its birth cluster. The orbit of Sedna in particular is important: it is highly eccentric (e ~ 0.84) with a closest approach to the Sun of 70 AU, more than twice the distance to Neptune.

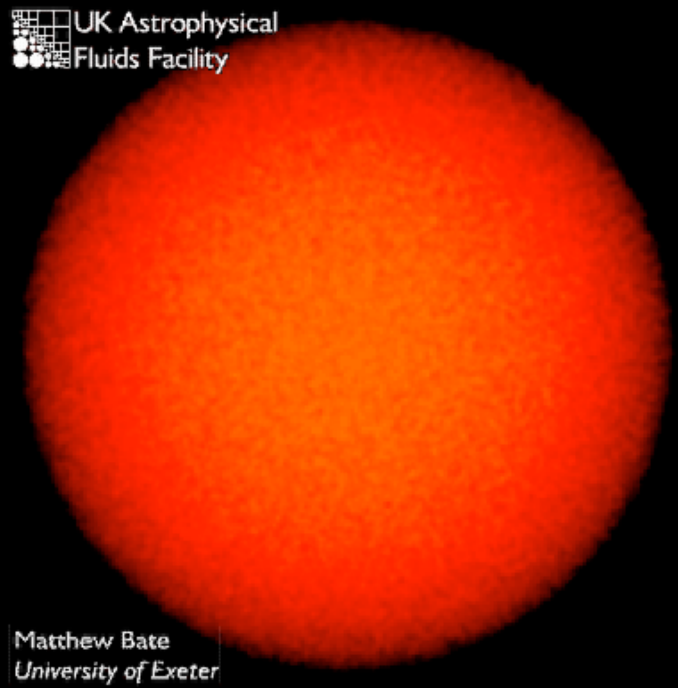




To perturb Sedna's orbit as much as this requires another star to approach within 200–300 AU. A star born in a typical cluster will usually have such a close encounter once in 10 million years.

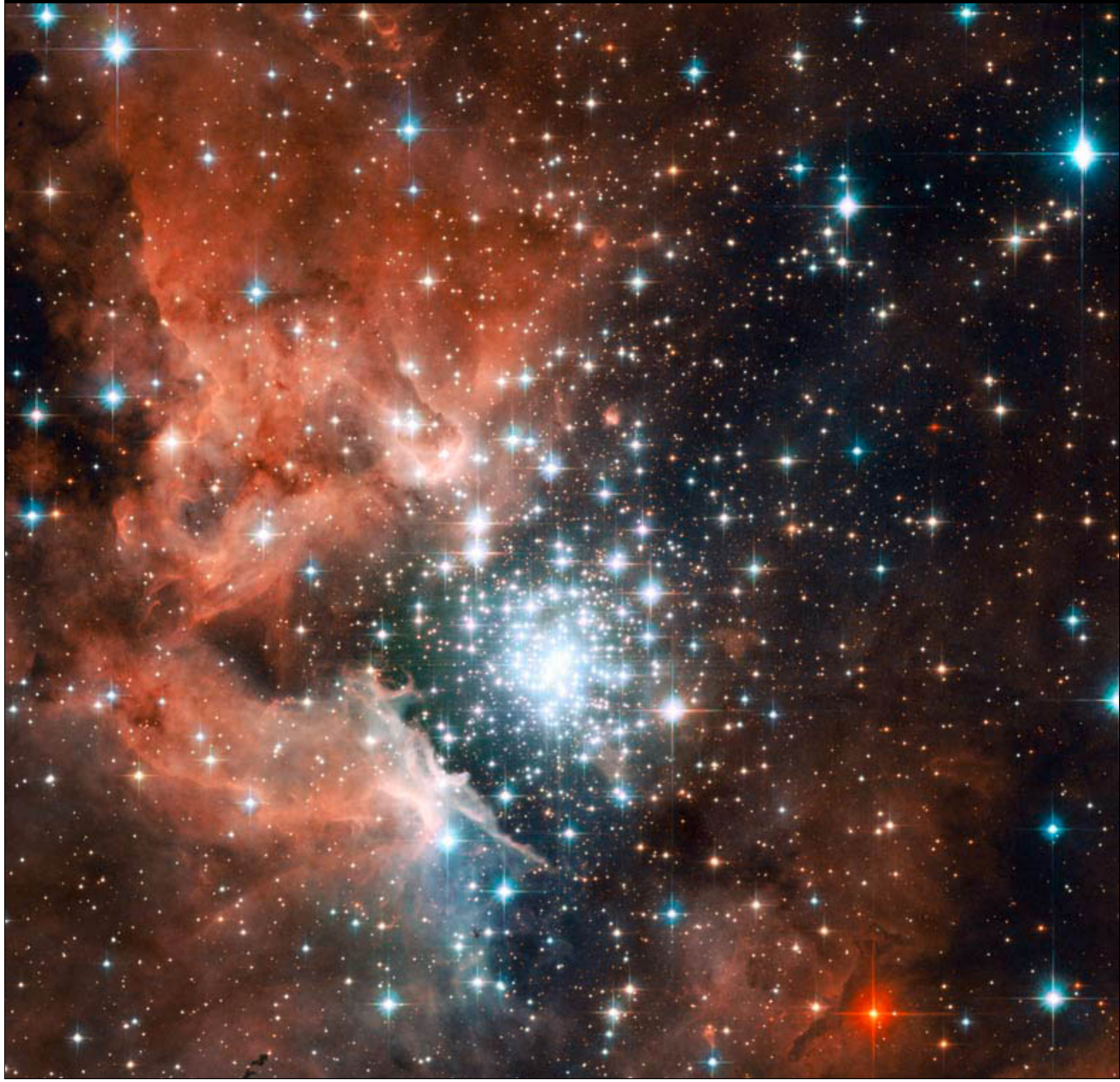
Sedna is like a fossil remnant of the birth of the solar system.

However, there cannot have been too many close encounters, or the proto-planetary disk or the orbits of the planets would have been disrupted.



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)

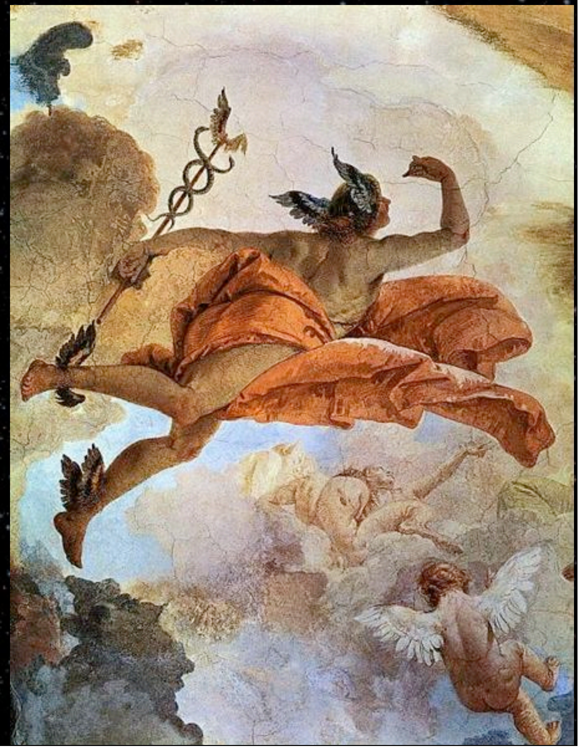
Taken all together, the most likely scenario is that the Sun was born in a cluster of 1000–10,000 stars. Provided the Sun was not in the core of the cluster, the proto-planetary disk would not be truncated too much by encounters with other stars.



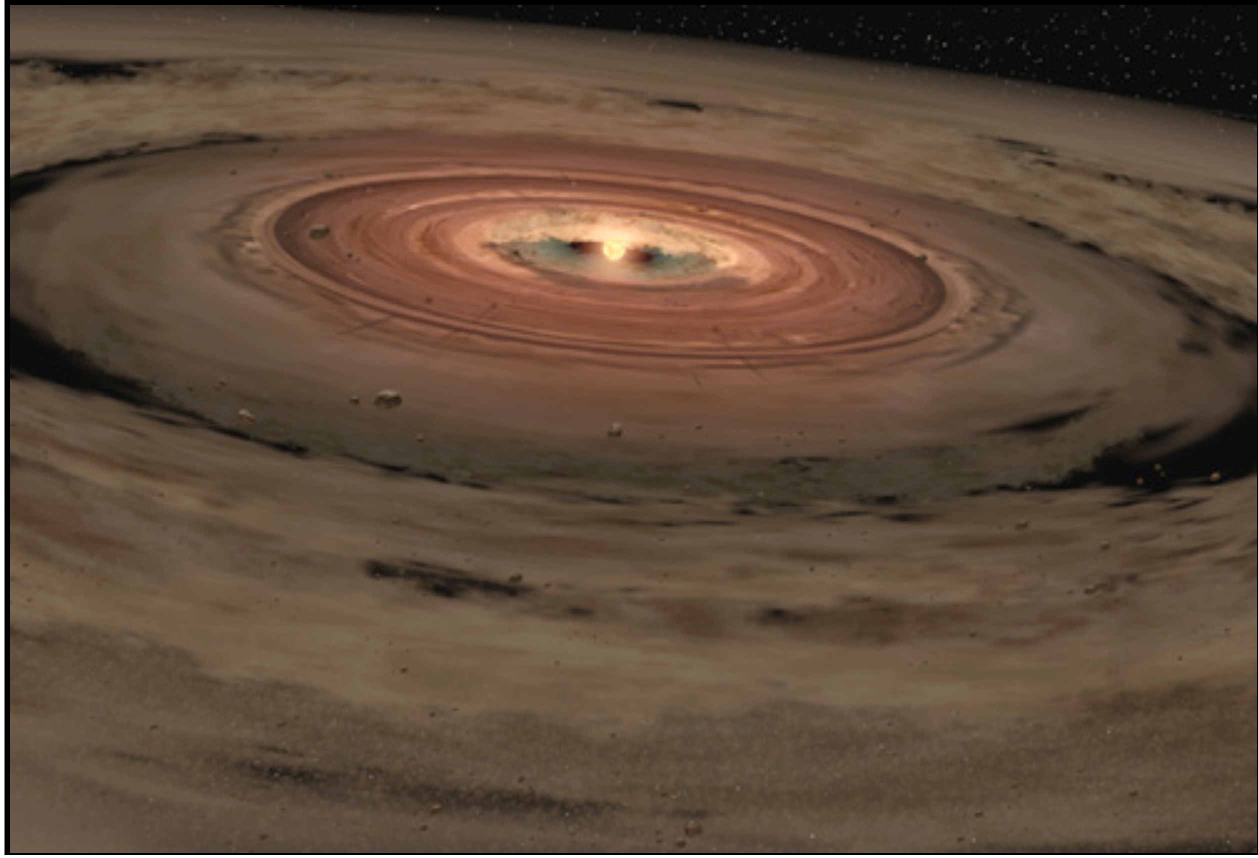
A supernova explosion within a few parsecs then enriched the forming disk with radioactive elements. Some time later, after the giant planets have formed, a close encounter with another star disrupts the orbits of some of the outer Kuiper belt, and soon afterwards the Sun leaves its birth cluster.

