Astrophysical Objects

Planet Formation

An introduction to modern Astrophysics chapter 23

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Planetary system formation

The question of how Earth and the Solar System formed has intrigued humans in all cultures for thousands of years.

Some early ideas:

- In 1778 it was proposed that a giant comet collided with the Sun, causing the ejection of a disk of material that ultimately condensed to form the planets.
- Competing tidal theories argued that a close encounter with a passing star ripped material from the Sun.

Unfortunately, each of these theories suffers from a number of difficulties, **including inadequate energy, composition differences between the planets and the Sun, and the sheer improbability of such an event.**

- Another class of theories suggested that the Sun accreted planetary material from interstellar space, taking care of the difficulty of composition differences between the Sun and the planets, but not those among the planets themselves.
- Yet another class of theories, the basis of today's models, argue for the **simultaneous formation of the Sun and the planets** out of the same nebula. Among the early proponents of these so-called nebular theories.

Accretion disks and Debris disks

There is a **wide range of observational data** related to the formation and pre-main-sequence evolution of stars.

It is clear from both observational and theoretical studies that stars form from the gravitational collapse of clouds of gas and dust. If a collapsing cloud contains any **angular momentum** at all, the collapse leads to the formation of an **accretion disk around the growing protostar.**

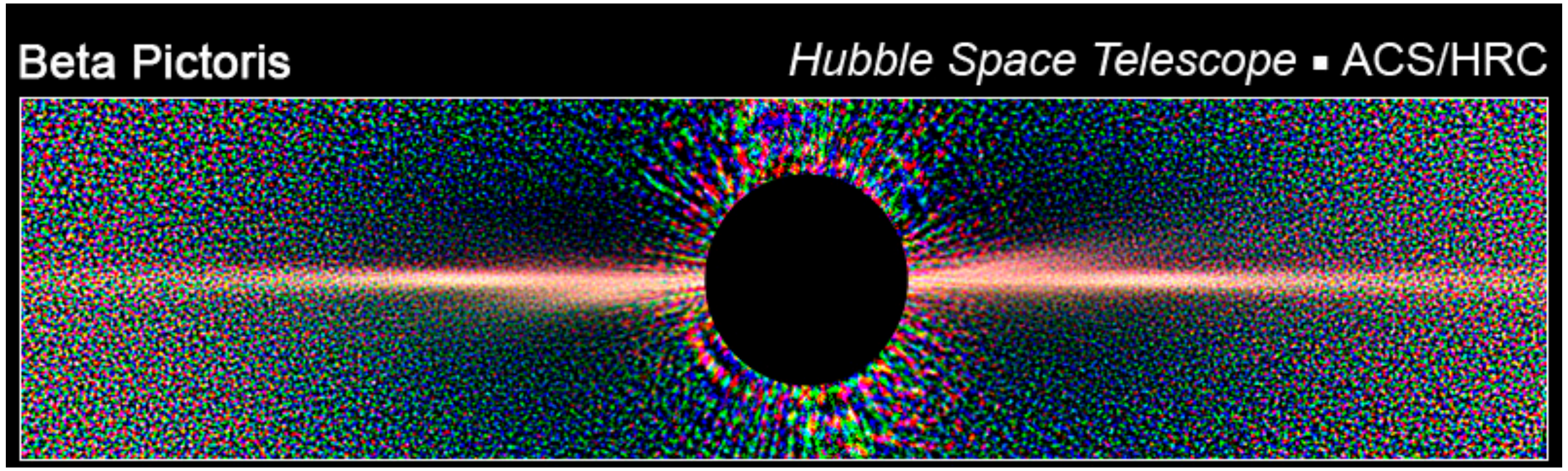
As a direct observational consequence of the conservation of angular momentum, numerous examples of accretion disk formation have been discovered and studied in detail, including the many **proplyds** observed in the Orion Nebula and elsewhere and the **jets and Herbig–Haro objects** associated with young protostars. In addition, there is growing evidence that **clumps of material exist in these disks.**

There is also substantial evidence of **debris disks** around older stars, such as **β Pictoris.** The implication is that **material is left over in the disk after the star has finished forming**. Debris disks **may be the extrasolar analogs to the asteroid belt and the Kuiper belt.**

What is the Kuiper belt?

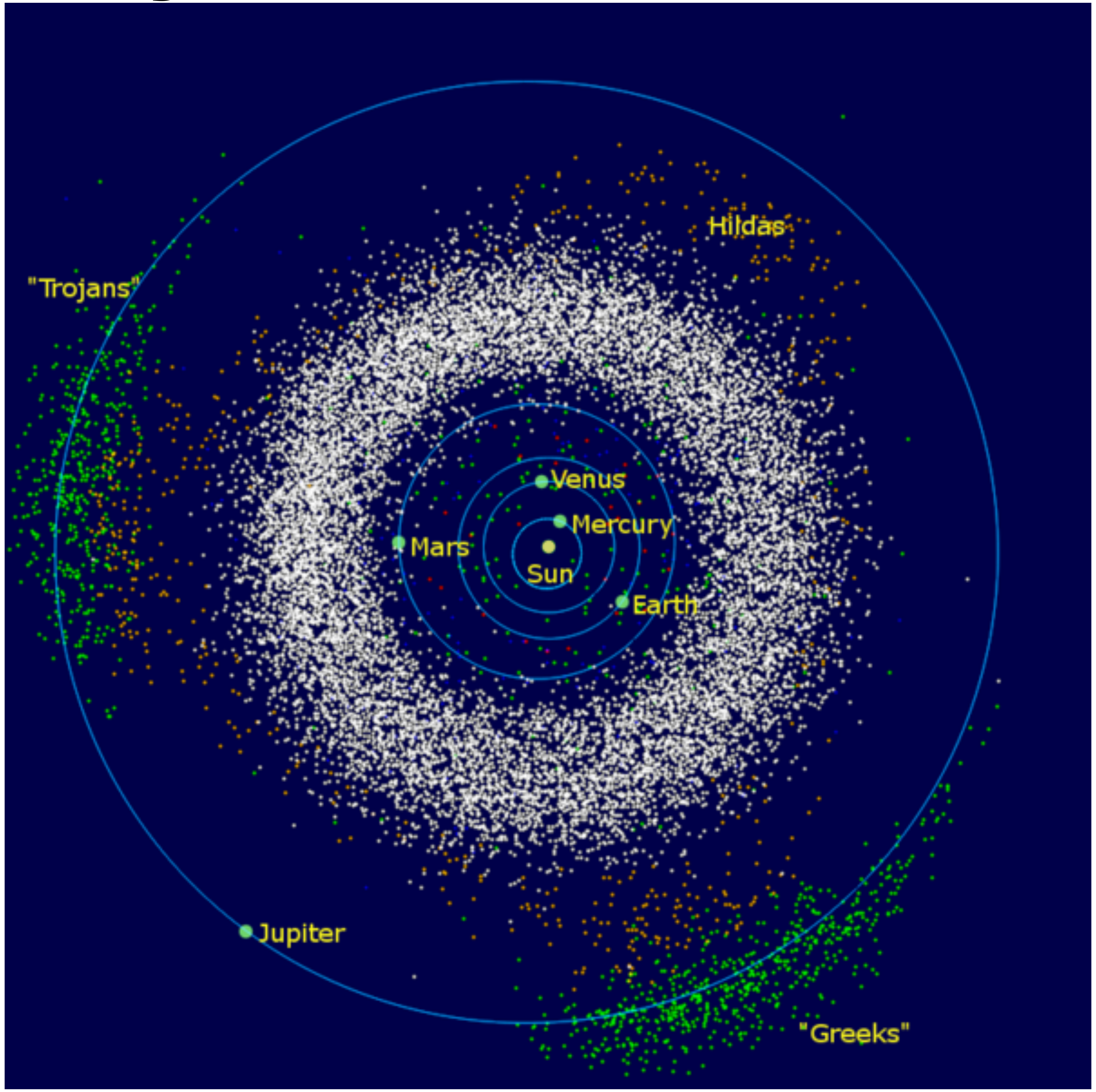
What is the asteroid belt?

What is the Oort cloud?



Minor bodies in the Solar system

The **asteroid belt** is a torus-shaped region in the Solar System, centered on the Sun and roughly spanning the space between the orbits of the planets Jupiter and Mars. It contains a great many solid, irregularly shaped bodies called asteroids or minor planets. The identified objects are of many sizes, but much smaller than planets, and, on average, are about one million kilometers (or six hundred thousand miles) apart. This asteroid belt is also called the main asteroid belt or main belt to distinguish it from other asteroid populations in the Solar System.

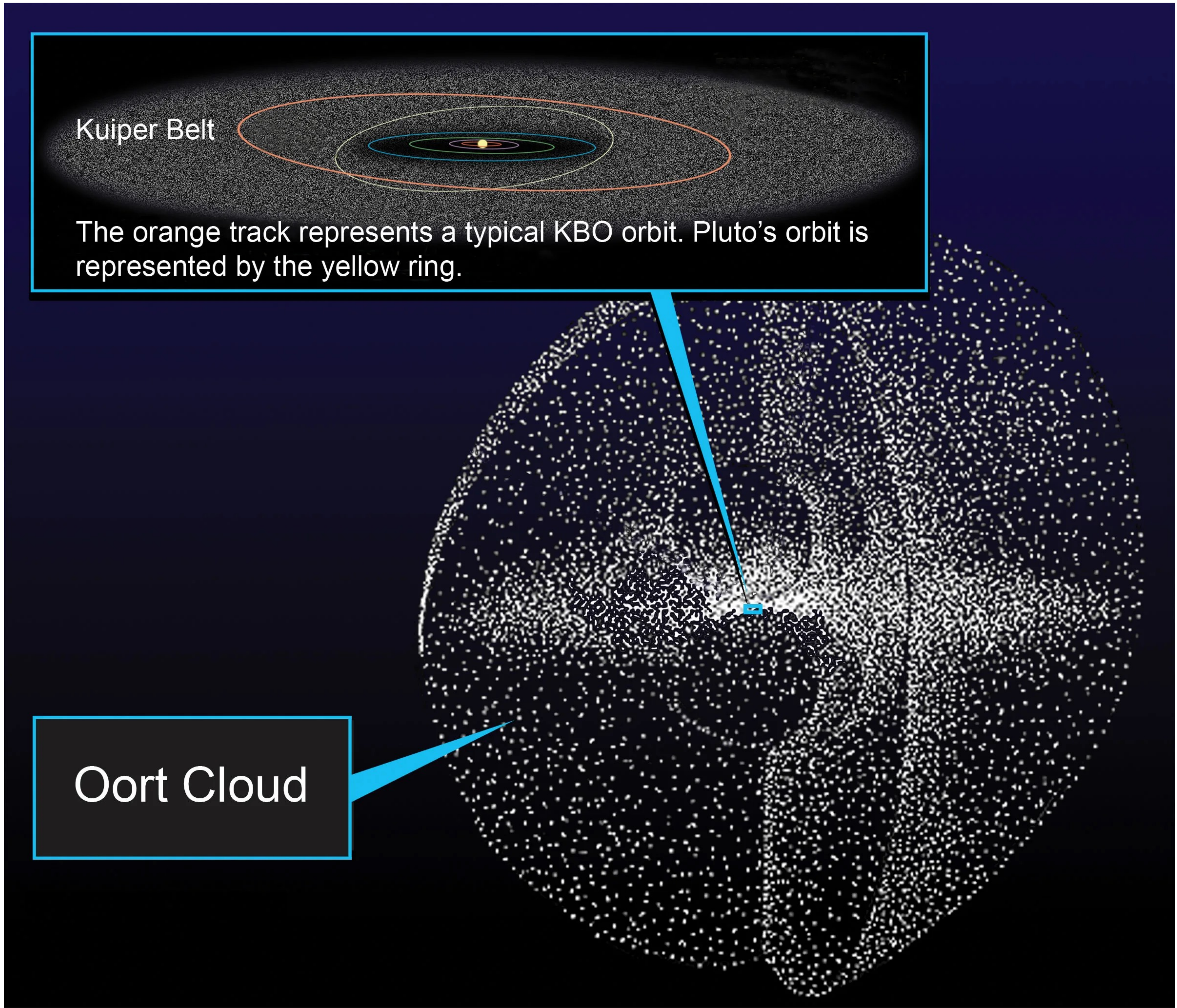


Minor bodies in the Solar system

The Kuiper belt is a circumstellar disc in the outer Solar System, extending from the orbit of Neptune at 30 AU to approximately 50 AU from the Sun. It is similar to the asteroid belt, but is far larger—20 times as wide and 20–200 times as massive.

Like the asteroid belt, it consists mainly of small bodies or remnants from when the Solar System formed. While many asteroids are composed primarily of rock and metal, most Kuiper belt objects are composed largely of frozen volatiles (termed "ices"), such as methane, ammonia, and water.

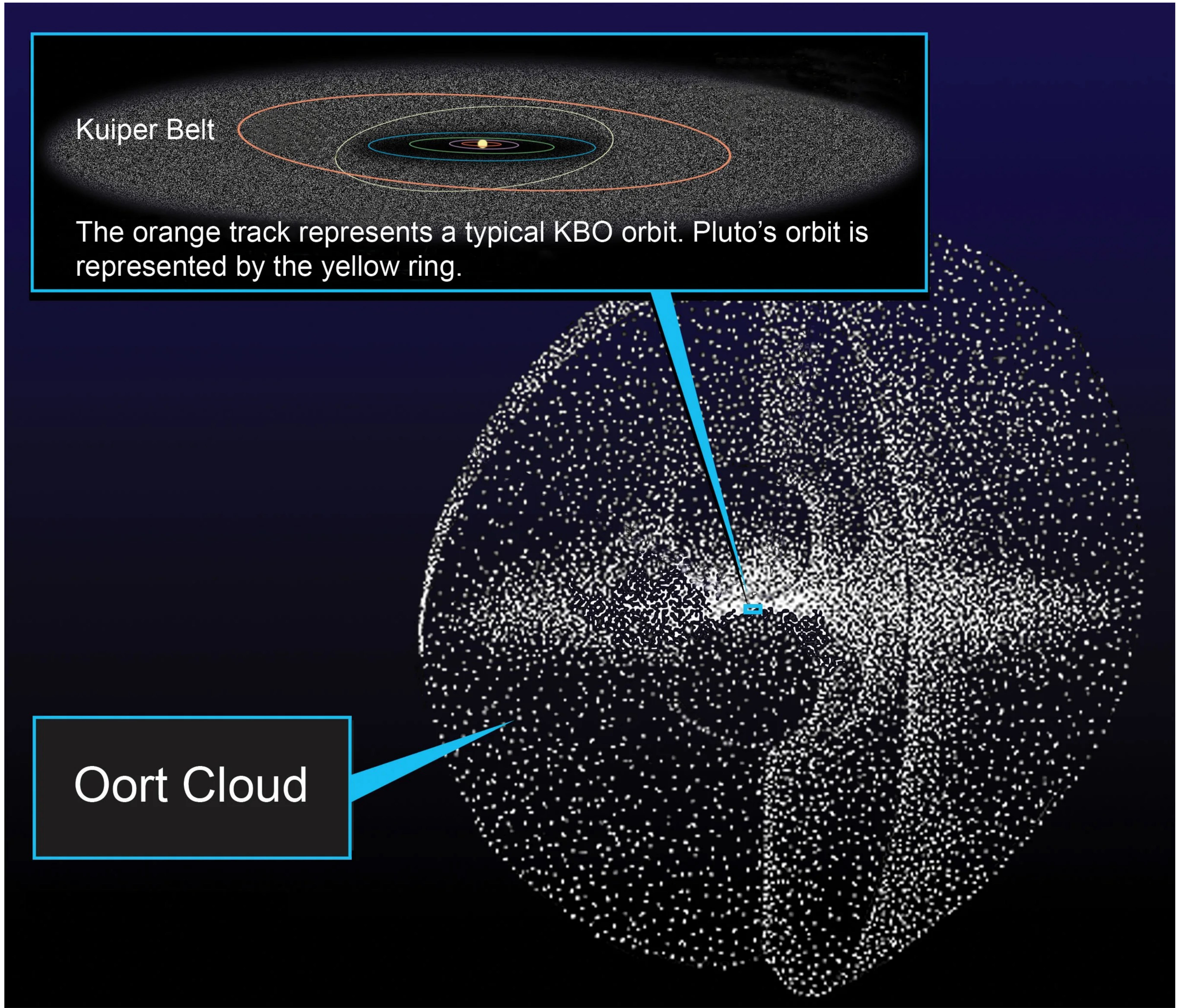
The Kuiper belt is home to most of the objects that astronomers generally accept as dwarf planets: Orcus, Pluto, Haumea, Quaoar, and Makemake. Some of the Solar System's moons, such as Neptune's Triton and Saturn's Phoebe, may have originated in the region.