It ought to be possible to identify the Sun's siblings, by looking for stars which have the same age, orbit, and chemical composition as the Sun. No siblings have yet been found, though since only very nearby stars have been checked, this is not unexpected.

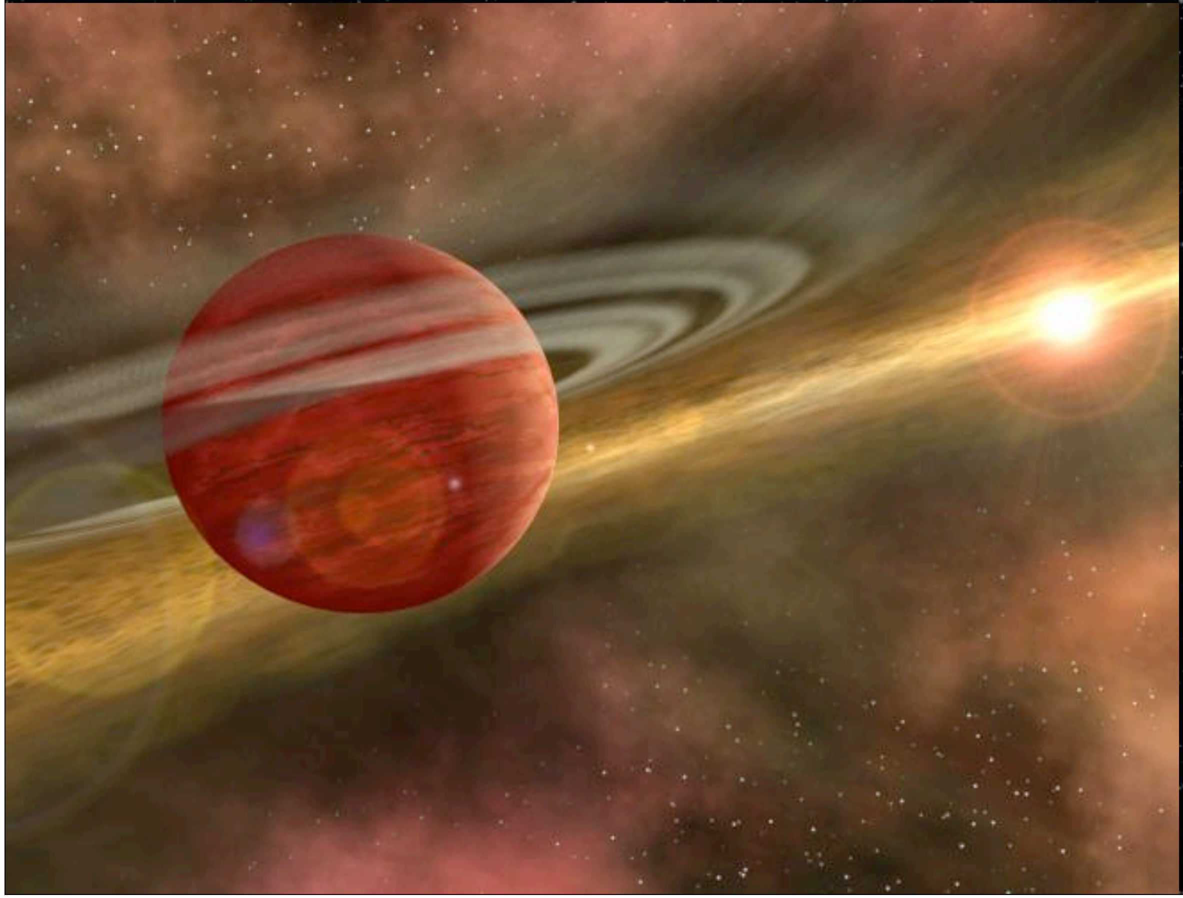
The *Gaia* space astrometry mission, combined with projects like the *HERMES* project on the AAT, should be able to identify the solar siblings.



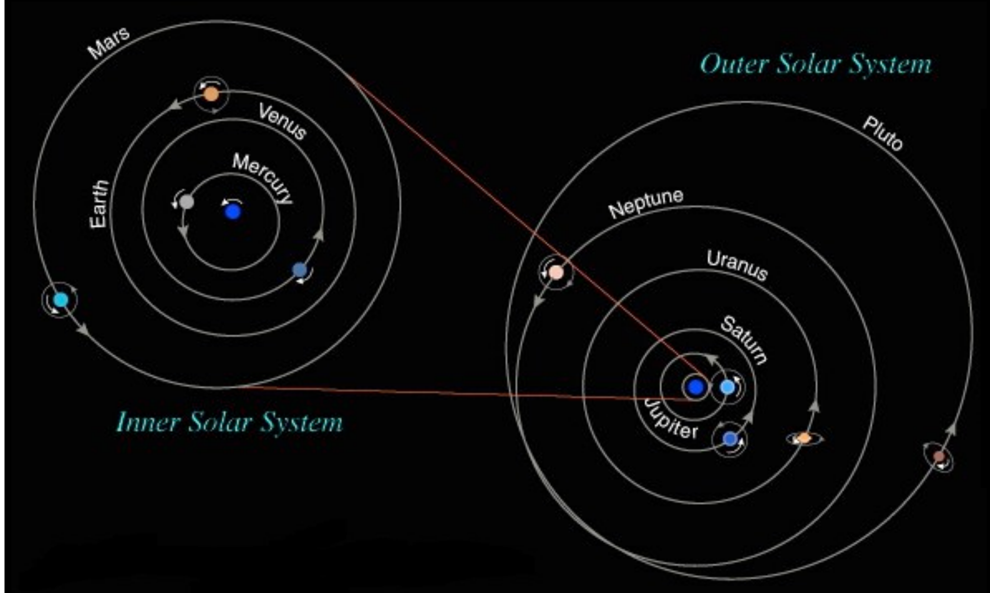
Let's return to the formation of the Sun. Recall that stars like the Sun form from the collapse of a gas cloud. The cloud collapses from the inside out, which increases the temperature of the gas. Eventually the core, which contains most of the mass, reaches the temperature where hydrogen can begin fusing into helium. This produces enough energy to stop the collapse, and marks the birth of the star.

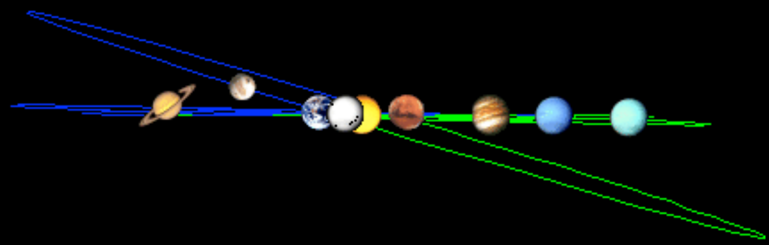


Meanwhile, in the disk planets are starting to form. They need to form quickly, because as the new Sun turns on, its wind will sweep away any gas and dust which has not already been incorporated into planets. This would have taken between 3 and 10 million years, which puts a limit on how long it can have taken planets to form.



The best evidence that the planets formed in a disk is the arrangement of their orbits: all the planets have orbits which are in the same direction, in the same plane, and concentric.

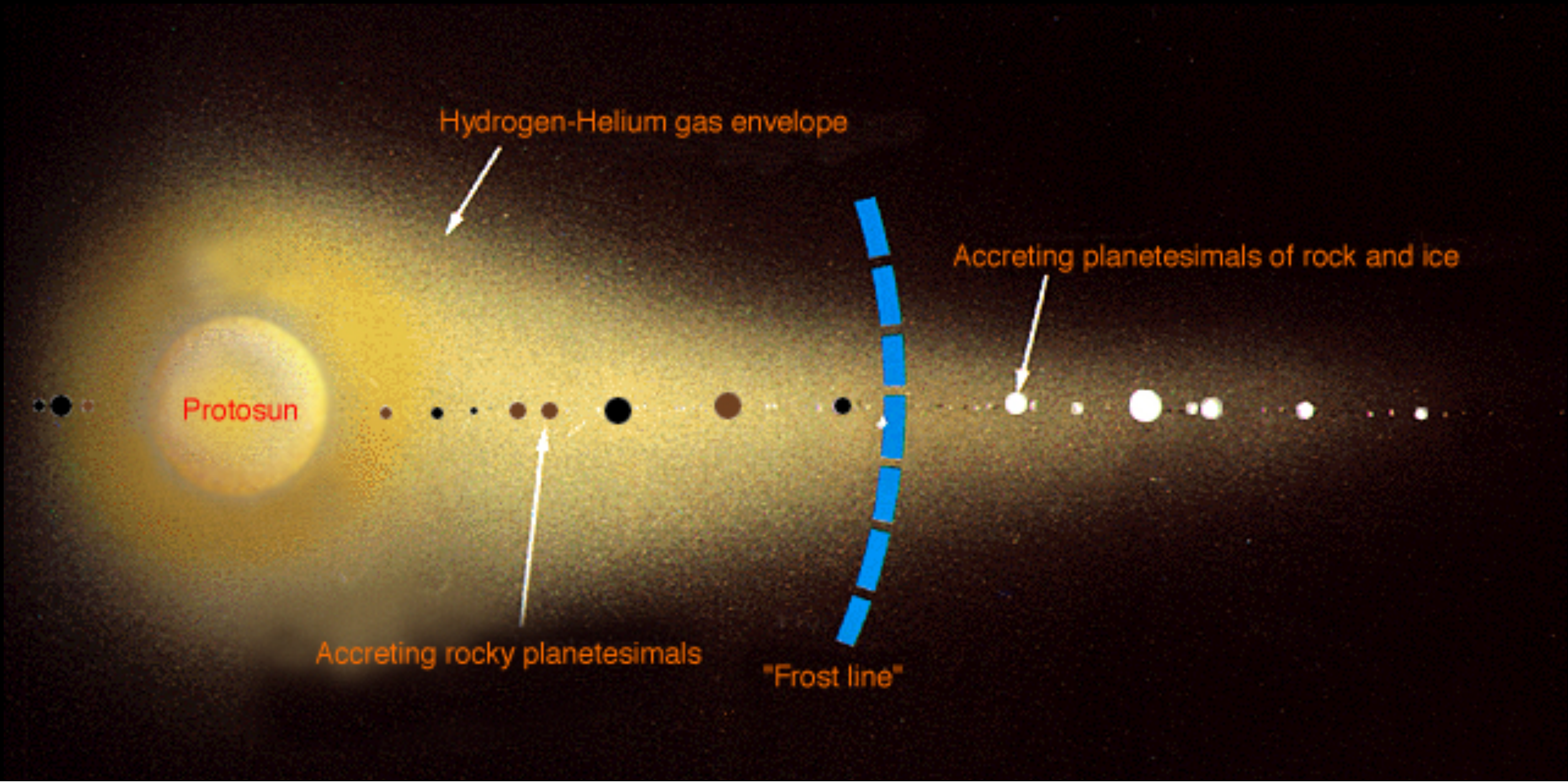




We think that planets form in a four-stage process.

The first phase is *coagulation*. Molecules begin to form in the disk, which has the same composition as the molecular cloud: nearly all gas, with a little dust. The disk is hotter near the centre, close to the protostar, so different materials condense out at different radii.

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

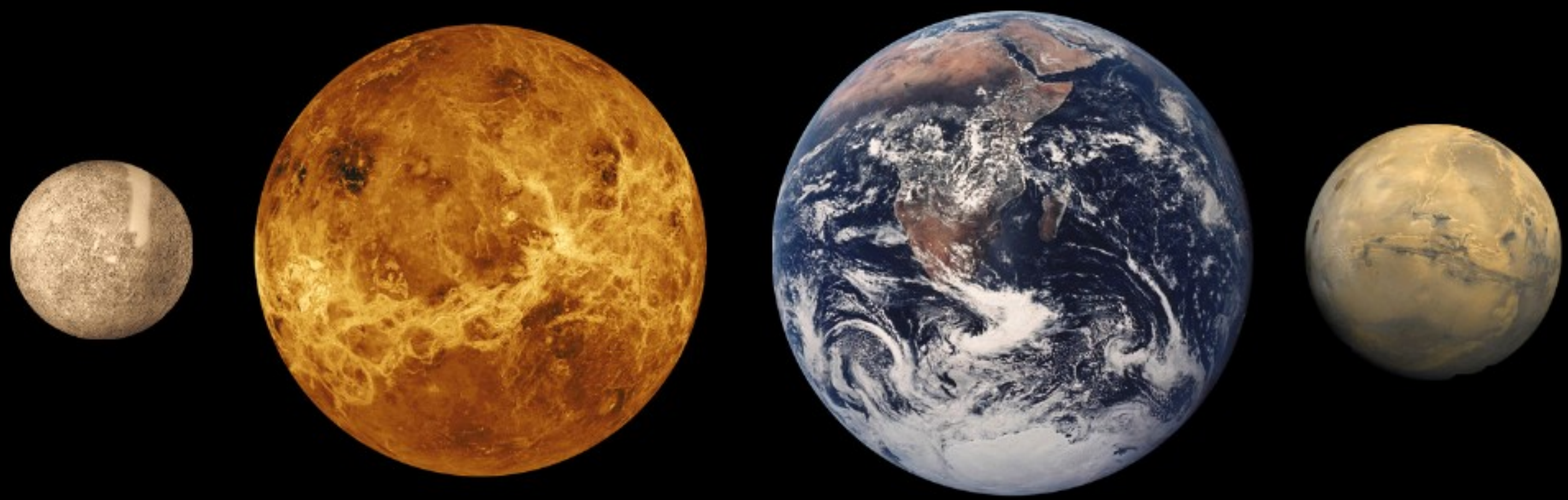


At high temperatures (< 2000K) rocky minerals and metals like iron condense.

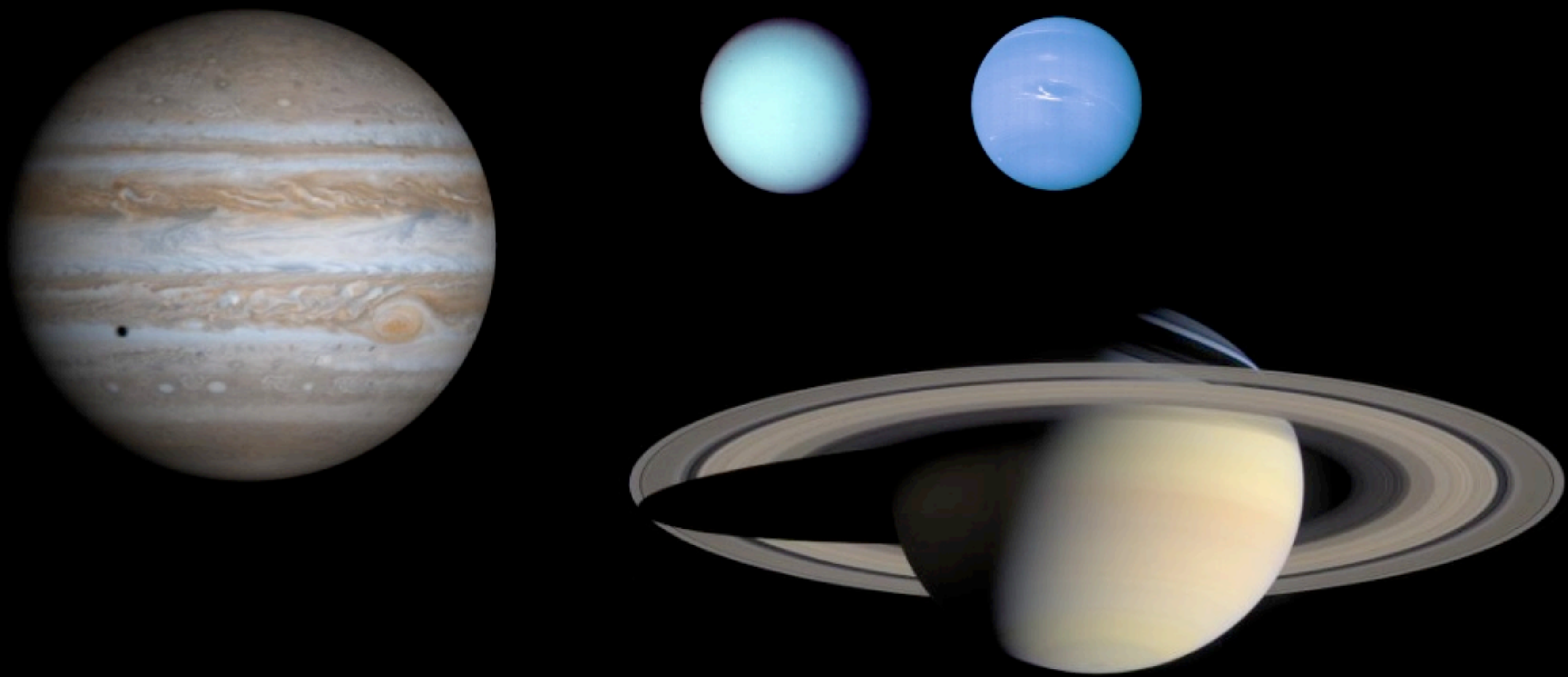
Below about 270 K water ice condenses, as well as ammonia and methane. Water is the most abundant of these ices, and condenses at the highest temperature.