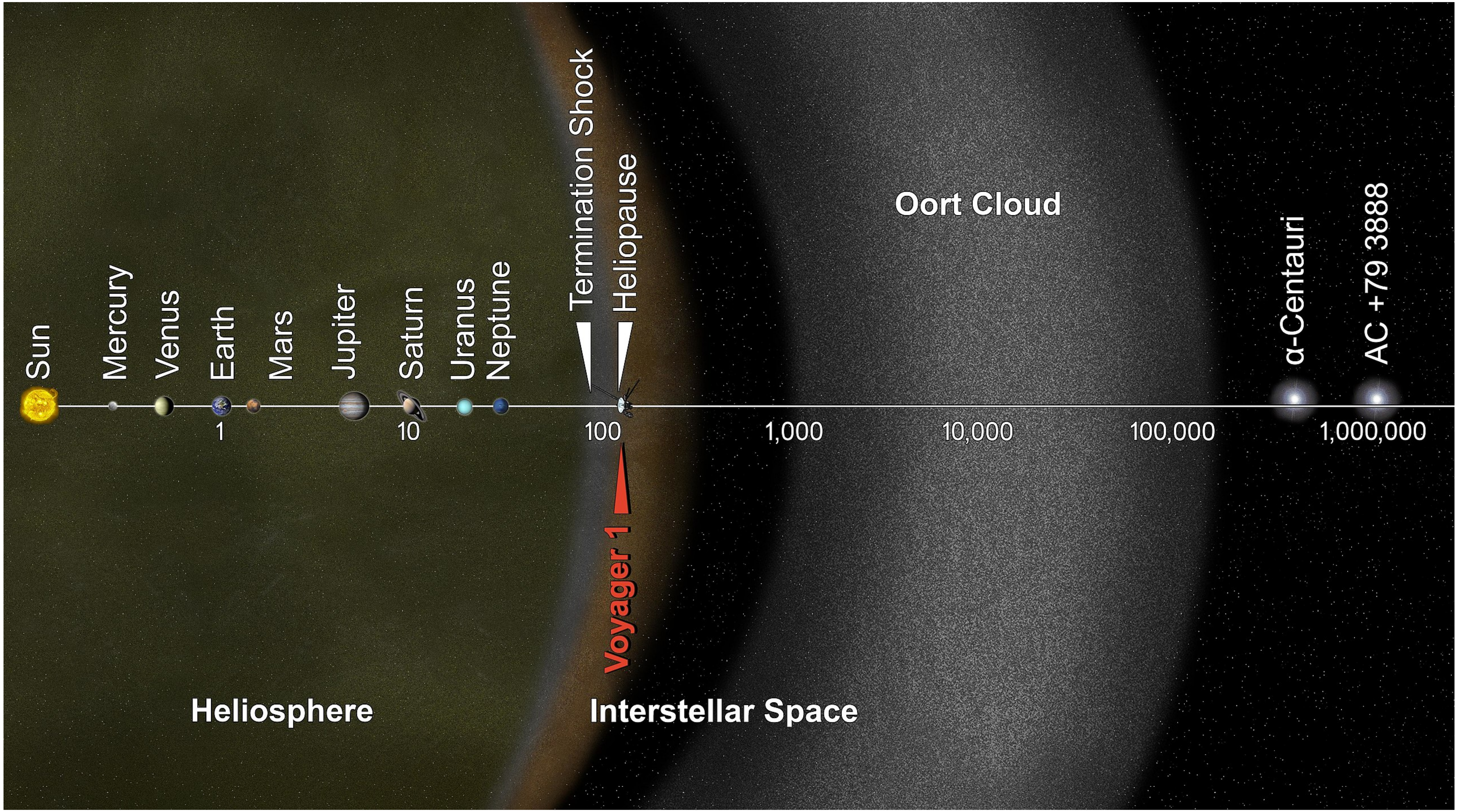
Minor bodies in the Solar system

The **Oort cloud** is theorized to be a vast cloud of icy planetesimals surrounding the Sun at distances ranging from 2,000 to 200,000 AU.

Oort proposed that the bodies in this cloud replenish and keep constant the number of long-period comets entering the inner Solar System—where they are eventually consumed and destroyed during close approaches to the Sun.
The outer limit of the Oort cloud defines the cosmographic **boundary of the Solar System**. This area is defined by the Sun's Hill sphere, and hence lies at the **interface between solar and galactic gravitational dominion.**
Astronomers hypothesize that the material presently in the Oort cloud formed much closer to the Sun, in the protoplanetary disc, and was then scattered far into space through the gravitational influence of the giant planets.



Minor bodies in the Solar system



Angular momentum distribution in the Solar system

However, one problem that has frustrated most attempts to put together an adequate picture of how our own Solar System developed concerns the present-day *distribution* of its angular momentum. A simple calculation of the angular momentum in the Sun and Jupiter reveal that the **orbital angular momentum of that planet exceeds the rotational angular momentum of the Sun by roughly a factor of twenty.** A more detailed analysis shows that even though the **Sun contains 99.9% of the mass, it contains only about 1% of the angular momentum of the entire Solar System,** and most of the remainder is associated with Jupiter.

To complicate matters further, the Sun's spin axis is tilted 7° with respect to the average angular momentum vector of the planets, making it hard to envision how such a distribution of angular momentum could develop.

An additional interesting component of the angular momentum question concerns the amount of angular momentum possessed by other stars. It turns out that, **on average, main-sequence stars that are more massive rotate much more rapidly and contain more angular momentum per unit mass than do less massive ones.**

How is this possible?

Angular momentum distribution in the Solar system

Moreover, as can be seen in Fig. 8, a very discernible break occurs in the amount of angular momentum per unit mass as a function of mass near spectral class A5.

If the total angular momentum of the Solar System were included, rather than just the angular momentum of the Sun, the trend along the upper end of the main sequence would extend to include our Solar System as well.

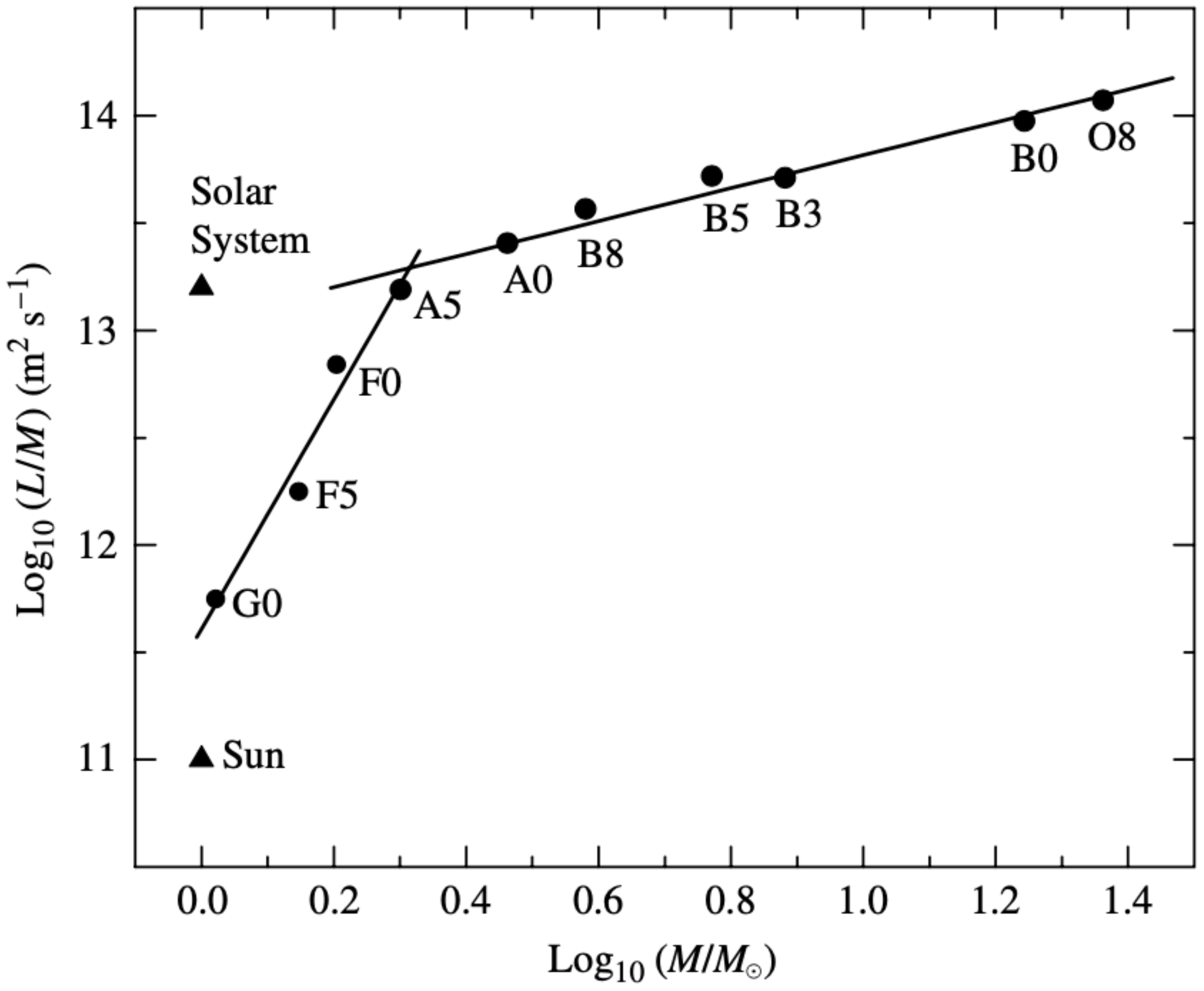
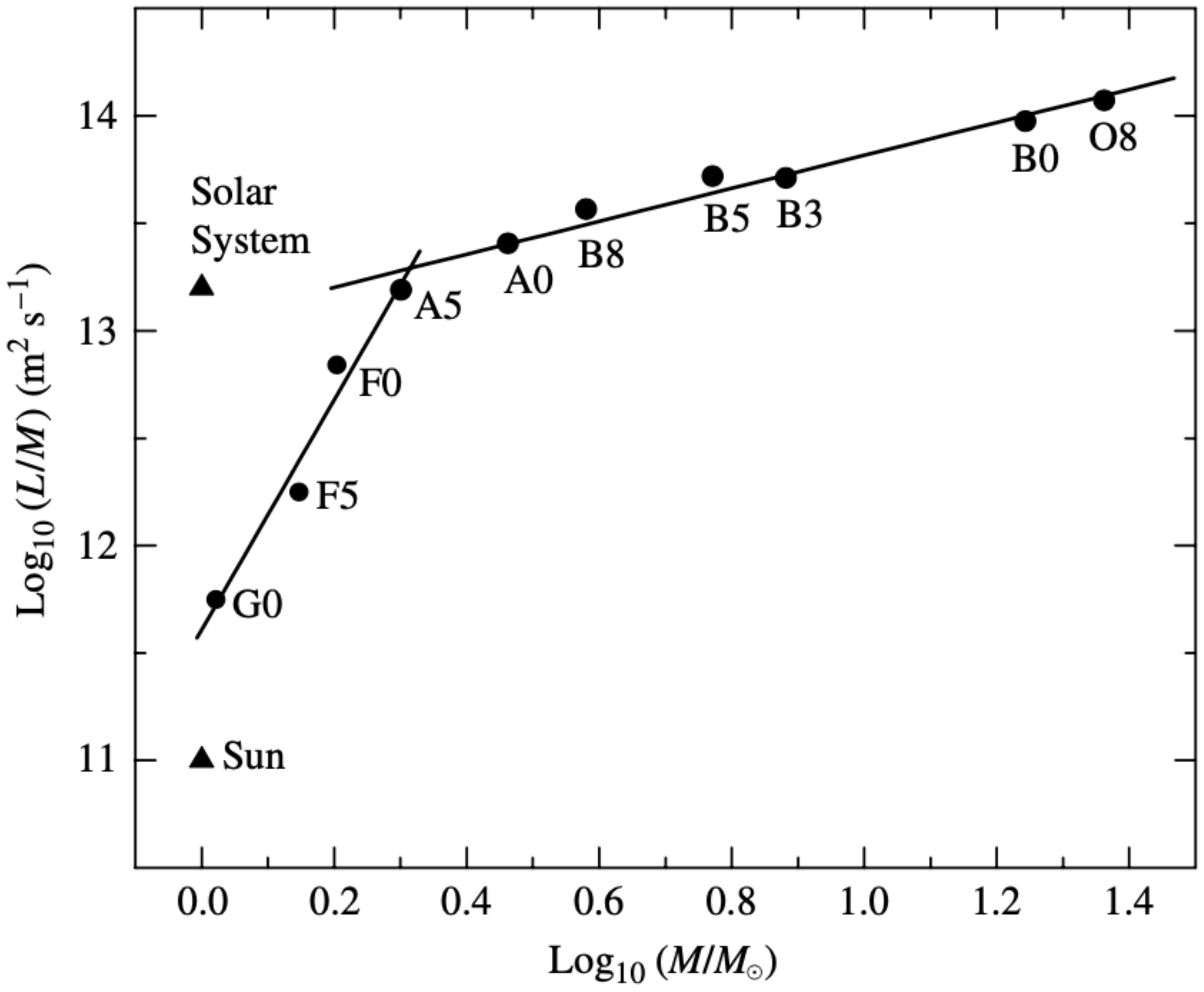


FIGURE 8 The average amount of angular momentum per unit mass as a function of mass for stars on the main sequence. The Sun's value and the total for the entire Solar System are indicated by triangles. Best-fit straight lines have been indicated for stars A5 and earlier, as well as for stars A5 and later (not including the Sun).

Angular momentum distribution in the Solar system

A portion of the angular momentum problem may be solved by the **transport of angular momentum** outward via **plasma drag in a corotating magnetic field.** Charged particles trapped in the protosun's field would have been dragged along as the field swept through space. In response, the protosun's rotation speed slowed because of the torque exerted on it by the magnetic field lines.

In addition, much of the rotational angular momentum of the newly formed Sun was probably also **carried away by the particles in the solar wind.**



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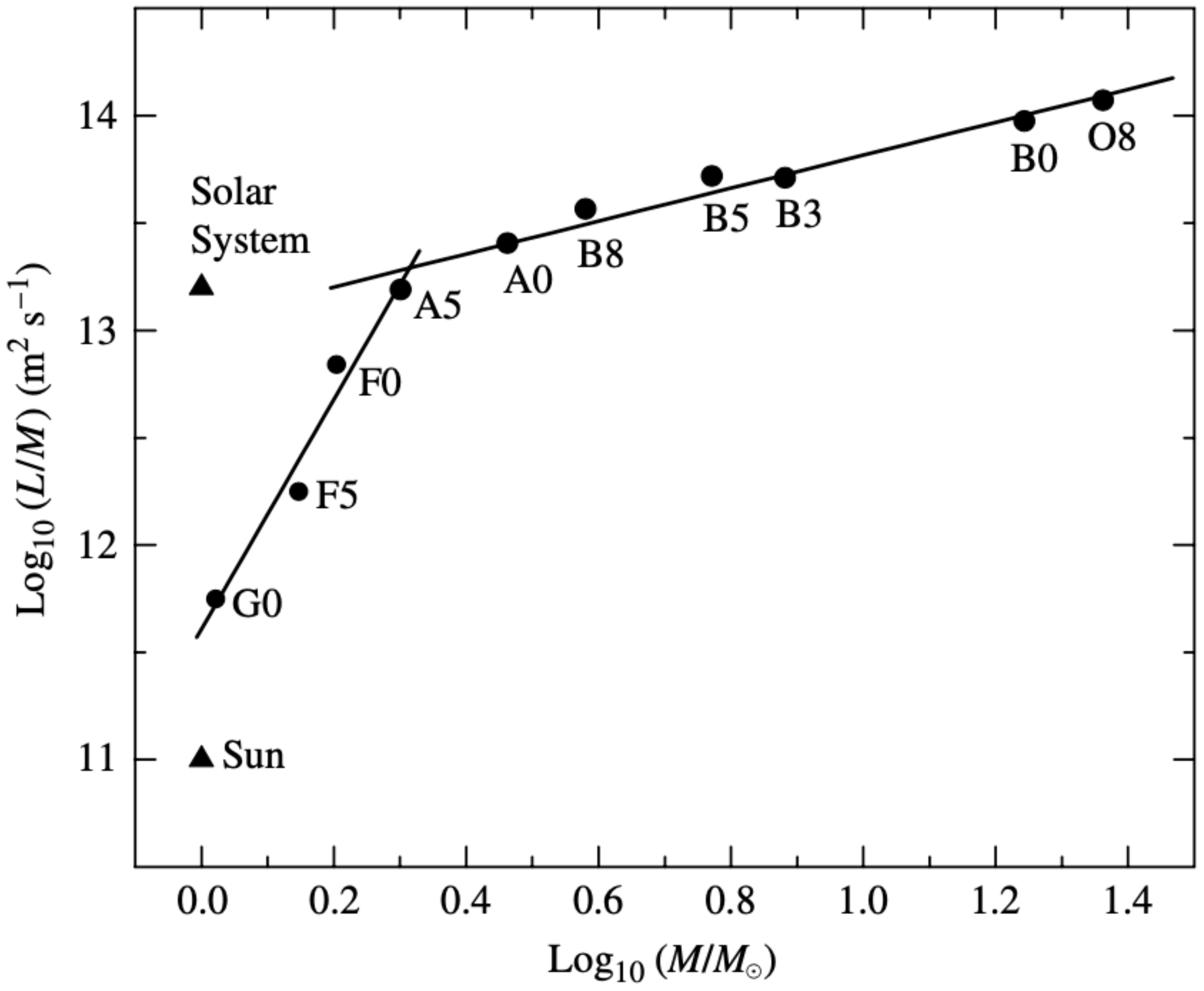
Angular momentum distribution in the Solar system

In support of these mechanisms is Fig. 8. The change in slope of the angular-momentum-per-unit-mass curve corresponds well with the **onset of surface convection in low-mass stars,** which in turn is linked to the **development of coronae and mass loss**. Other mechanisms for angular momentum transport will be discussed later.



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Composition in the Solar system

Lower-mass stars with metallicities similar to or greater than the solar value seem able to form planetary systems routinely. Therefore, the process of planetary system formation must be robust. The process must also be capable of producing systems with planets that are far from the parent star and systems where the planets are very close in.

A crucial piece of any successful theory must be the ability to explain the clear **composition trends that exist among the planets in our Solar System:**

- The inner **terrestrial planets are small, generally volatile-poor, and dominated by rocky material,**
- while the **gas and ice giants contain an abundance of volatile material.**
- The ice giants Uranus and Neptune contain substantial volatiles, the gas giants Jupiter and Saturn contain the overwhelming majority of volatile material in the Solar System.

Composition in the Solar system

The **moons of the giant planets** also exhibit composition trends.

- In going from Jupiter out to Neptune, the progression is **from rocky moons to increasingly icy bodies,** first containing water-ice and then methane- and nitrogen-ice.
- The pattern even includes such objects as the asteroids, the Centaurs, the Kuiper belt objects, and other cometary nuclei.
- It is particularly important to note that a composition trend also exists across the asteroid belt itself.
- Even on the **smaller scale of Jupiter's system of satellites**, the Galilean moons change from volcanic Io to the thick-ice surface of Callisto.

How is this possible?

Temperature gradient

Apparently, **either a composition gradient or a temperature gradient** (or both) must have existed in the early solar nebula while these objects were forming.

- For instance, the observations just described could be accounted for **if the temperature of the nebular disk had decreased sufficiently across the asteroid belt.** In that case, water would not have condensed in the region of the terrestrial planets but could have condensed in the form of ice in the vicinity of the giant planets.
- **Another temperature gradient associated with the formation of Jupiter** could help to explain the formation of the Galilean moons from the Jupiter subnebula.

An accretion disk that forms in a binary star system has a well-determined temperature gradient [$T \propto r^{-3/4}$]. An analogous sort of temperature structure should have existed in the solar nebula as well.

Temperature gradient

The **temperature structure for an equilibrium solar nebula** model is shown in Fig. 9.

Even though specific features of the distribution may change with more sophisticated modeling (by including time dependence, turbulence, and magnetic fields), it seems apparent that the **condensation temperature of water-ice must be reached at some point near the current position of Jupiter,** perhaps in the outer portions of the main asteroid belt (roughly 5 AU).

The position in the solar nebula **where water-ice could form** has been variously referred to as the **"snow line," the "ice line,"** or, more dramatically, the "blizzard line."

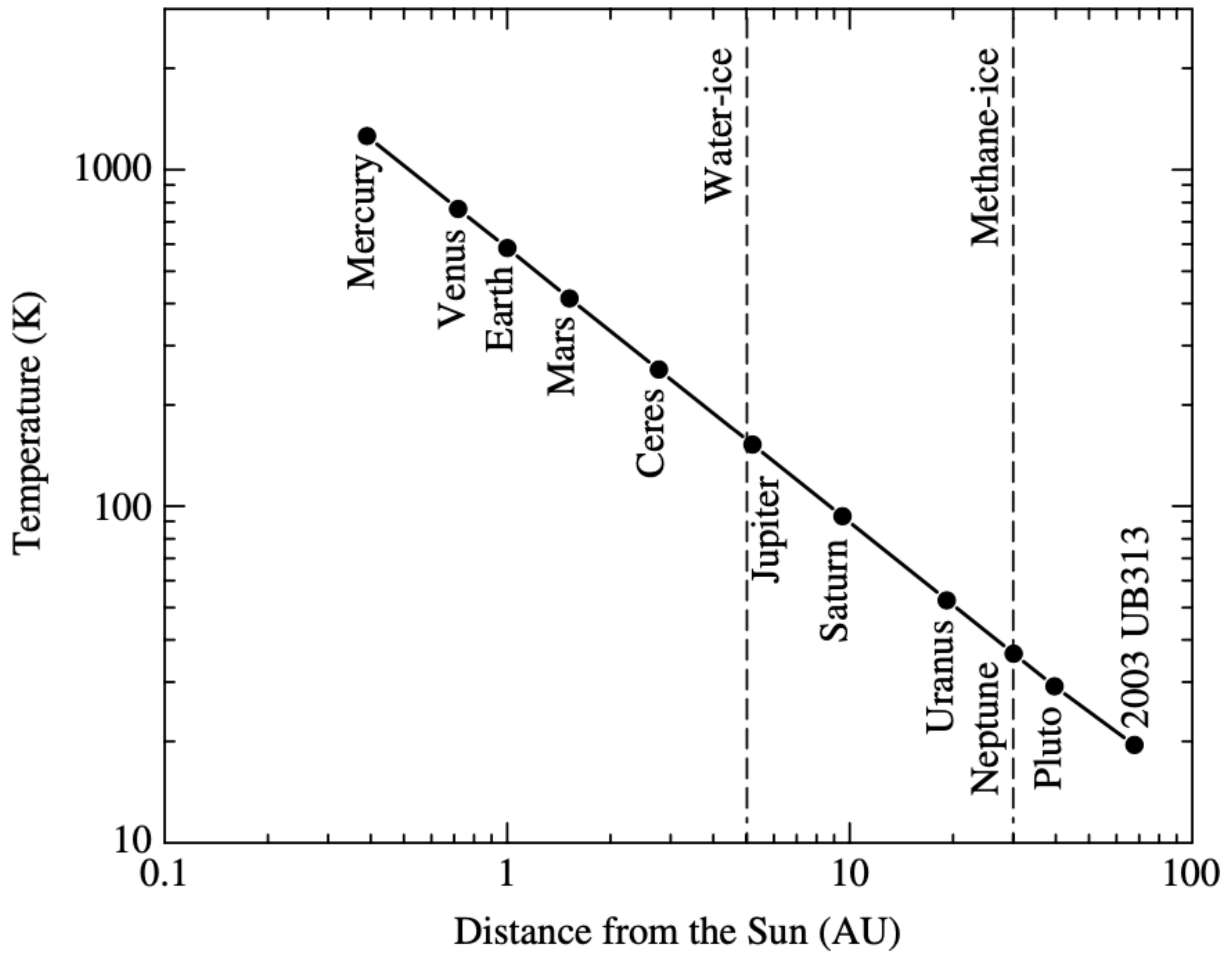


FIGURE 9 An equilibrium model of the temperature structure of the early solar nebula. Water-ice was able to condense out of the nebula in those regions beyond approximately 5 AU, and methane-ice could condense out of the nebula beyond 30 AU. The positions of the planets and Ceres represent their present-day locations.

Temperature gradient

We have also learned that the environments around newly forming stars can be very dynamic places, with **mass accretion and mass loss happening at virtually the same time** in T-Tauri systems.

During FU Orionis events, the environment around the star can become particularly active, with **significant outbursts of energy** occurring because of greatly increased mass accretion rates. It also seems certain that these environments will have **complex magnetic fields that would lead to frequent and intense flares,** analogous to the solar flares on our Sun that are produced by magnetic field reconnection events.

Heavy Bombardment

At least within our own Solar System, the **formation of the Sun was accompanied by the formation of a wide range of objects, including small rocky planets, gas giants, ice giants, moons, rings, asteroids, comets, Kuiper belt objects, meteoroids, and dust**.

Of course, it is readily apparent that our Solar System is riddled with evidence of **collisions in the past, leaving cratered surfaces on objects** of all sizes, from planets and moons to asteroids and comets. As a consequence, any formation theory must also be able to **account for the heavy bombardment** endured by bodies in the early Solar System.

The **high mass density of Mercury** and the extremely **volatile-poor composition of the Moon** strongly suggest that both of these worlds were directly **influenced by cataclysmic collisions** involving very large planetesimals (the Moon's formation is tied to just such a collision with Earth).

Heavy surface cratering shows that collisions continued even after their surfaces formed, with a brief episode of late heavy bombardment about 700 Myr after the formation of the Moon.


Google Moon

Heavy Bombardment

How was the Moon formed?

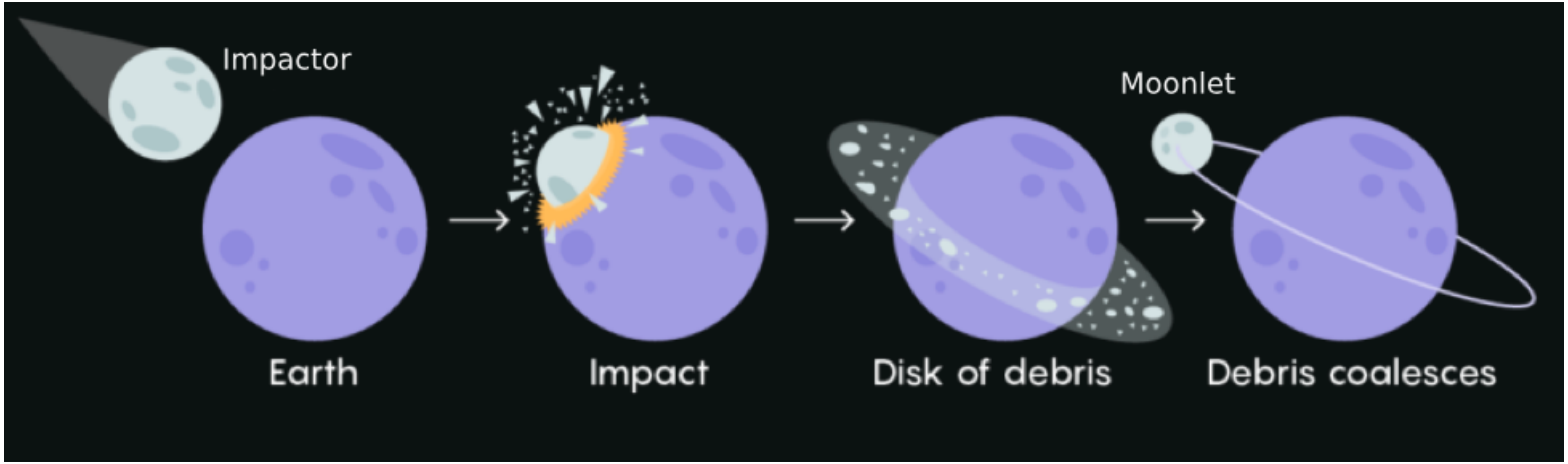
Google Moon

Heavy Bombardment

Formation of the Moon:

The proto-Earth collided with a Mars sized object. The Moon formed from the resulting debris.