In the Solar System, this line is at about 5 AU, which marks the separation between the terrestrial and the jovian planets.

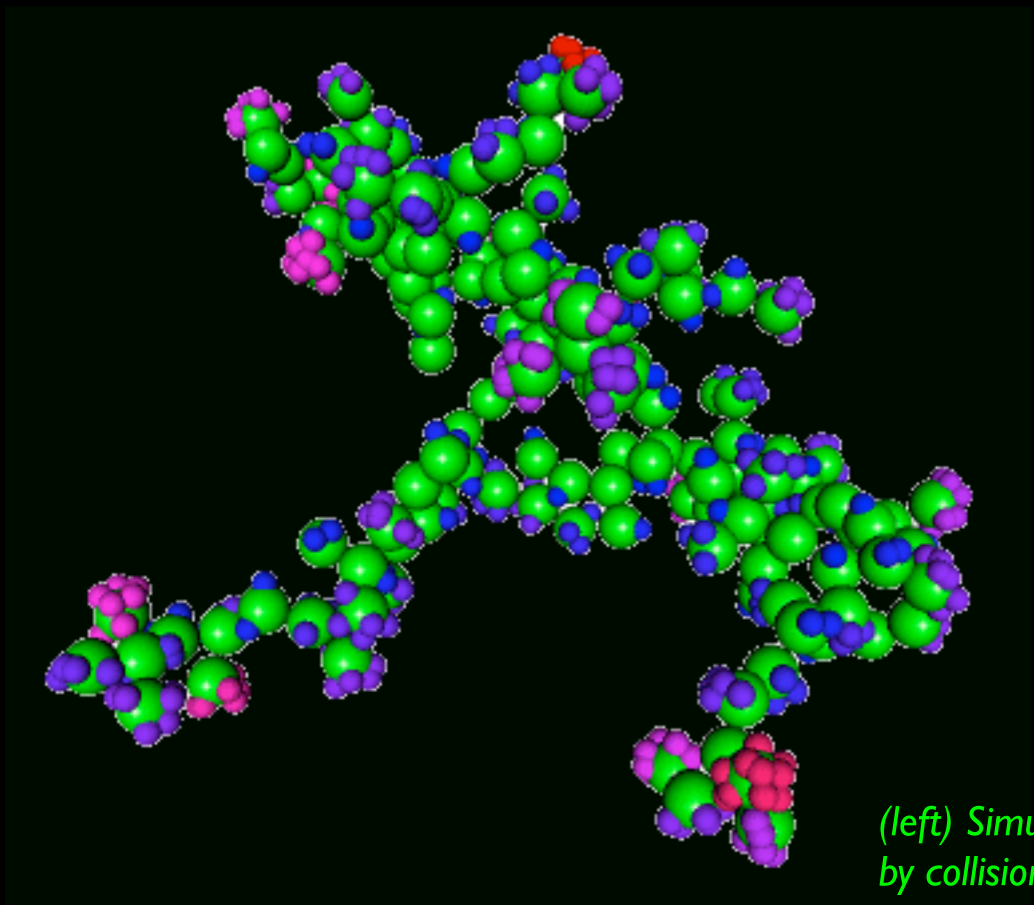
The small rocky terrestrial planets and asteroids lie closer to the Sun. They are characterized by a relatively small size, a relatively high density, and a small number of satellites.

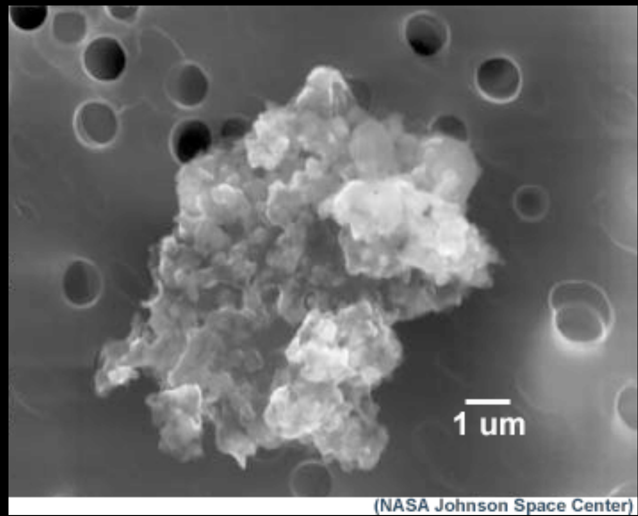


Beyond 5 AU, the giant planets have the opposite characteristics: large sizes, low densities, and many satellites and ring systems.



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

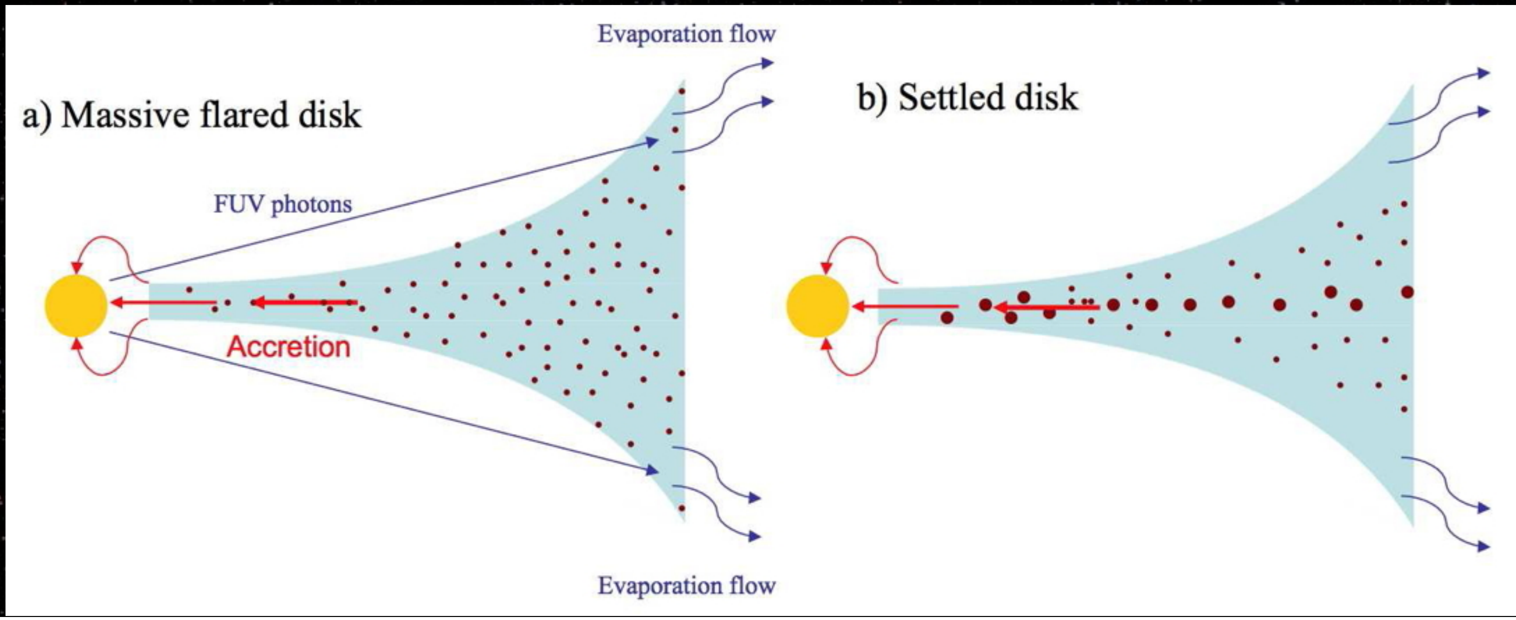




(left) Simulation of a molecular aggregate formed by collisions; (above) Electron microscope image of a typical cosmic dust particle