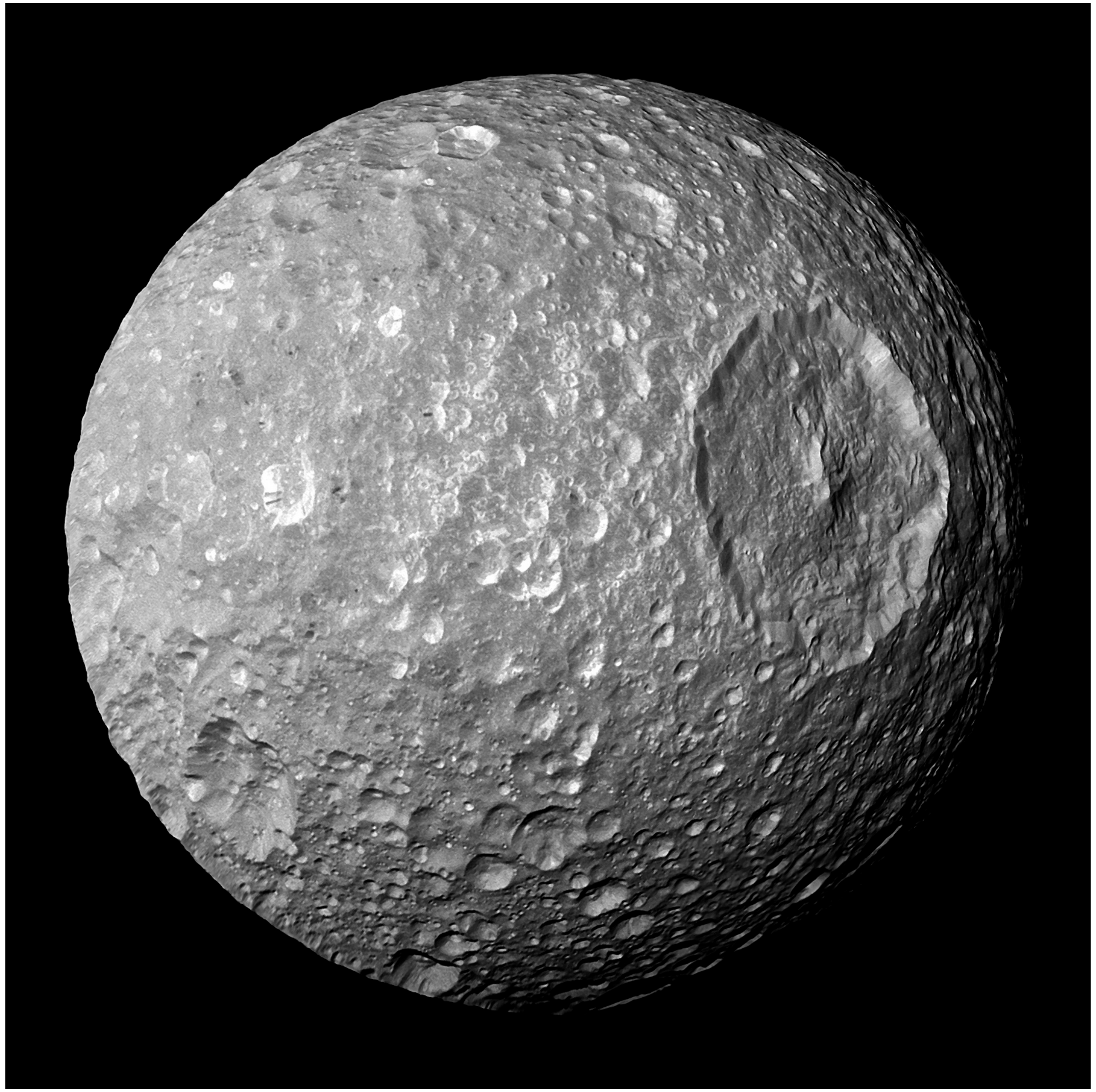
Evidence: chemical composition of the crust of the Earth and the Moon are very similar



https://astrobites.org/2019/08/12/a-proposed-moon-formation-theory-the-multiple-impact-hypothesis/

Heavy Bombardment

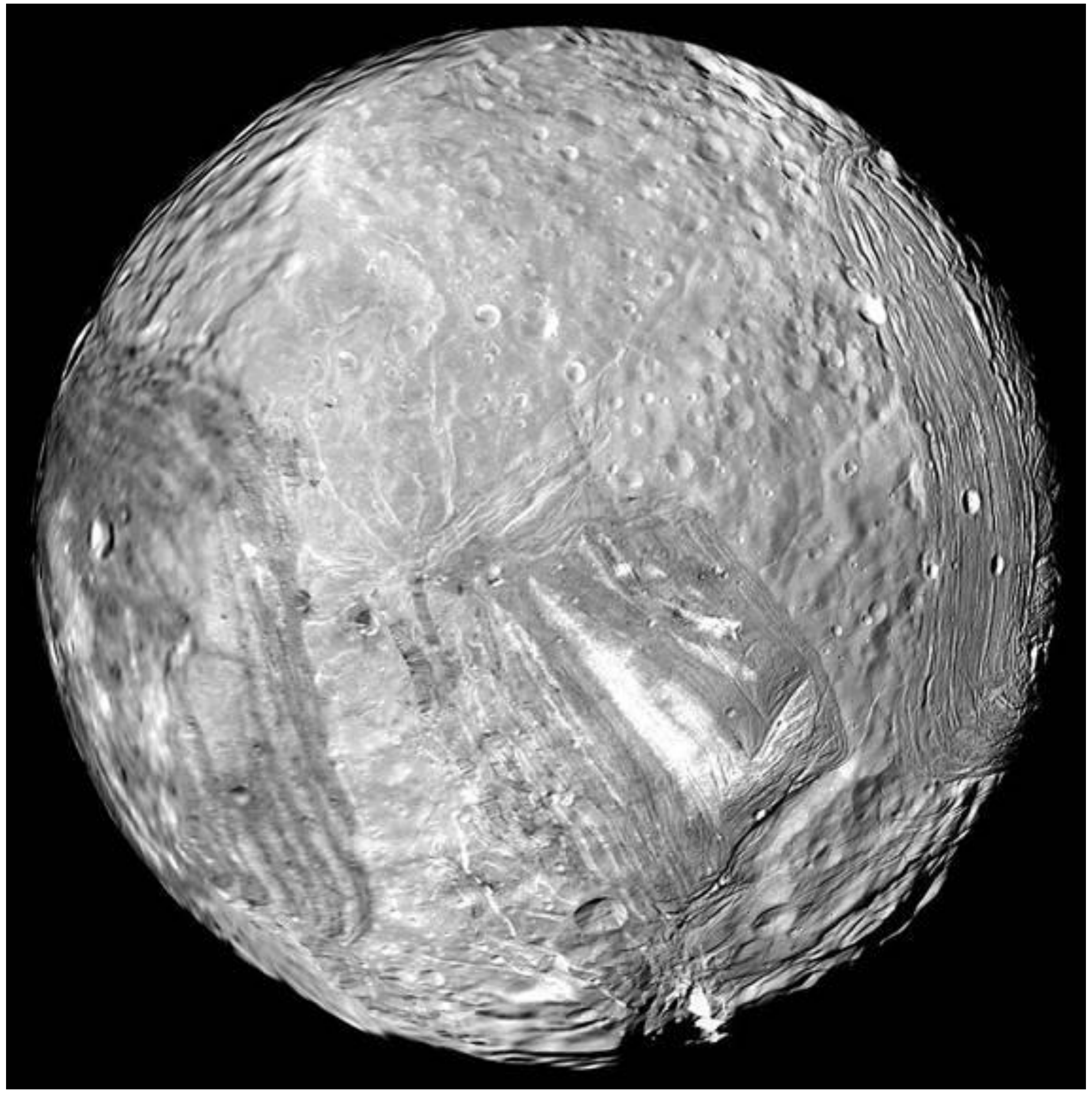
Features such as the enormous Herschel crater on Mimas and the bizarre surface of Miranda testify to the fact that the other bodies in the Solar System underwent the same intense barrage from planetesimals.



Mimas, Saturn
The Herschel crater measures 139 kilometres across, about one-third of Mimas's mean diameter (396.4 kilometres),and is believed to be formed from an extremely energetic impact event.

Mimas is the smallest astronomical body known to be roughly **rounded in shape due to its own gravity.**
Mimas's **low density,** 1.15 g/cm3, indicates that it is composed **mostly of water ice with only a small amount of rock.**

Miranda, Uranus



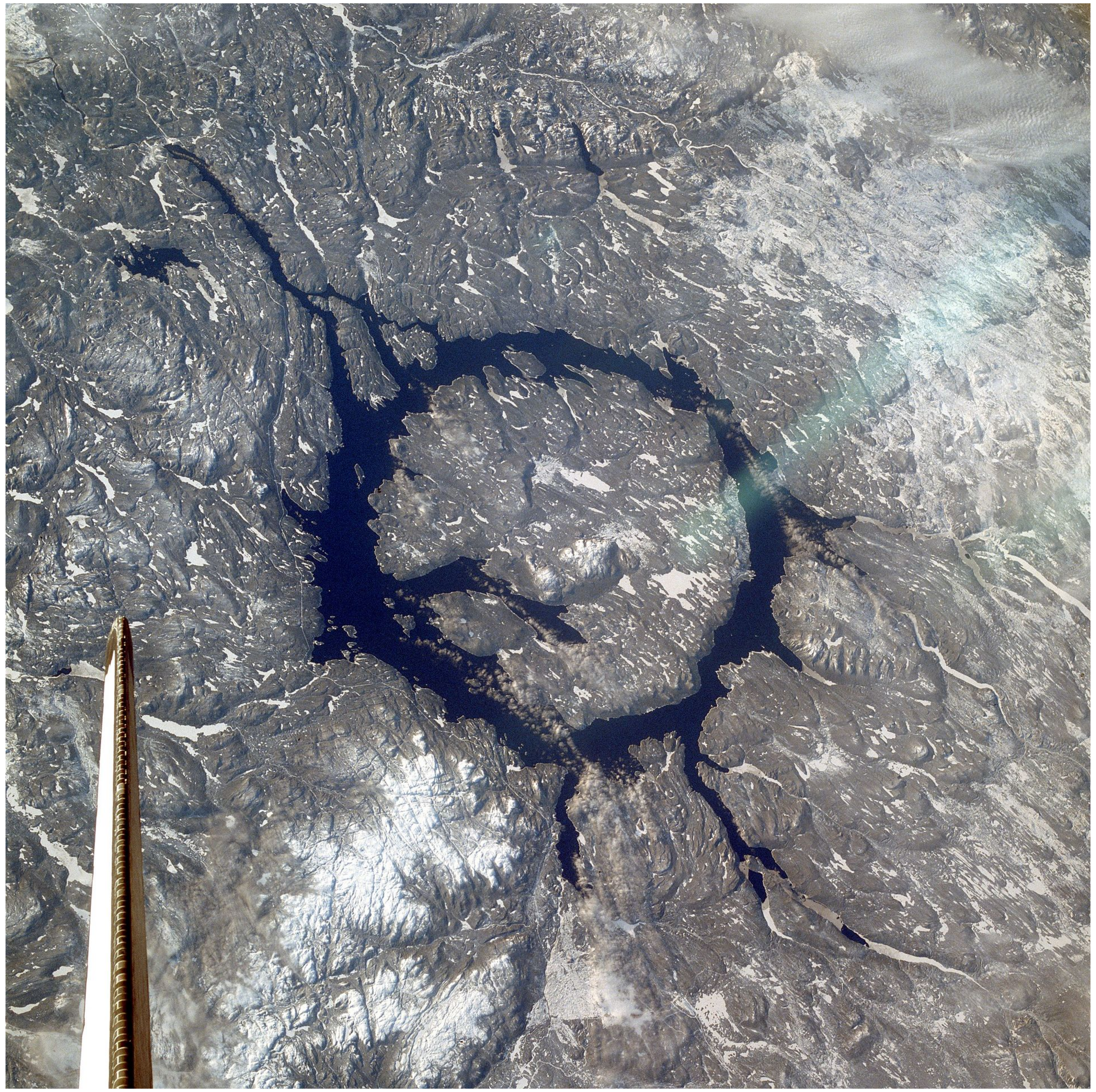
Impact craters on Earth

There is a list on Wikipedia:

https://en.wikipedia.org/wiki/List_of_impact_craters_on_Earth

Image credit: Dick and Pip Smith

Kandimalal (Wolf Creek)
in Australia
Diameter: 875 m
Age ~ 15000 years



Manicouagan Reservoir
in Canada
Diameter: 100 km
Age ~ 210 Myears

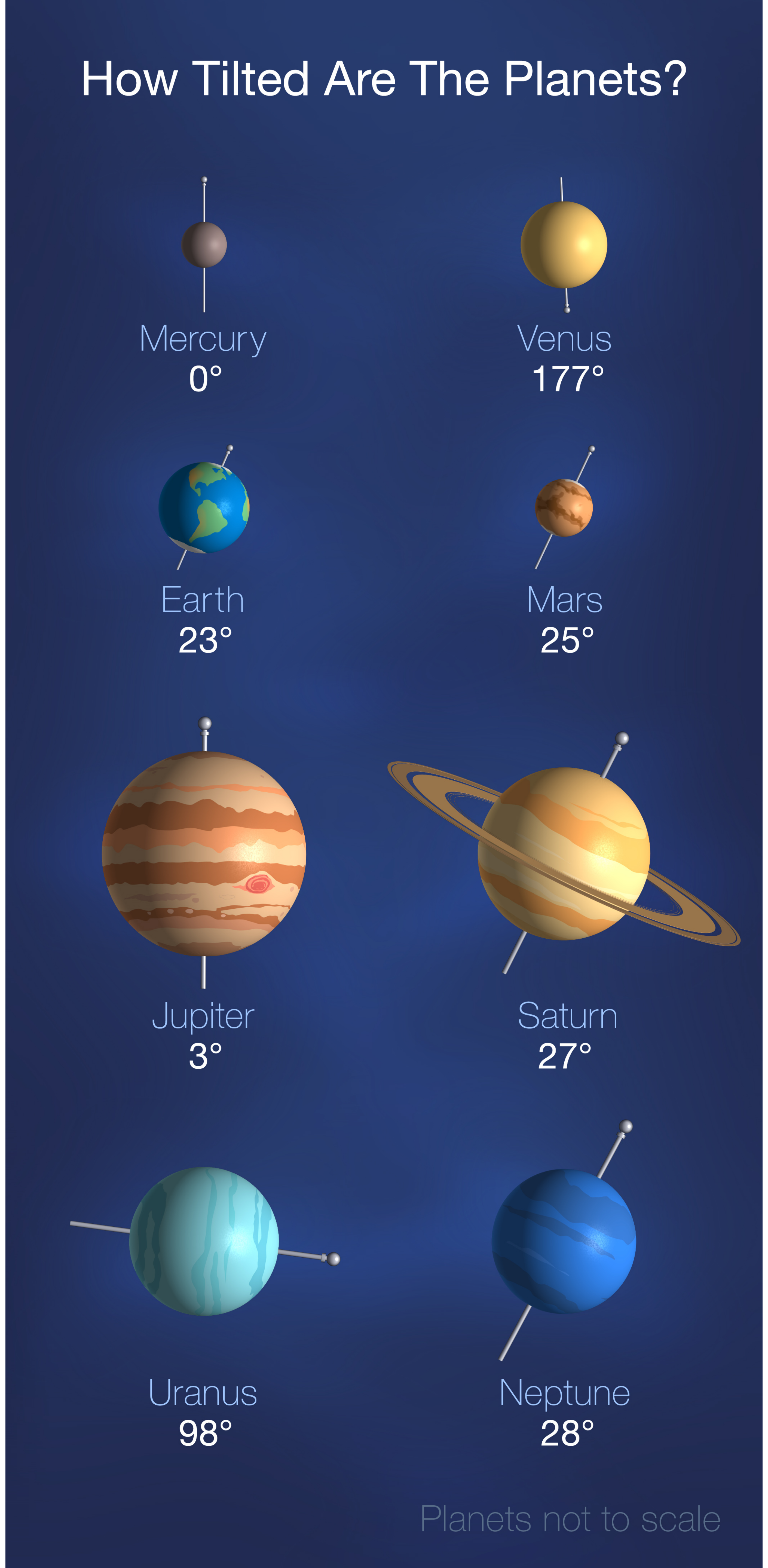
Heavy Bombardment

Another consequence of the heavy bombardment by planetesimals is the variety of **present-day orientations for the spin axes of the planets.**

The extreme examples of the **retrograde rotations of Uranus and Pluto**, but the other planets must have had their rotation axes shifted as well.

Assuming that the planets did form out of a flattened nebular disk, the inherent angular momentum of the system would have resulted in rotation axes being **initially aligned nearly perpendicular to the plane of the disk**. Because this is not the case today, some event (or e**vents) must have occurred to alter the directions of the planets' rotational angular momentum vectors.**

With the exception of Venus's and Mars's complex tidal interactions with the Sun and the other planets, the only likely mechanism suggested to date that can naturally account for the range of orientations observed requires **collisions of planets or protoplanets with large planetesimals.**



Distribution of mass within planetary systems

Other features of the present-day Solar System that should be explained in a model of Solar System formation include the relatively **small mass of Mars** compared with its neighbors, the very **small amount of mass present in the asteroid belt**, and the **existence of the Oort cloud and the Kuiper belt.**

Furthermore, if we are to seek a general, unifying model of planetary system formation that includes our own Solar System as one example, it is necessary to **understand the distributions of planets in other systems.**

- Particularly perplexing when first discovered was the existence of **“hot Jupiters”** such as 51 Peg b.
- How could a gas giant form and survive so close to its parent star? In our own Solar System, none of the giant planets resides closer to the Sun than 5.2 AU.

Distribution of mass within planetary systems

What is a hot Jupiter?

Hot Jupiters

Hot Jupiters are a class of gas giant exoplanets that are inferred to be physically similar to Jupiter but that have very short orbital periods ($P < 10$ days). The **close proximity to their stars and high surface-atmosphere temperatures** resulted in their informal name "hot Jupiters".

Hot Jupiters are the easiest extrasolar planets to detect via the radial-velocity method, because the oscillations they induce in their parent stars' motion are relatively large and rapid compared to those of other known types of planets.

One of the best-known hot Jupiters is **51 Pegasi b.** Discovered in 1995, it was the **first extrasolar planet found orbiting a Sun-like star**. 51 Pegasi b has an orbital period of about 4 days.

Formation Timescales

One aspect of all formation theories that cannot be neglected are constraints imposed by **timescales:**

- Once the collapse of a molecular cloud is initiated, on the order of **10^5 years** is required for the formation of a **protosun and nebular disk.**
- The onset of violent **T-Tauri and FU Orionis activity** and extensive mass loss follows the initial collapse in some **10^5 to 10^7 years**. This means that any nebular gas and dust that has not been accreted into a planetesimal or a protoplanet will be swept away within about **10 Myr, terminating further formation of large planets.**
- The presence of ^{26}Al in carbonaceous chondrites indicates that these meteorites must have been formed within a few million years after the creation of the aluminum, whether it was through a supernova detonation or through flares during FU Orionis activity. Otherwise, all of the radioactive nuclides that were created would have decayed into ^{26}Mg. This observation puts severe constraints on condensation rates in the early solar nebula.
- The oldest meteorites, including Allende, date back to near 4.566 Gyr, while the age of the Sun itself is 4.57 Gyr. Clearly these oldest meteorites must have formed rapidly within the solar nebula.

Formation Timescales

- The ages of rocks returned from the **Moon** show that the **surface** of that body must have **solidified some 100 Myr after the collapse of the solar nebula.** Similar constraints exist on the formation of the surface of Mars judging on the basis of the age of the Martian meteorite, ALH84001.
- The lunar surface underwent a spike of **late heavy bombardment about 700 Myr after the Moon formed.**
- As we will learn later, as **planets** grow in accretion nebulae, they **tend to migrate inward due to tidal interactions with the nebula and viscosity effects**. It is estimated that a planetesimal could drift all the way into its parent star from a distance of 5 AU within roughly 1 to 10 Myr.
- A rather loose constraint on any model requires that all of the planets, moons, asteroids, Kuiper belt objects, and comets must be fully formed today, **4.57 Gyr years after the process started.** Although this may seem trivial, not all models of Solar System formation have been successful in creating planets this rapidly!

Formation Mechanism

Two general, competing mechanisms have been proposed for the formation of planets within the accretion disks of proto- and pre-main-sequence stars.

- One mechanism is based on the idea that planets (or perhaps brown dwarfs) could form in accretion disks in a manner analogous to star formation. In regions where there may be a **greater density of material** in the disk, **self-collapse** could result.
- As the mass accumulates in that region, its gravitational influence on the surrounding disk increases, **causing additional material to accrete** onto the newly forming planet. This mechanism could even result in a **local subnebula accretion disk** forming around the protoplanet that could lead to the **creation of moons and/or ring systems.**
- While this **"top-down" gravitational instability** mechanism has several attractive features, including simplicity and being strongly analogous to the formation of protostars, its general applicability suffers from numerous **difficulties**.

Formation Mechanism

- By observations of other accretion disks, along with T-Tauri accretion and mass-loss rates, and combined with detailed numerical simulations, it appears that the **solar nebula's lifetime would not have been sufficient** to allow objects like Uranus and Neptune to grow quickly enough to attain the masses we observe before the nebula was depleted.
- This mechanism also **does not explain the large number of other, smaller objects** that are present in our Solar System and are likely to exist in other planetary systems as well (recall the β Pic debris disk).
- In addition, the gravitational instability mechanism **doesn't appear to readily account for the mass distribution of extrasolar planets,** the correlation between **planetary system formation and metallicity**, or the **wide range in the densities and core sizes of planets,** both within our Solar System and among the extrasolar planets.

The Accretion Formation Mechanism

- An alternative model, and the one general favored by most astronomers, is that **planets grow from the "bottom up"** through a process of **accretion of smaller building blocks.**
- Based on all of the observational and theoretical information presently available, it appears that a reasonable description of the formation of planetary systems can now be given. What follows is a possible scenario for the formation of our own Solar System, although references to general aspects of planetary system formation will also be made. It is important to note, however, that because of the complexity of the problem, revisions in the model (both minor and major) are likely to occur in the future.

Example: the formation of the Solar System

- Within an interstellar gas and dust cloud (perhaps a giant molecular cloud), the **Jeans condition** was satisfied locally, and a portion of the cloud began to collapse and fragment.
- The **most massive segments evolved rapidly into stars** on the upper end of the main sequence, while less massive pieces either were still in the process of collapsing or had not yet started to collapse.
- Within a period of a few million years or less, the most massive stars would have **lived out their entire lives** and died in spectacular **supernovae** explosions.
- As the e**xpanding nebulae** from one or more of the supernovae traveled out through space at a velocity of roughly 0.1c, the gases cooled and became less dense.
- It may have been during this time that the most **refractory elements began to condense** out of the supernova remnants, including calcium, aluminum, and titanium, the ingredients of the ***CAIs (Ca-Al–rich inclusions)*** that would eventually be discovered in carbonaceous chondrites that would fall to Earth billions of years later.
- When a supernova remnant encountered one of the cooler, denser components of the cloud that had not yet collapsed, the remnant began to break up into “fingers” of gas and dust that penetrated the nebula unevenly. The small cloud fragment would have also been **compressed** by the shock wave of the high-speed supernova remnant when the expanding nebula collided with the cooler gas.

Example: the formation of the Solar System

- It is possible that this compression may have even helped **trigger the collapse of the small cloud.** In any case, the material in the solar nebula was now **enriched with elements** synthesized in the exploded star.
- Assuming that the solar nebula possessed some initial angular momentum, conservation of angular momentum demands that the cloud "spun up" as it collapsed, producing a **protosun surrounded by a disk of gas and dust.** In fact, the disk itself probably formed more rapidly than the star did, causing much of the mass of the growing protosun to be funneled through the disk first.
- Although this important point is not entirely resolved, it has been estimated that the solar nebular disk may have contained a few hundredths of a solar mass of material, with the remaining 1 $M_\odot$ of the nebula ending up in the protosun. At the very least, a minimum amount of **mass must have ended up in the nebular disk to form the planets and other objects** that exist today. Such a disk is referred to as the **Minimum Mass Solar Nebula**.

Example: the formation of the Solar System

- Within the nebular disk, **small grains with icy mantles were able to collide and stick together** randomly. When objects of appreciable size were able to develop in the disk, they began to **gravitationally influence** other material in their areas.
- To **quantify the influence** that these growing planetesimals had, we can define the **Hill radius**, R_H , to be that ***distance from the planetesimal where the orbital period of a test particle around the planetesimal is equal to the orbital period of the planetesimal around the Sun.***
- Assuming a circular orbit, the orbital period of a test particle (m_t) around an object of mass M ($M \gg m_t$) at a distance R is given by Kepler's third law as

$$P \simeq 2\pi\sqrt{\frac{R^3}{GM}}.$$

At a distance a from the Sun, the orbital period of the growing planetesimal around the Sun equals the orbital period of a massless test particle around the planetesimal at the Hill radius when

$$\sqrt{\frac{a^3}{M_\odot}} = \sqrt{\frac{R_H^3}{M}}.$$

Example: the formation of the Solar System

Thus, the Hill radius is given by

$$\boxed{R_H = \left(\frac{M}{M_\odot}\right)^{1/3} a.}$$

Rewriting in terms of the density of the Sun and the density of the planetesimal (assumed to be spherical), the Hill radius becomes

$$R_H = R/\alpha$$

where R is the radius of planetesimal and

$$\alpha \equiv \left(\frac{\rho_\odot}{\rho}\right)^{1/3} \frac{R_\odot}{a}.$$

The physical significance of the Hill radius is that **if a particle comes within about one Hill radius of a planetesimal** with a relative velocity that is sufficiently low, the particle **can become gravitationally bound** to the planetesimal. In this way, the **planetesimal** acquires the mass of the particle and **continues to grow**. Of course, as the planetesimal's radius grows, so does its Hill radius.

Example: the formation of the Solar System

Example: For a planetesimal of density $\rho = 800$ kg m^{-3} and radius 10 km, located 5 AU from the Sun ($\rho_\odot =$ 1410 kg m^{-3}), the planetesimal's Hill radius would be

$$R_H = R/\alpha = R\left(\frac{\rho}{\rho_\odot}\right)^{1/3}\left(\frac{a}{R_\odot}\right) = 8.9 \times 10^6 \text{ m} = 1.4\,\mathrm{R}_\oplus .$$

This planetesimal is similar to present-day **cometary nuclei.**

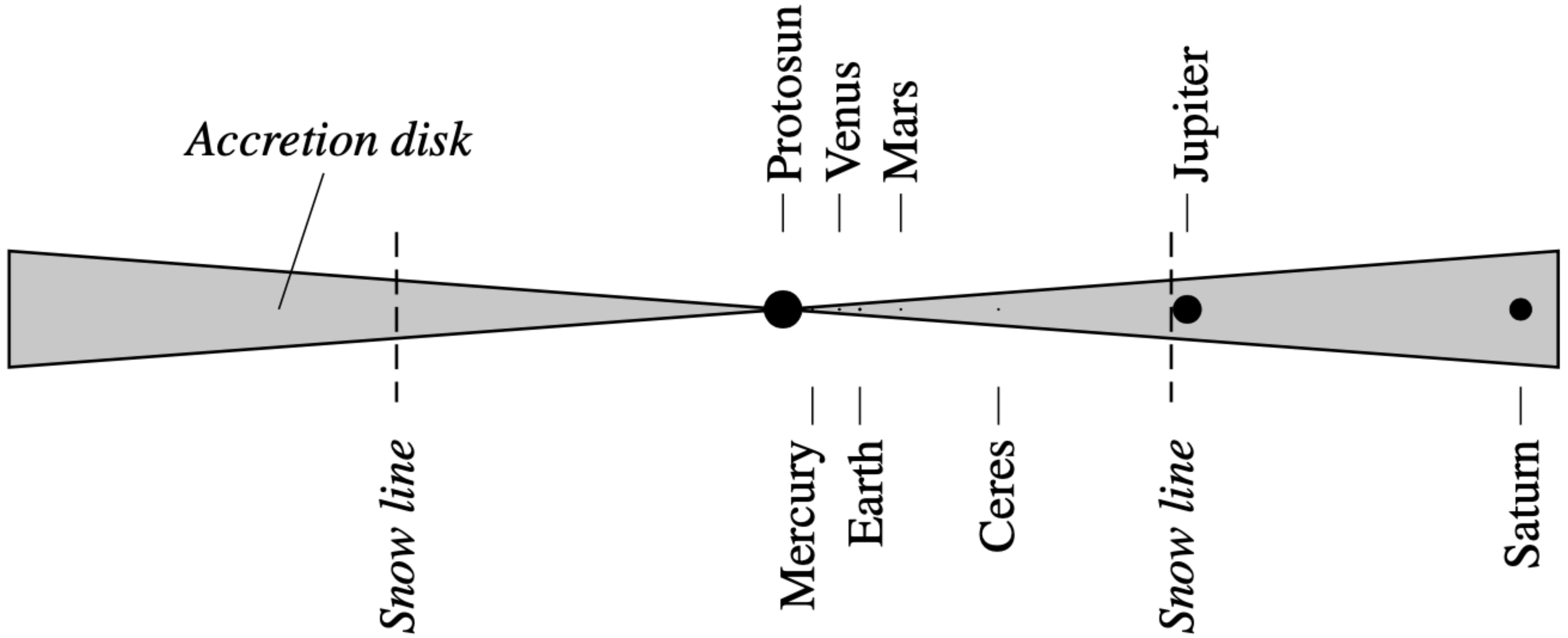
Formation of the Gas and Ice Giants

As the low-energy collisions continued, progressively larger planetesimals were able to form.