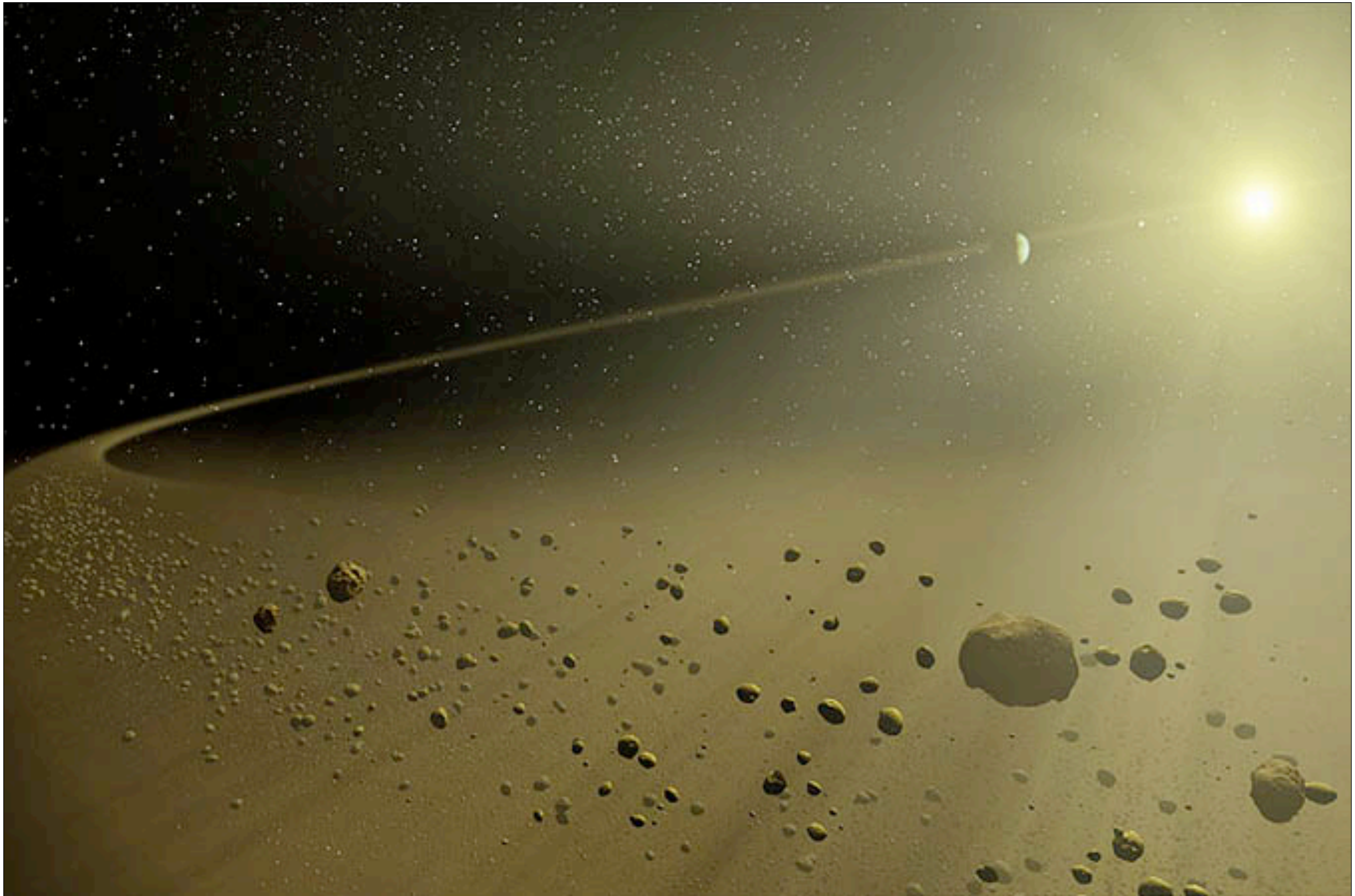
The next phase is the formation of *planetesimals* (bodies up to about 1 km in size) through accretion.

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. Friction with the gas makes them spiral towards the Sun, growing as they do so.



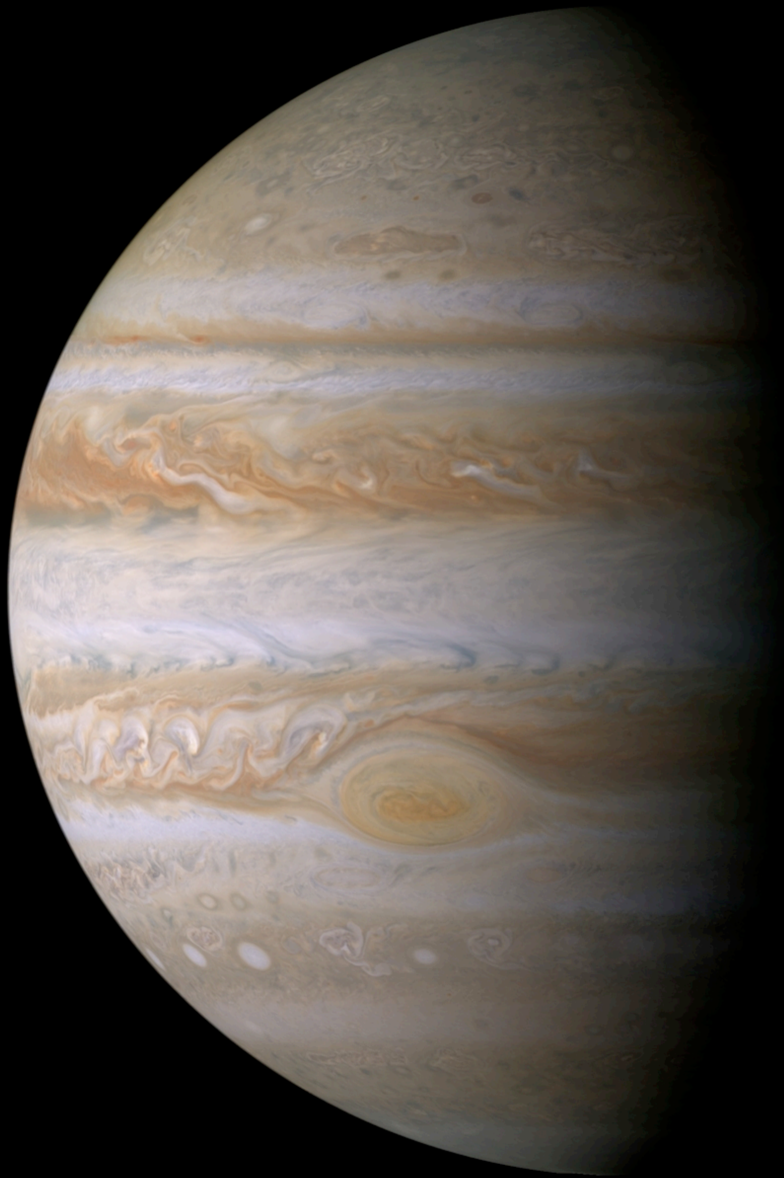
Now gravity becomes important. The larger planetesimals can sweep up more material, so the biggest bodies grow much faster than smaller ones – a process known as *runaway growth*.

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

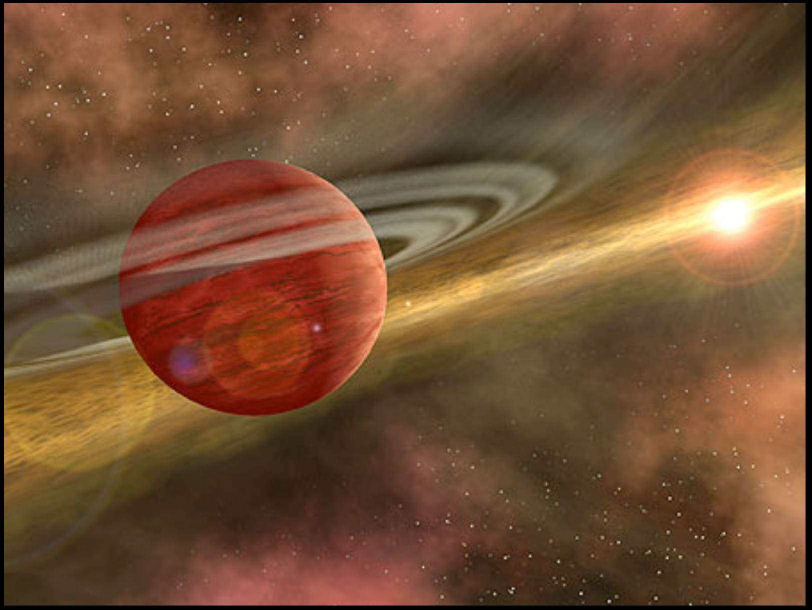


NASA/JPL-Caltech/T. Pyle (SSC)

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.

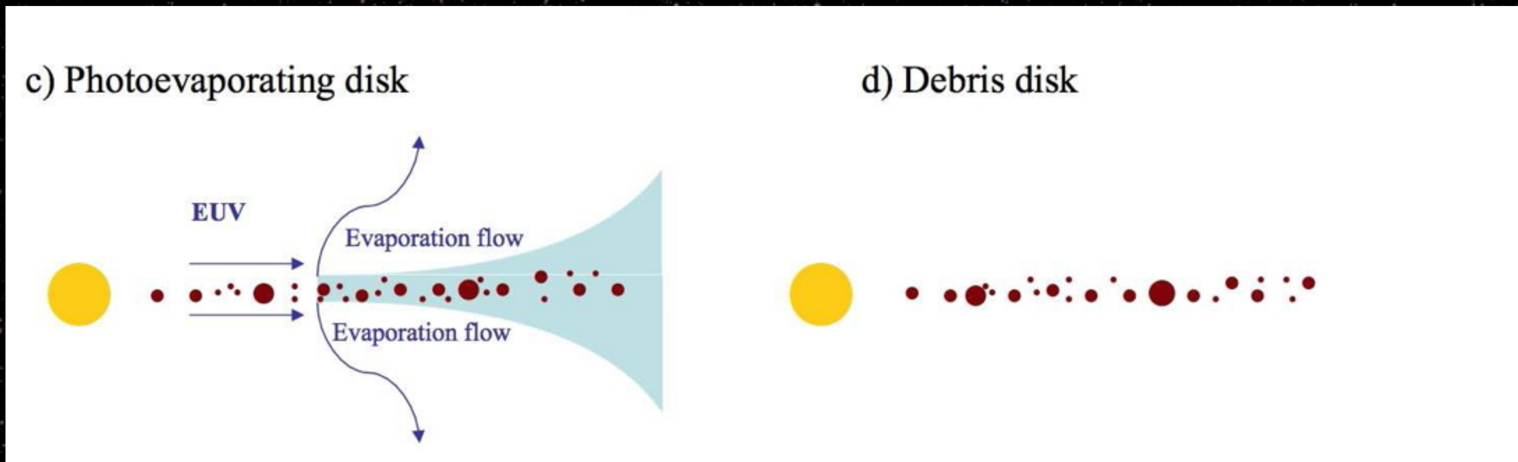


The giant planets were hot when they were accreted. This expanded their atmospheres to vastly larger dimensions than they have today. Gradually they radiated away this heat and shrank, leaving a disk of gas, ice and dust in orbit: a small-scale analogue of the solar nebula. From these disks emerged the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

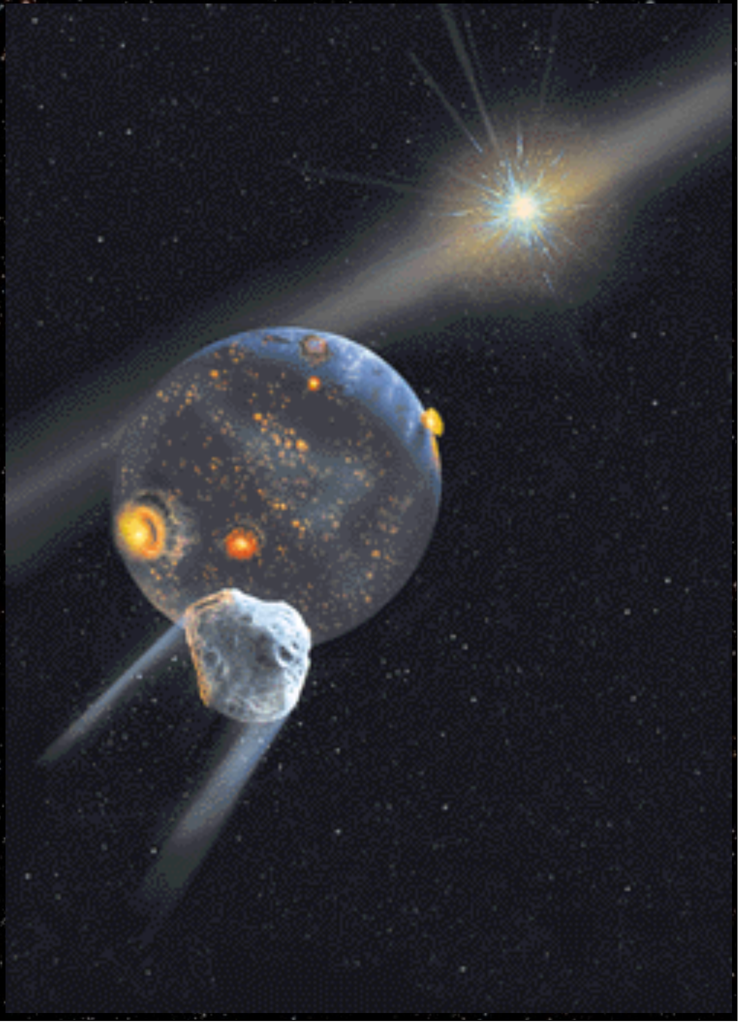


Recent observations of the star T Cha show evidence of a gap in a dusty disk surrounding a young star, which must be due to the presence of a planet sweeping out a gap.

Meanwhile, radiation from the young Sun has started to evaporate the disk. Gas and small dust grains are blown away, leaving only large grains and planetesimals. The gas giants must have completed most of their growth before this happens, though the terrestrial planets will continue to grow via collisions.



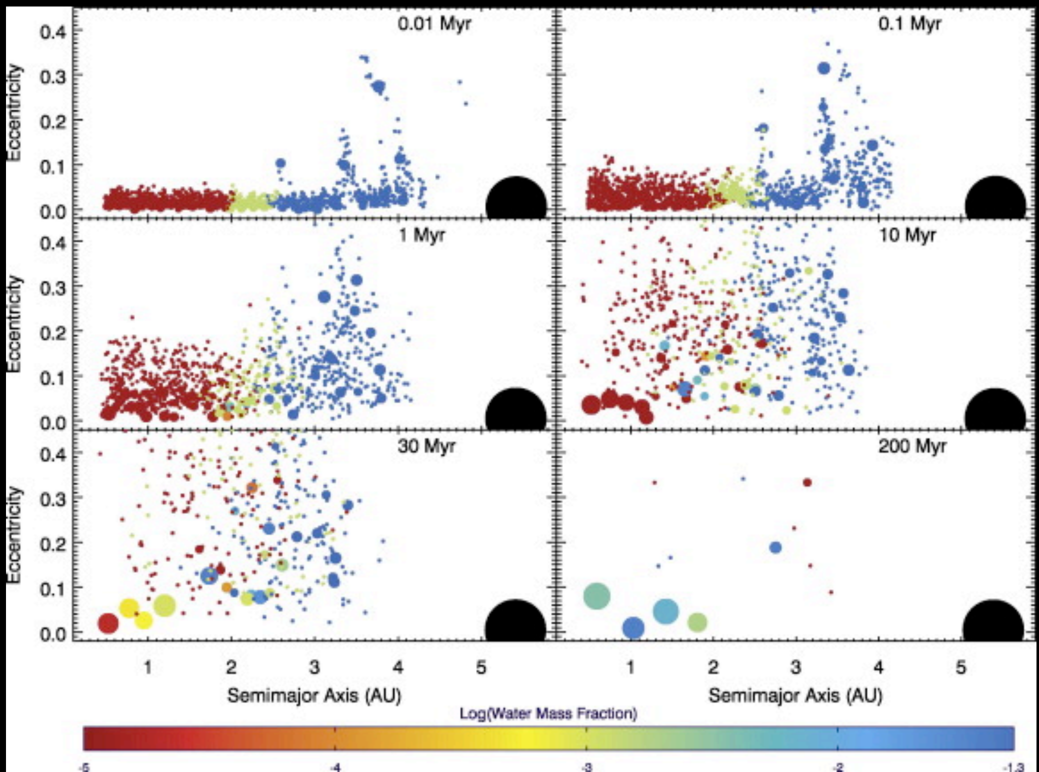
Once the protoplanets have reached the size of the Moon or larger, the final stages of planet formation begins, where the hundred or so protoplanets are reduced to the current handful. The planetary embryos perturb each other into crossing orbits, leading to giant impacts: this has been called the *Era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



Every old surface bears witness to having been battered by impacts of all sizes.

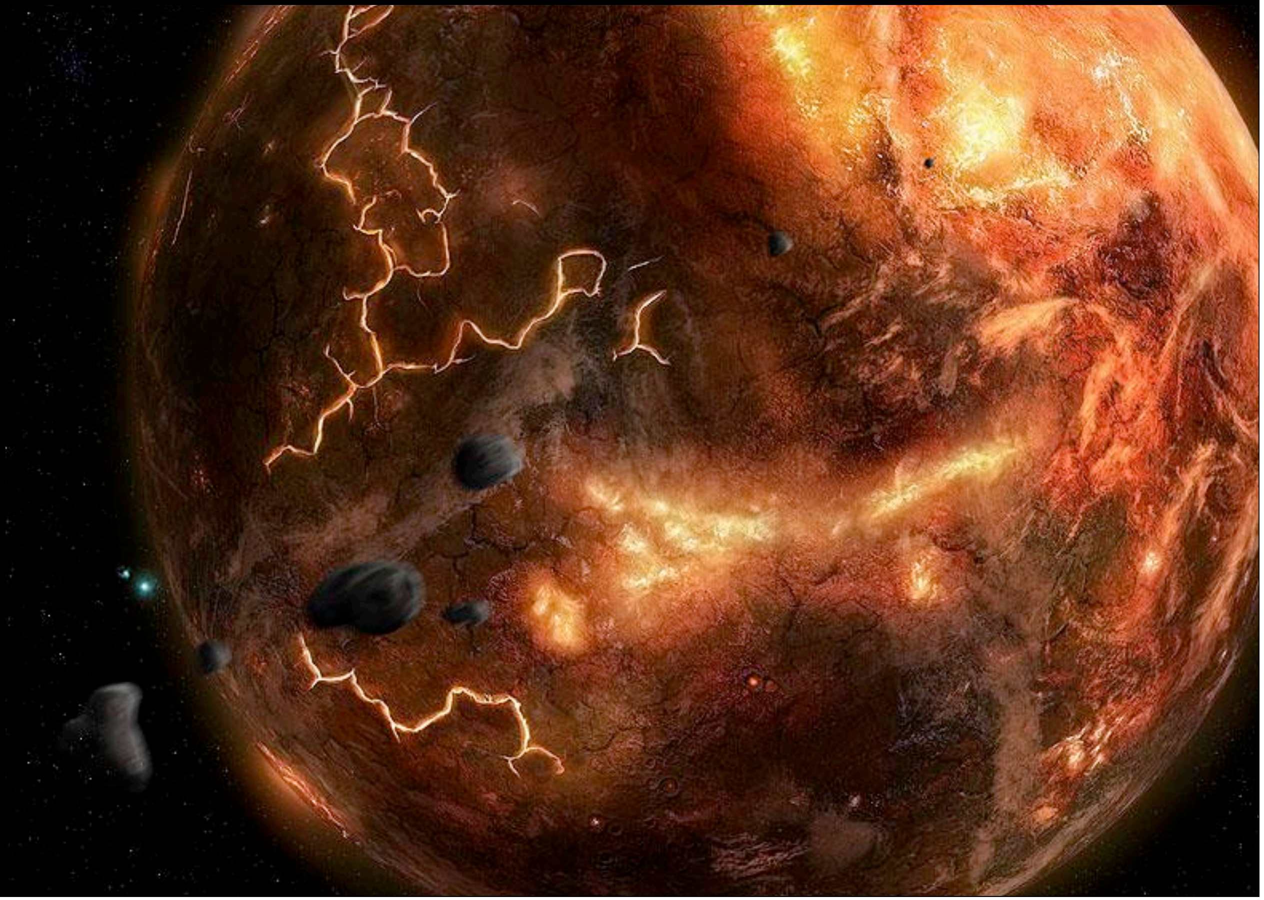

Mercury, Mathilde, Mimas and the Moon

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.