In the innermost regions of the disk the accreting particles were composed of CAIs, silicates (some in the form of chondrules), iron, and nickel; **relatively volatile materials were unable to condense out of the nebula because of the high temperatures** in that region.

At distances **greater than 5 AU from the growing protosun**, just inside the present-day orbit of Jupiter, the nebula became sufficiently **cool that water-ice could form** as well. The result was that water-ice could also be included in the growing planetesimals beyond that distance.

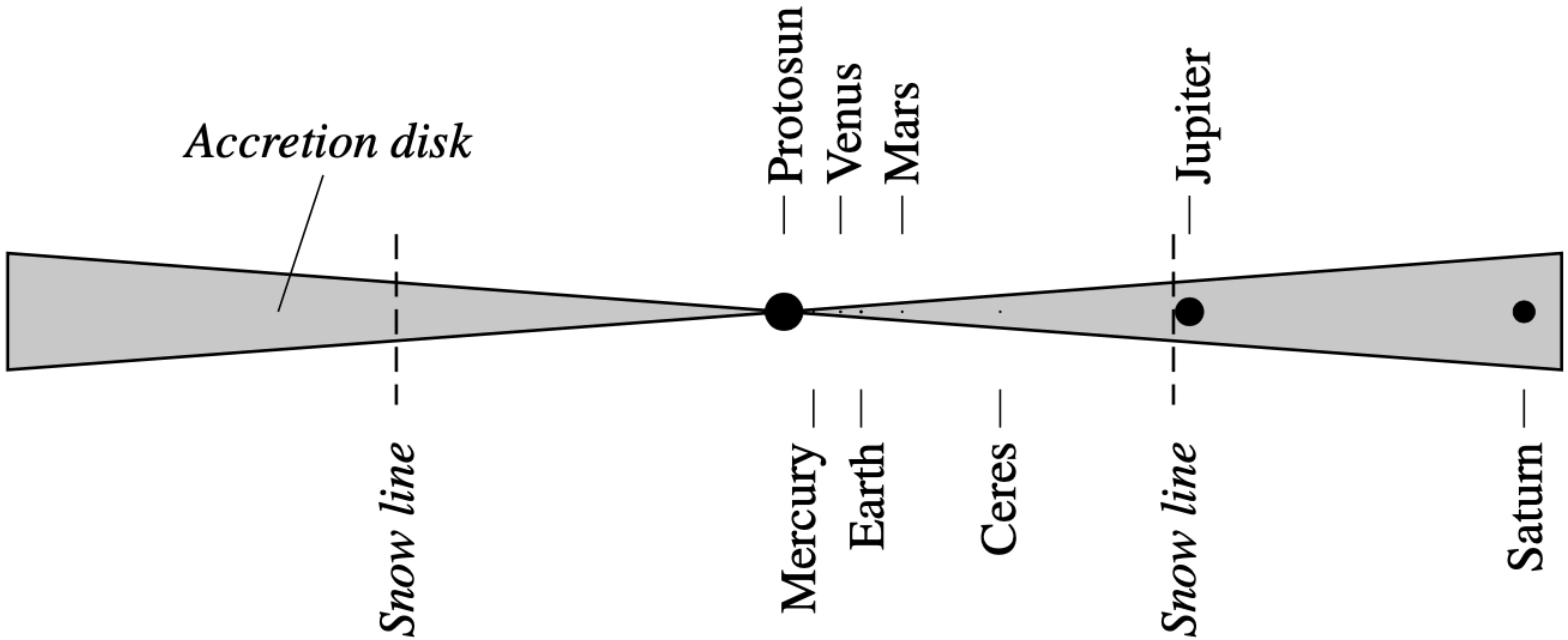
Even farther out (perhaps near **30 AU,** the present-day orbit of Neptune), **methane-ice also participated in the development of planetesimals.** The location of the "snow line" where water-ice could form is shown in Fig. 10 (recall also Fig. 9).



Formation of the Gas and Ice Giants

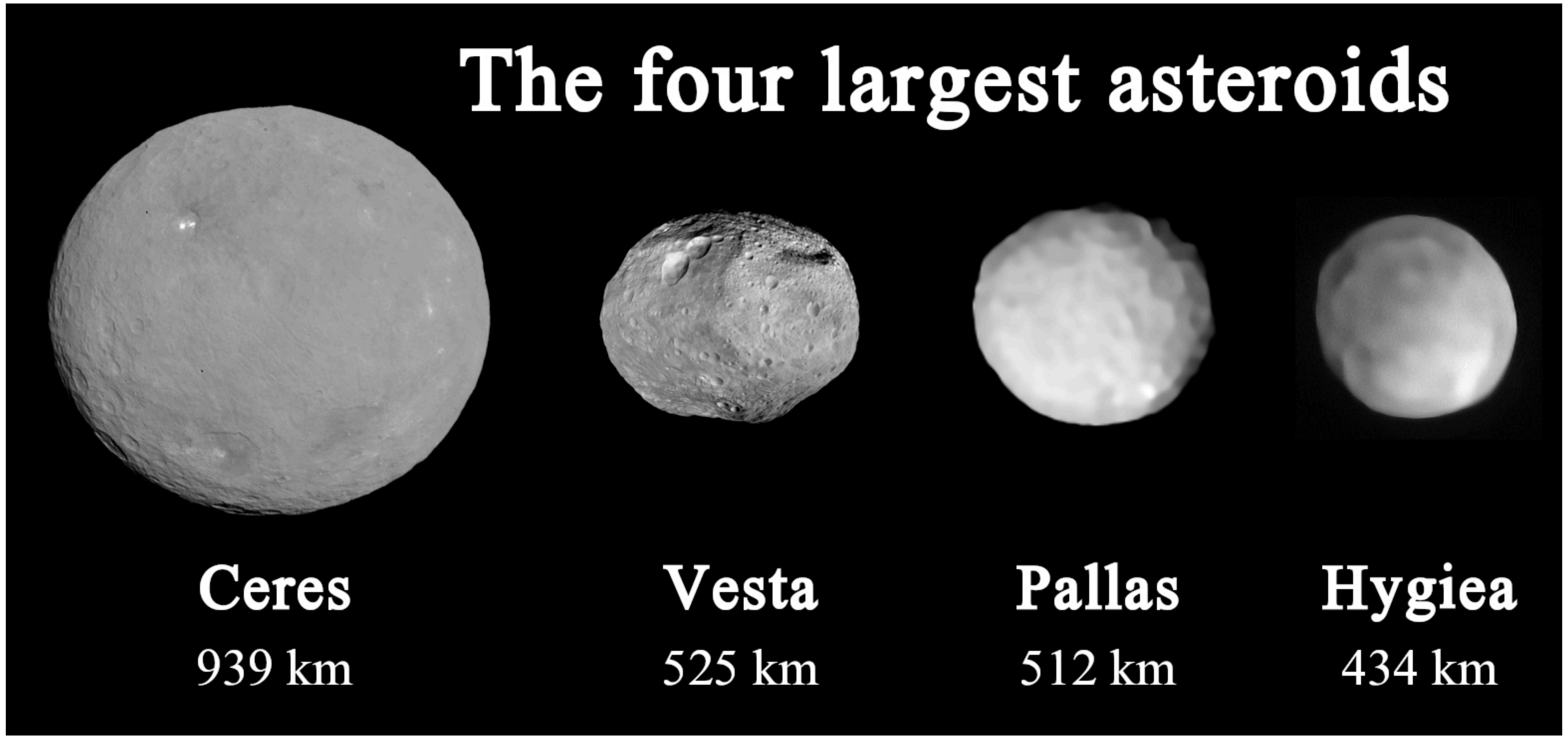
A schematic drawing of the solar nebular disk, indicating the position of the water-ice **"snow line" 5 AU** from the protosun. **Methane-ice** began forming at roughly **30 AU** from the protosun as well.

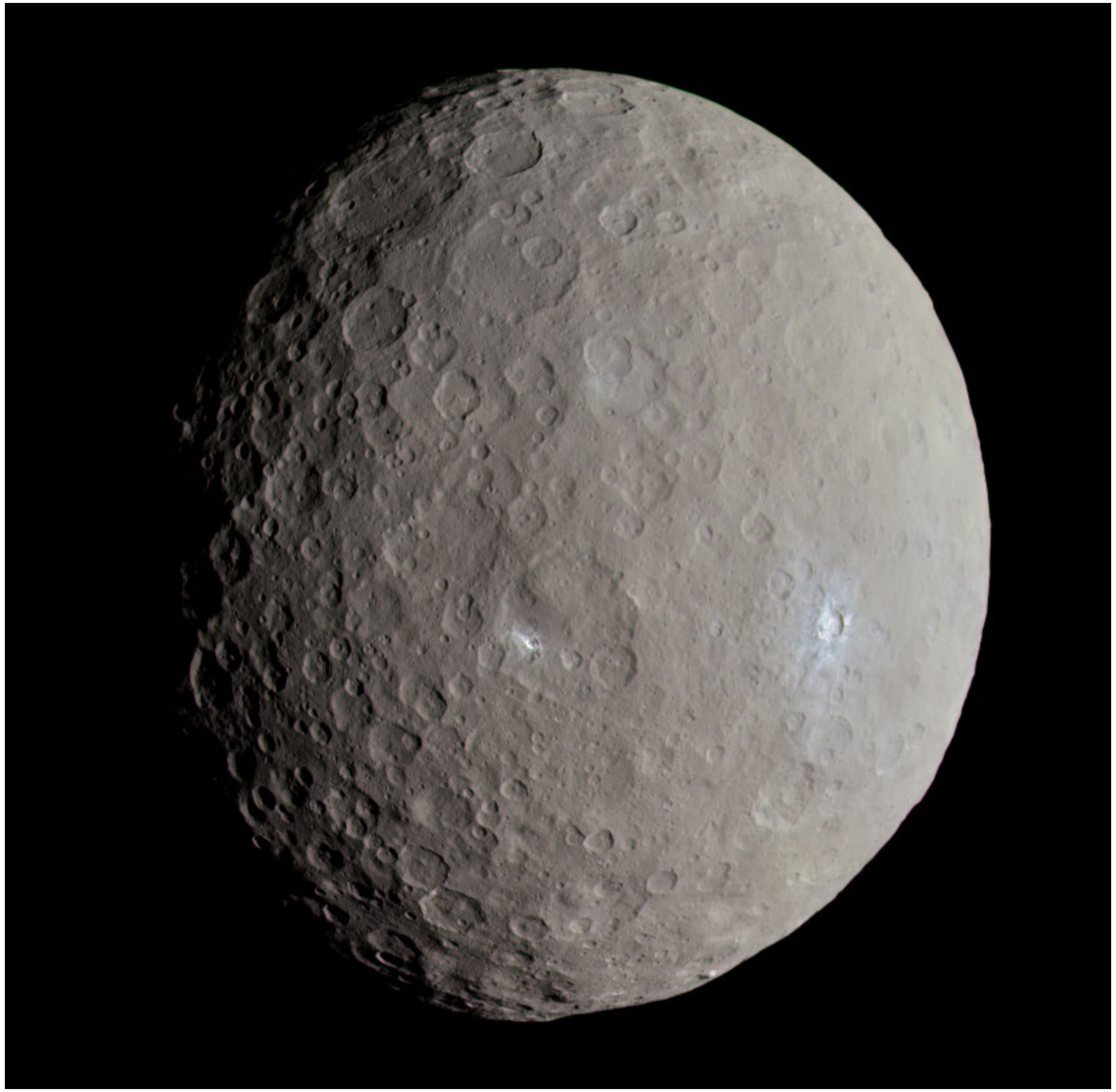
The protosun, the protoplanets, and Ceres are located at their relative present-day distances, but their relative sizes are not correct.