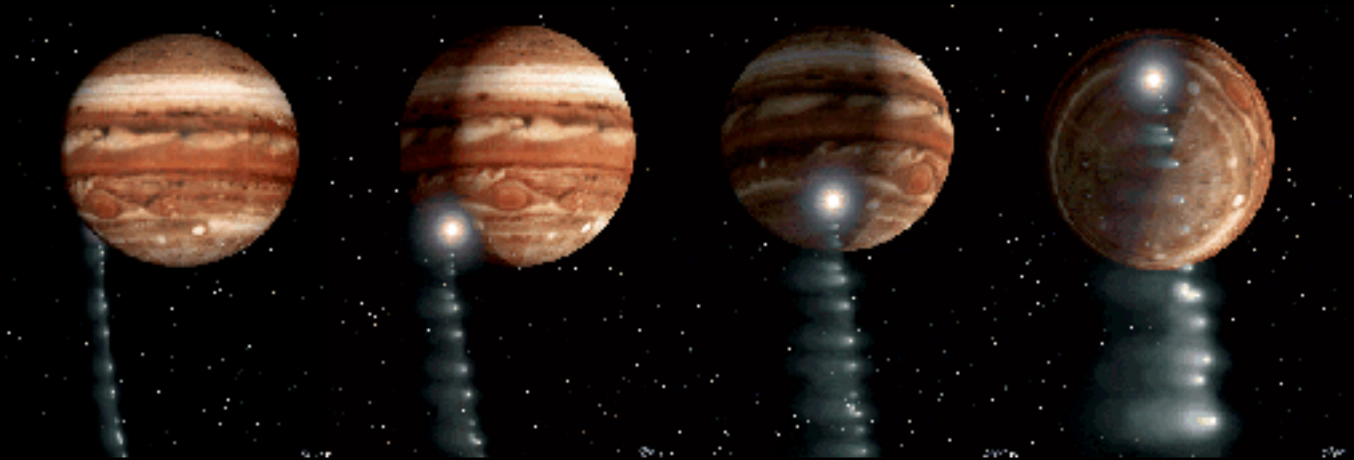
The collisions produced enormous amounts of heat, so the planets would have been molten, with surface temperatures of about 1500°. The surface of the planet melts, with heavier material sinking and lighter material floating: the interior *differentiates*.



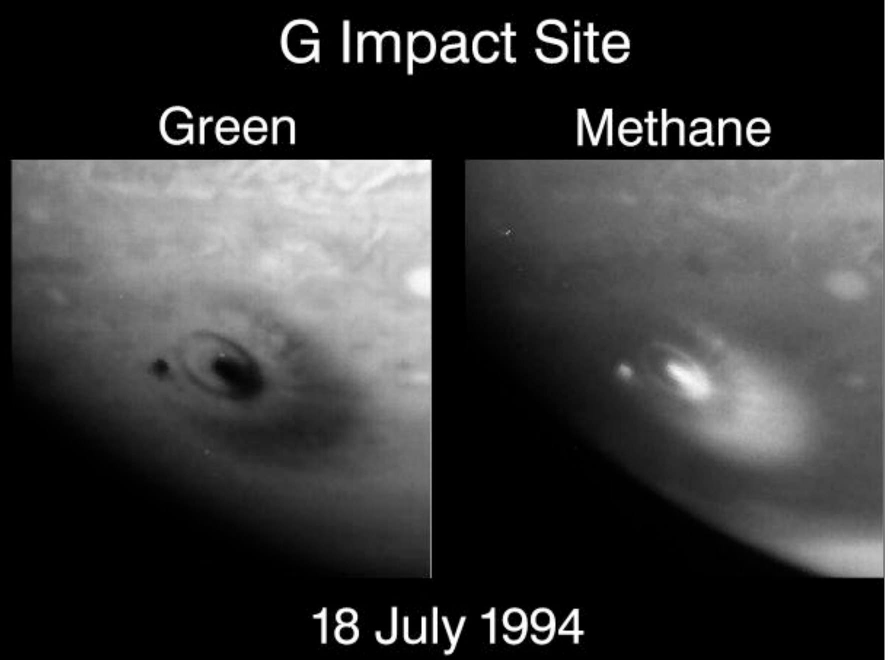
We think that the Earth's moon was formed in this last phase of planet formation, as the result of a collision between the proto-Earth and another planet-sized body. Material from the impact was thrown into orbit and coalesced into the Moon.

The impacting body must have been about the size of Mars; most of the material left in orbit came from the impactor, but all volatiles were lost.

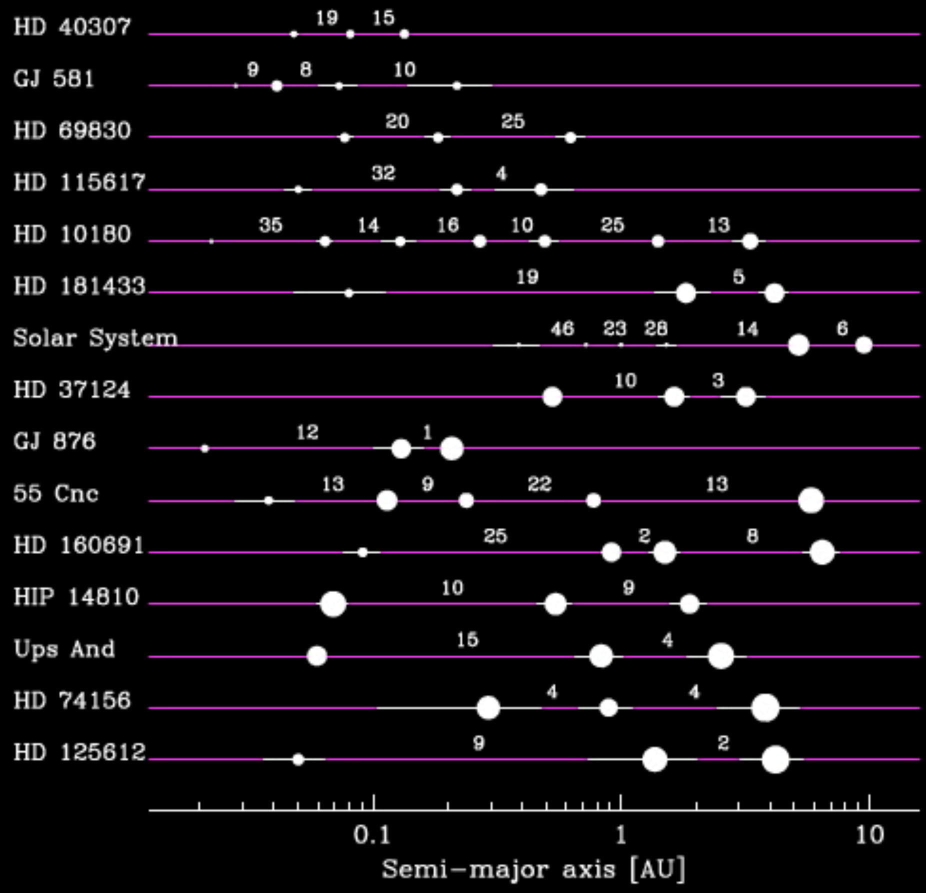
The bombardment of the Solar System has not stopped, only reduced in intensity. In July 2004, we got a chance to see an impact in detail, when Comet Shoemaker-Levy 9 impacted on Jupiter: the very-very-late stages of planetary accretion.



(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.



The end of the Era of Carnage comes when the planets find themselves in stable orbits far enough apart to be stable of billions of years. This naturally leads to well-spaced planets, a pattern also seen in the exoplanet systems with at least three planets.