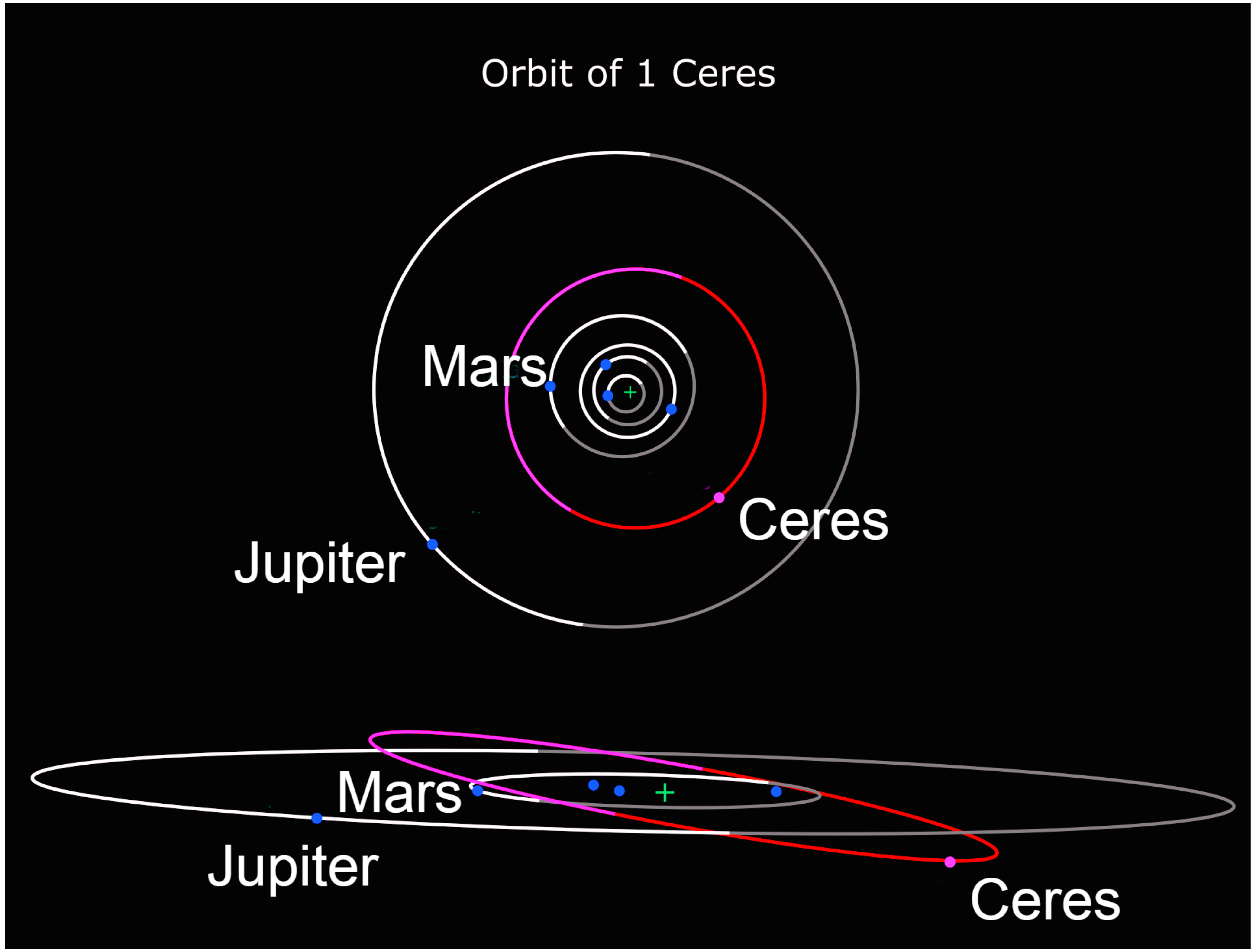
Formation of the Gas and Ice Giants

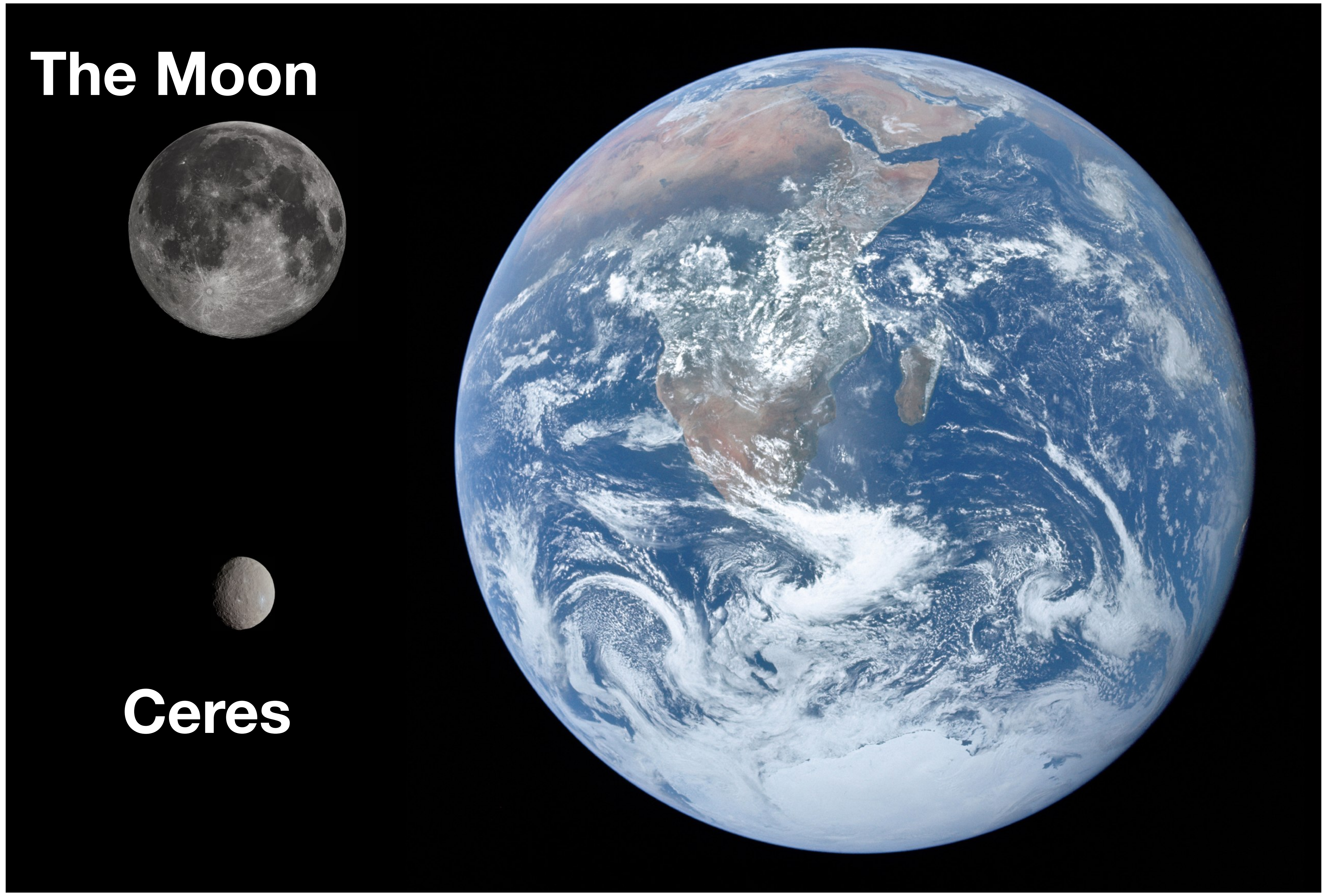
Ceres is a dwarf planet in the middle main asteroid belt between the orbits of Mars and Jupiter. It was the first asteroid discovered, on 1 January 1801.



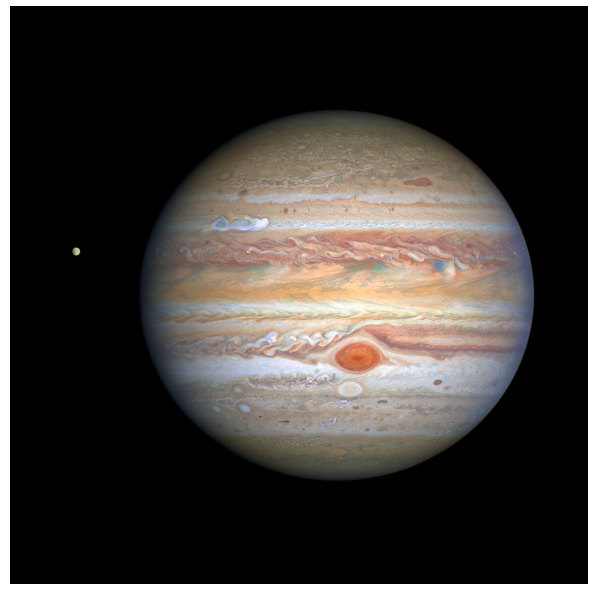


Formation of the Gas and Ice Giants



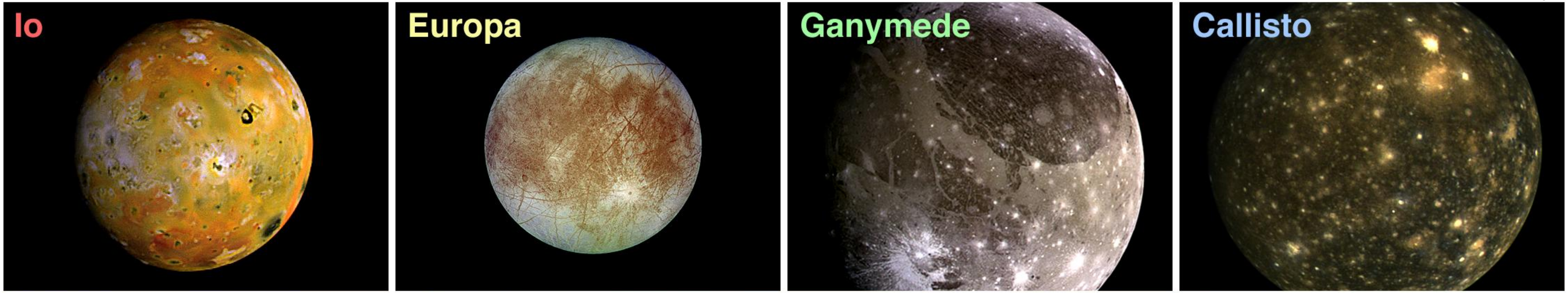


Formation of the Gas and Ice Giants



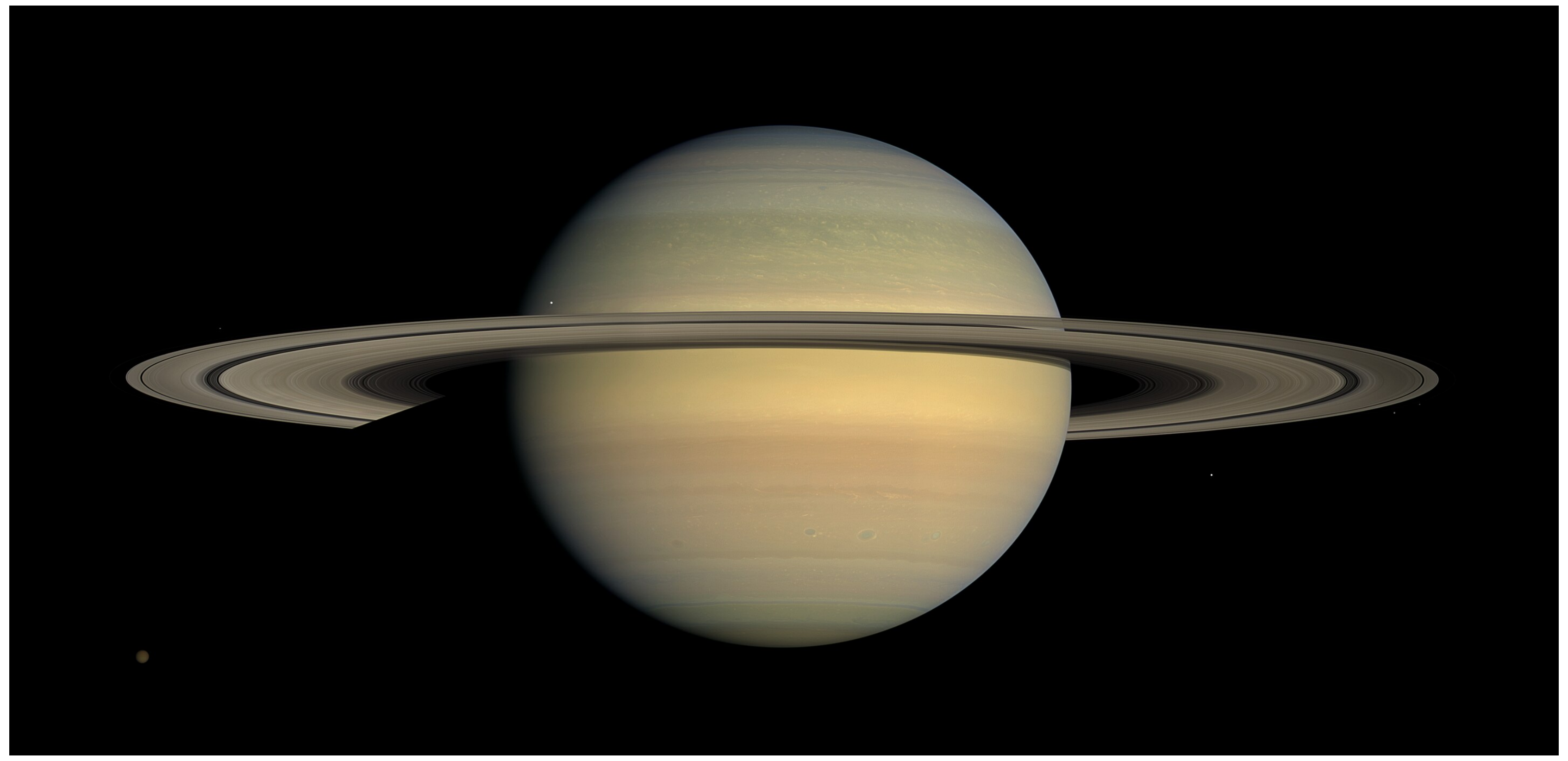
- The object that grew most rapidly was Jupiter.
- Thanks to the presence of water-ice along with rocky materials, and with a nebula that was **sufficiently dense in its region**, Jupiter's core reached a mass of between 10 and 15 $M_{\oplus}$. At that point the planet's **gravitational influence** became great enough that it started to **collect the gases in its vicinity** (principally hydrogen and helium).
- In effect, this **created a localized subnebula,** complete **with its own accretion disk.**
- The outcome was the formation of the massive **planet**, together with the **Galilean satellites.**
- Heat generated in the gravitational collapse of Jupiter, combined with tidal effects, led to the eventual evolution of its moons.