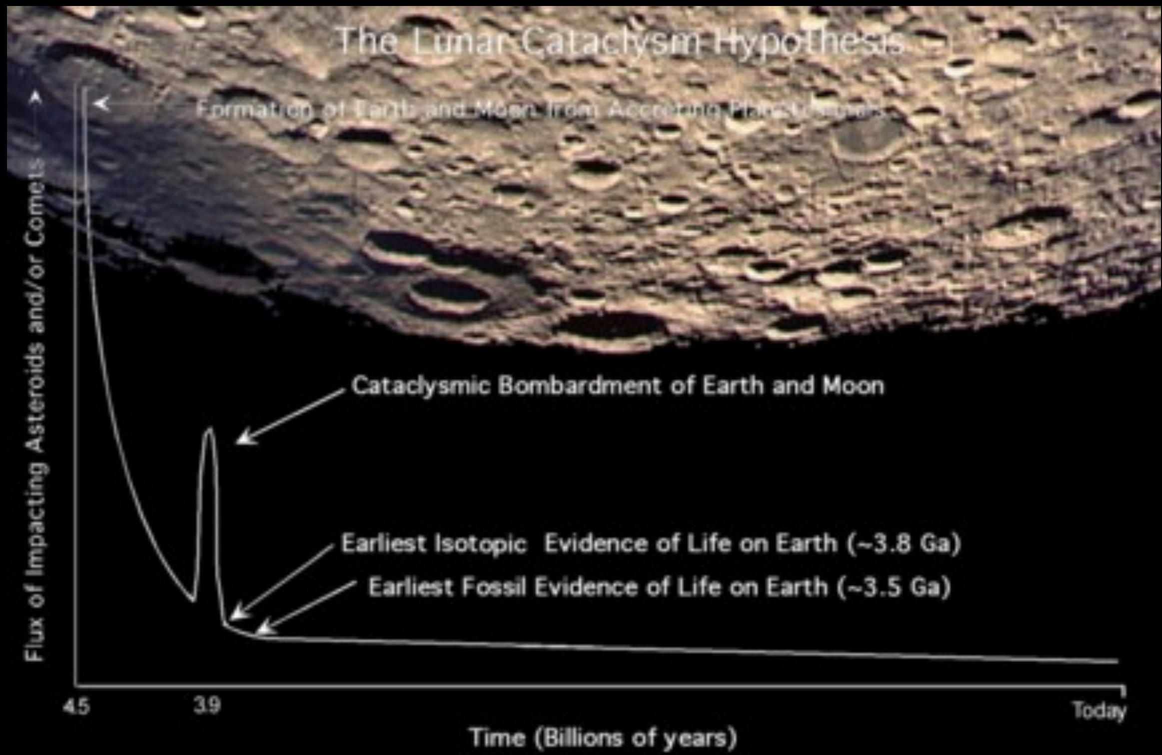
The 15 planetary systems with at least three known planets as of May 2010. From Lovis et al. 2010

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 called the *Kuiper Belt* (more generally *trans-Neptunian objects*).

In the past few years, more and more of these tiny icy bodies have been discovered. We now know that Pluto is just one of the largest of these.

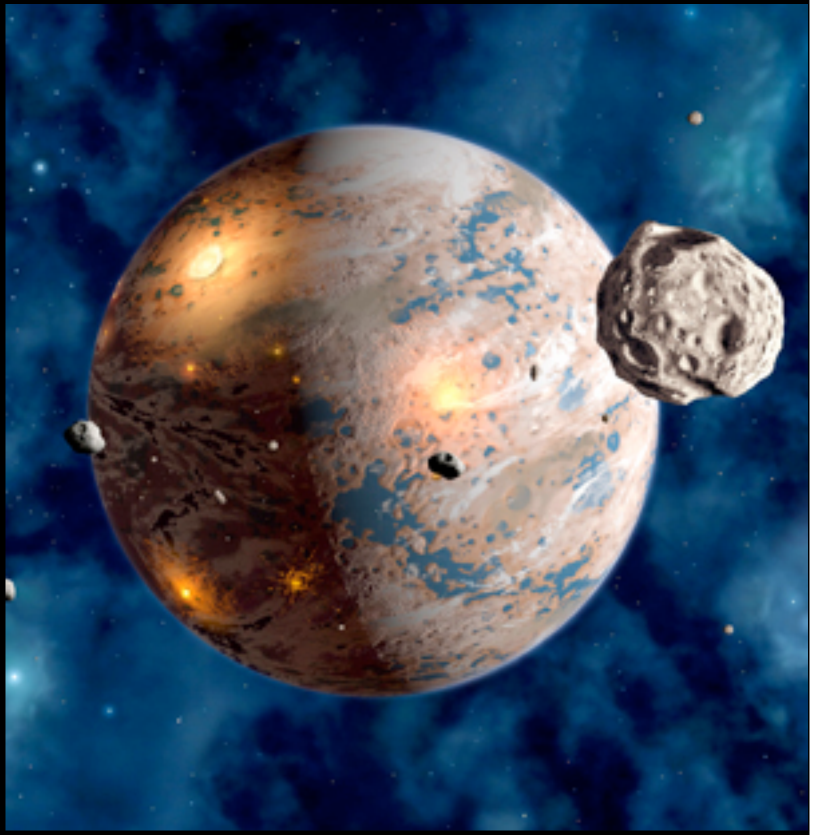
The largest known trans-Neptunian objects

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.



It appears the late heavy bombardment may have been caused by the orbits of Uranus and Neptune going unstable and migrating into the Kuiper Belt, which scattered many of the minor bodies. During this period, the whole inner Solar System was pummeled. The Earth would have been hit by an impact similar to the one that killed the dinosaurs every twenty years.

After the bombardment stopped, the planet cooled. The rocky crust solidified, clouds formed, and rain created the oceans. Now geology begins...



Next week...

... I'll hand over to Tom Hubble, who will tell us all about the Earth.

Further reading

Books:

- Star birth is very well covered in **“The birth of stars and planets”** by John Bally and Bo Reipurth (Cambridge, 2006). It’s written by two experts in the field, is entirely non-technical, and has fantastic illustrations all the way through.

- Mike Brown, the discoverer of many of the trans-Neptunian objects, has a book out called “**How I killed Pluto,** and why it had it coming” (Spiegel & Grau, 2010). It’s a very amusing read, and does a good job of explaining why the discovery of object in the outer Solar System is so important.

- **“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.

Websites:

- The website for the Gaia mission is at http://www.esa.int/science/gaia. See also http://www.astro.utu.fi/~cflynn/galdyn/lecture10.html for a description of what else the Gaia mission will be able to accomplish. The HERMES project is described at http://www.aao.gov.au/HERMES/
- 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/projects/moon/moon.html

Sources for images used:

- Title image: artist's impression of planets around HD 10180, from ESO Science Release 1035 http://www.eso.org/public/news/eso1035/
- Young star cluster NGC 7129: image by Ken Crawford, from APOD 2010 September 4 http://apod.nasa.gov/apod/ap100904.html
- Milky Way: from http://en.wikipedia.org/wiki/File:236084main_MilkyWay-full-annotated.jpg. The calculation about the number of orbits the Sun has made comes from Simon Portegies Zwart, "The Lost Siblings of the Sun", ApJLett 696 L13 (2009), http://adsabs.harvard.edu/abs/2009ApJ...696L..13P
- Meteorite section: from "Triggering the Formation of the Solar System" by G. Jeffrey Taylor, Planetary Science Research Discoveries, May 2003, http://www.psrd.hawaii.edu/May03/SolarSystemTrigger.html
- Eagle nebula: image by T.A. Rector & B.A. Wolpa, NOAO/AURA, from APOD 2009 February 8 http://apod.nasa.gov/apod/ap090208.html
- Pillars of Creation: from APOD 2010 March 28 http://apod.nasa.gov/apod/ap100328.html
- Carina nebula: HubbleSite news release STScI-2007-16, http://hubblesite.org/newscenter/archive/releases/2007/16/
- Proplyds in Orion: from Hubblesite http://hubblesite.org/newscenter/newsdesk/archive/releases/2001/13/
- Sedna: from Wikipedia http://en.wikipedia.org/wiki/90377_Sedna
- Simulation of molecular cloud collapse: from Matthew Bate's Animations, http://www.astro.ex.ac.uk/people/mbate/animations.html
- NGC 3603: from http://hubblesite.org/gallery/album/entire/pr2007034b/
- Young solar system: from http://www.spitzer.caltech.edu/images/1966-ssc2008-19a-Epsilon-Eridani-Double-the-Rubble
- GAIA: from http://www.esa.int/export/esaSC/120377_index_0_m.html; Hermes from http://www.aao.gov.au/HERMES/
- Protoplanetary disk: image by David Darling, from http://www.ast.obs-mip.fr/users/donati/press/fuori_eng.html
- Gas giant forming in disk: from http://photojournal.jpl.nasa.gov/catalog/PIA05988
- 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
- Co-planar orbits: generated by http://www.fourmilab.ch/cgi-bin/Solar for 2011-03-23, heliocentric latitude 0°, longitude 25°. Circular orbits: from "The Cosmic Perspective" by Bennett, Donahue, Schneider and Voit, (Benjamin Cummings, 2000), http://dosxx.colorado.edu/Pluto/orbits.jpg

- Terrestrial planets: Wikipedia http://en.wikipedia.org/wiki/Terrestrial_planet; Jovian planets: from Astronomy Notes by Nick Strobel: Determining Planet Properties http://www.astronomynotes.com/solarsys/s2.htm
- Disk settling: from Williams & Cieza, "Protoplanetary disks and their evolution", Fig. 6, http://adsabs.harvard.edu/abs/2011arXiv1103.0556W
- Belt of dust: from http://www.spitzer.caltech.edu/images/2405-sig05-027-Belt-of-Dust
- Cassini Jupiter portrait: from http://photojournal.jpl.nasa.gov/catalog/pia04866
- Newly formed Neptune: by Don Dixon, from Scientific American, September 1999 issue http://www.sciam.com/article.cfm?articleID=00050729-BAAC-1C73-9B81809EC588EF21
- Planet in T Cha's dust belt: from http://www.eso.org/public/news/eso1106/
- Debris disk: from Williams & Cieza, "Protoplanetary disks and their evolution", Fig. 6, http://adsabs.harvard.edu/abs/2011arXiv1103.0556W
- Mercury: from http://messenger.jhuapl.edu/gallery/sciencePhotos/image.php?page=2&gallery_id=2&image_id=214
- Callisto: http://photojournal.jpl.nasa.gov/catalog/PIA03456
- Mimas: http://photojournal.jpl.nasa.gov/catalog/PIA06258
- Moon: from Galileo http://photojournal.jpl.nasa.gov/catalog/PIA00405
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