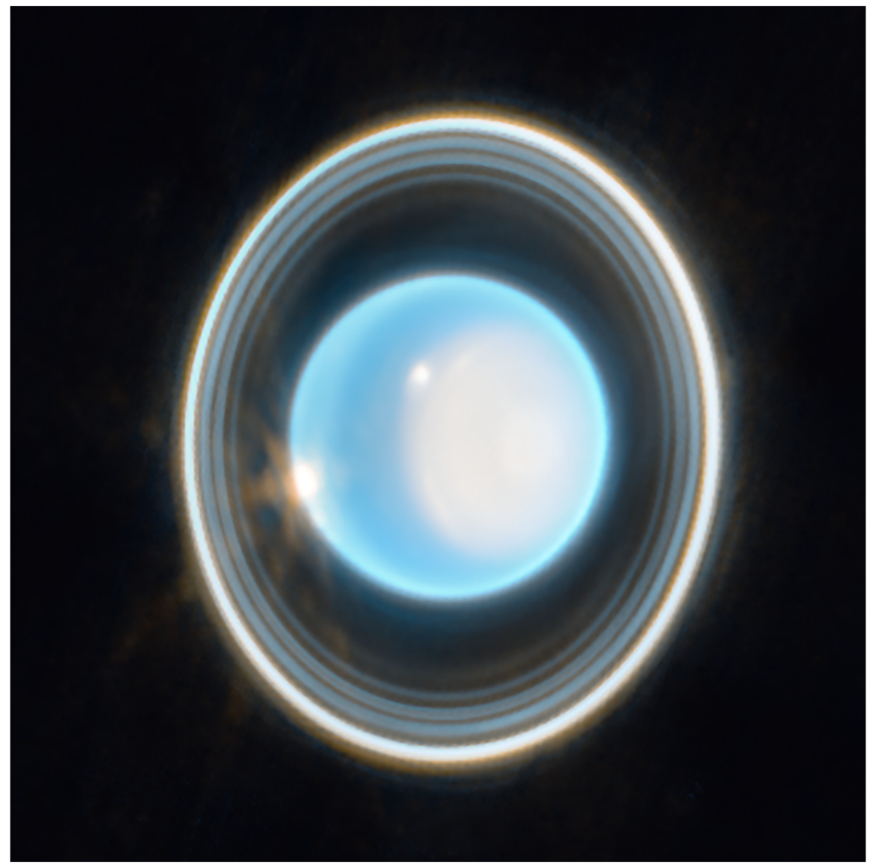
The Galilean moons of Jupiter

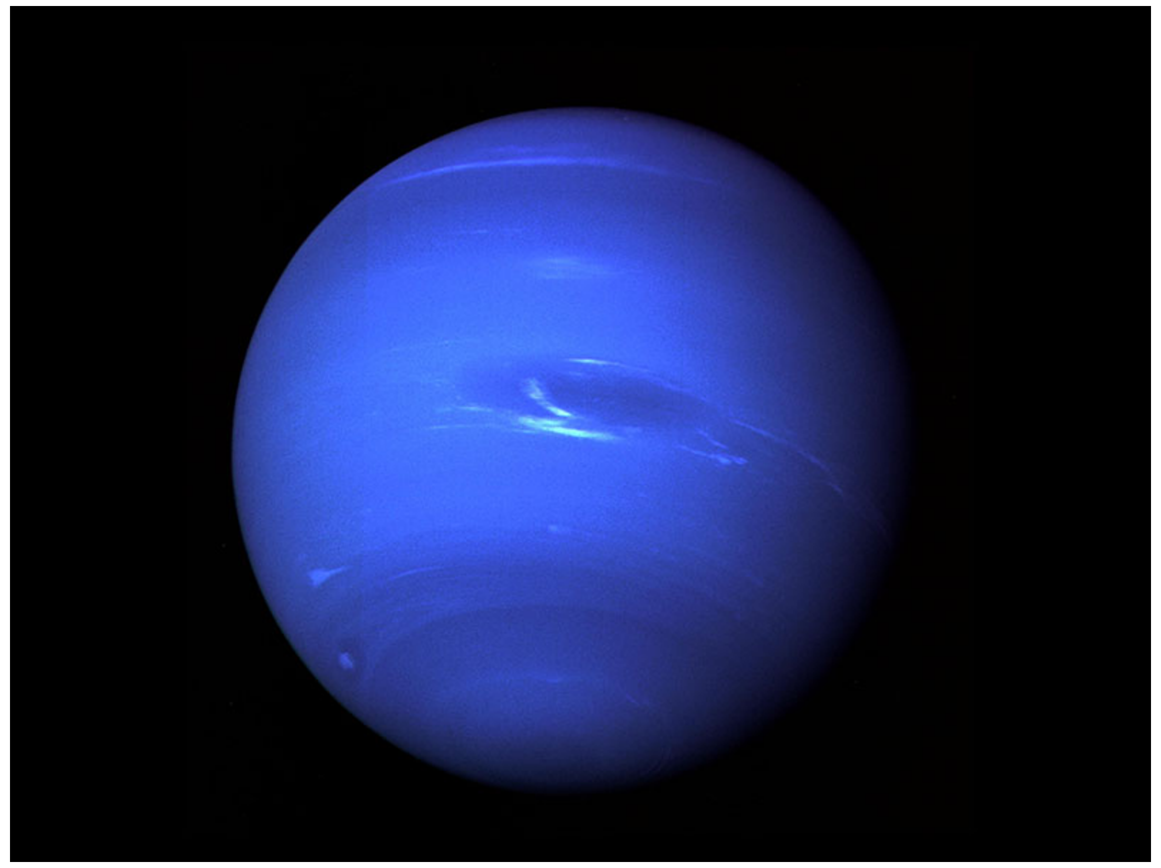


Formation of the Gas and Ice Giants

- We estimate that the entire process of forming Jupiter required on the order of $\mathbf{10^6}$ **years**, halting when the gas was depleted.
- The formation of the massive Jupiter had a **significant impact on the other three planetesimals** that had also grown to significant size beyond the snow line.
- Although **Saturn, Uranus, and Neptune** all developed **cores of 10 to 15** $\mathbf{M_{\oplus}}$**,** they were somewhat farther out in the nebula where the **density was lower.** As a result, they were unable to acquire the amount of gas that Jupiter captured in the same period of time.



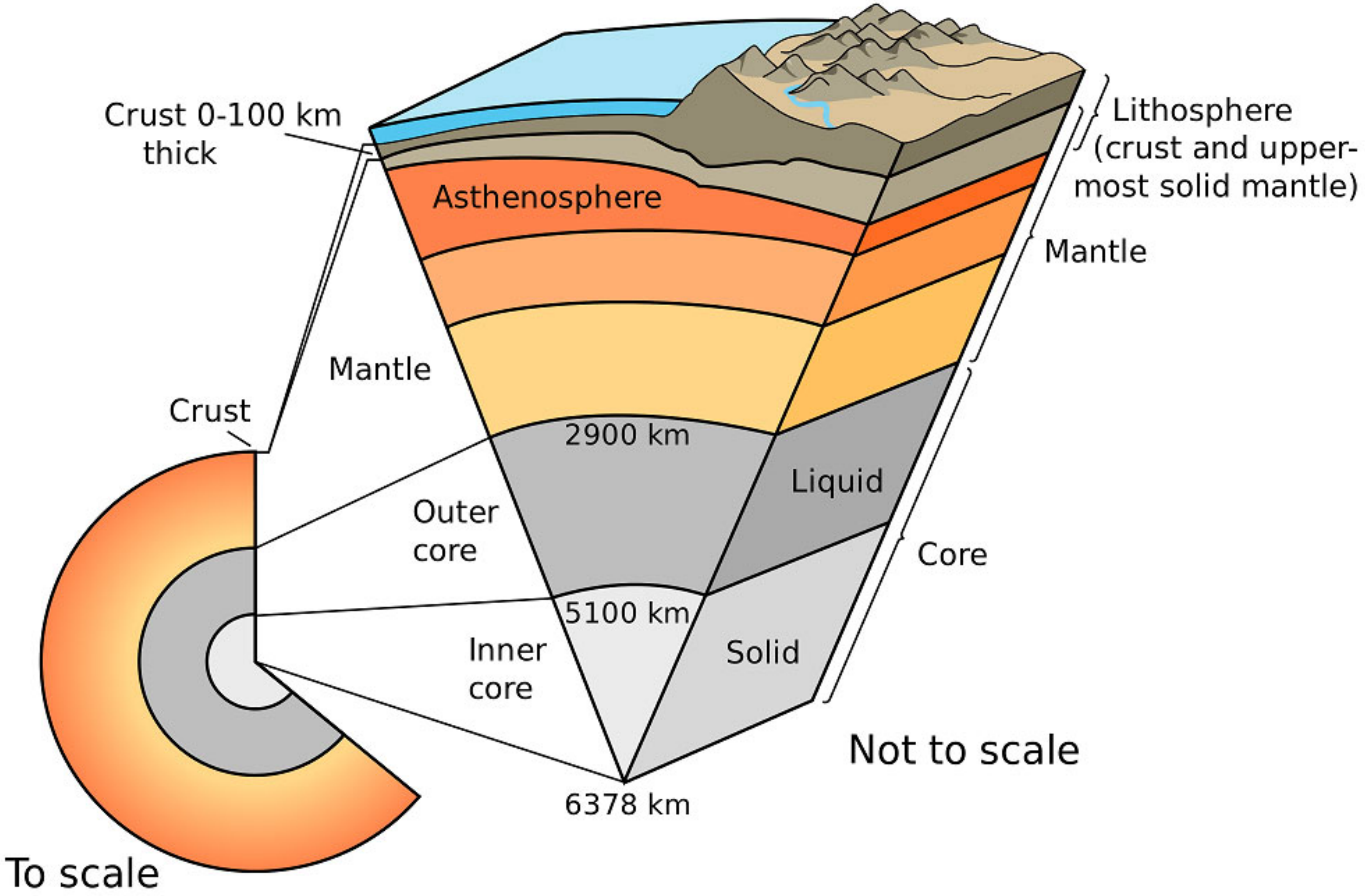




Formation of the Terrestrial planets

- In the inner portion of the solar nebula the **temperatures were too warm** to allow the volatiles to condense out and participate in the formation of planetesimals.
- But as the nebula cooled, the most refractory elements were able to **condense** out to form the **CAIs**. Next to condense were the **silicates** and other equally refractory materials.
- The slow relative velocities of silicate grains in nearly identical orbits resulted in **low-energy collisions** that promoted **grain growth.**
- Eventually, a hierarchy of **planetesimal sizes developed**.
- Computer **simulations** suggest that in the region of the terrestrial planets, along with a large number of smaller objects, there **may have been as many as 100 planetesimals roughly the size of the Moon**, **10 with masses comparable to Mercury's, and several as large as Mars.** However, during the accretion process, most of these large planetesimals became **incorporated into Venus and Earth.**
- When the forming planets became **massive enough, internal heat** that was generated by **decaying radioactive isotopes, together with energy released during collisions**, started the process of **gravitational separation.** The results were the **chemically differentiated** worlds we see today.

Formation of the Terrestrial planets



https://www.usgs.gov/media/images/earth-cross-section

Formation of the Terrestrial planets

- With the formation of the massive Jupiter just beyond 5 AU from the Sun, **gravitational perturbations** began to influence the orbits of planetesimals in the region.
- In particular, most of the objects in the present-day **asteroid belt** had their orbits "pumped up" into progressively more and more eccentric orbits until some of them were **absorbed by Jupiter** or the other developing planets **or were sent crashing into the Sun**, while most were **ejected from the Solar System** entirely.
- This process stole material from the "feeding zones" near Mars and in the asteroid belt, **resulting in a smallish fourth planet** and very little mass in the belt. Perhaps only 3% of the original mass near Mars's orbit remained and only 0.02% of the mass in the region of the belt.
- Continued **perturbations from Jupiter** meant that the remaining belt of planetesimals had rather high relative velocities and were never able to consolidate into a single object. In fact, the **high relative velocities imply that collisions cause fracturing, rather than growth.**

Formation of the Terrestrial planets

- As planetesimals continued to move throughout the forming Solar System, other **collisions occurred.**
- Some of the largest planetesimals in the inner Solar System **collided with Mercury**, **removing its low-density mantle,**
- and some struck Earth, **forming the Earth–Moon system**.
- Still other planetesimals of significant mass **crashed into Mars and the outer planets,** changing the **orientations of their axes.**
- Apparently, some of the planetesimals were also **captured as moons** or were torn apart by the giant planets when they wandered inside the planets' Roche limits.
- Long before the terrestrial planets finished "feeding" on planetesimals in their regions of the disk, however, the evolving **Sun reached the stage of thermonuclear ignition** in its core, initiating the **T-Tauri phase**.
- At this point the infall of material from the disk was reversed by the **strong stellar wind** that ensued, and any **gases and dust** that had not yet collected into planetesimals were **driven out of the inner Solar System.**

Formation of the Terrestrial planets

Migration

- The accretion scenario described above is not without its own challenges. For instance, a long-standing problem has to do with the **formation of the ice giants.** At their **current positions in the Solar System,** it appears that the **solar nebula would not have been dense enough** to allow them to reach their present-day masses before the remaining gas was swept away by the T-Tauri wind.
- In addition, how is the episode of **late heavy bombardment** to be explained as a spike in collision rates **roughly 3.8 Gyr ago**?
- The apparent solution to both of these problems seems to lie in understanding a perplexing problem with many extrasolar planets.
- With the discovery of **"hot Jupiters"** in extrasolar planetary systems, scientists realized that **planets must be able to migrate** inward while they are forming, and **Jupiter is no different**.
- Computer **simulations** of Solar System evolution suggest that **Jupiter formed about 0.5 AU farther out** in the nebula than its current position.
- One mechanism by which inward migration of Jupiter (and extrasolar planets) could occur involves **gravitational torques between the planet and the disk**. In this mechanism, initial deviations from axial symmetry produce density waves in the disk.

Migration

- The gravitational interaction between a growing planet and **density waves** results in the simultaneous **transfer of angular momentum outward and mass inward.** This so-called **Type I migration** mechanism can be shown to be proportional to mass, implying that **as the planet accretes more material, it moves more rapidly toward its parent star.** It may be that this can actually cause some planets to collide with the star on a timescale of one to ten million years.
- However, it initially appeared that the timescale for Type I migration was too short compared with the runaway accretion of gases onto the growing Jupiter; in other words, **Jupiter would crash into the Sun before it could fully form.** It also appeared that **Jupiter couldn't grow rapidly enough** to reach its present size before the nebula was dissipated by the T-Tauri wind.
- The solution to these problems may rest with the migration process itself. As the **growing planet moves through the solar nebula, it continually encounters fresh material to "feed on."** If the planet remained in a fixed orbit, it would quickly consume all of the available gas within several Hill radii and would grow only slowly after that.
- Migration allows it to move through the disk without creating a significant gap in the nebula.

Migration

- It has also been shown that **viscosity within the disk** can cause objects to **migrate inward.** This **Type II migration** mechanism causes slowly orbiting particles farther out to speed up because of collisions with higher-velocity particles occupying slightly smaller orbits. The **loss of kinetic energy by the inner particles causes them to spiral inward**.
- Type II migration can become the more significant, if slower, migration process **when a gap is opened up in the disk.**
- **Outward migration is also possible.** In this case, the scattering of planetesimals inward results in migration outward.
- Whether inward or outward migration occurs **depends on the density of the nebula and the abundance of planetesimals.**
- **Migration in the Solar System: Jupiter not only influenced objects interior to its present-day orbit but also was influential in causing Saturn, Uranus, and Neptune to migrate outward.**
- It seems that Uranus and Neptune initially formed their cores in a region of the nebula with a greater density, just as Jupiter and Saturn did. However, because of outward migration, they were able to put on only a small amount of extra gas and remain today as ice giants, rather than gas giants.

Resonance effects

- Assuming that **Jupiter originally formed at about 5.7 AU from the Sun** as some simulations suggest, and that **Saturn formed perhaps 1 AU closer to the Sun** than its current position, the two gas giants would have moved through a **critical resonance as Jupiter migrated inward and Saturn migrated outward.**
- When the **orbital periods of the two planets reached a 2:1 resonance** (i.e., the orbital period of Saturn was exactly twice the orbital period of Jupiter), their gravitational influences on other objects in the Solar System would have periodically combined at the same points in their orbits, **causing significant perturbations to orbits of objects in the asteroid belt and in the Kuiper belt.**
- Computer simulations suggest that this resonance effect may have occurred **about 700 Myr after the formation of the inner planets and our Moon.** It seems plausible that the passage of Jupiter and Saturn through this 2:1 resonance may have caused the **episode of late heavy bombardment** that is now recorded on the surface of the Moon.

Resonance effects

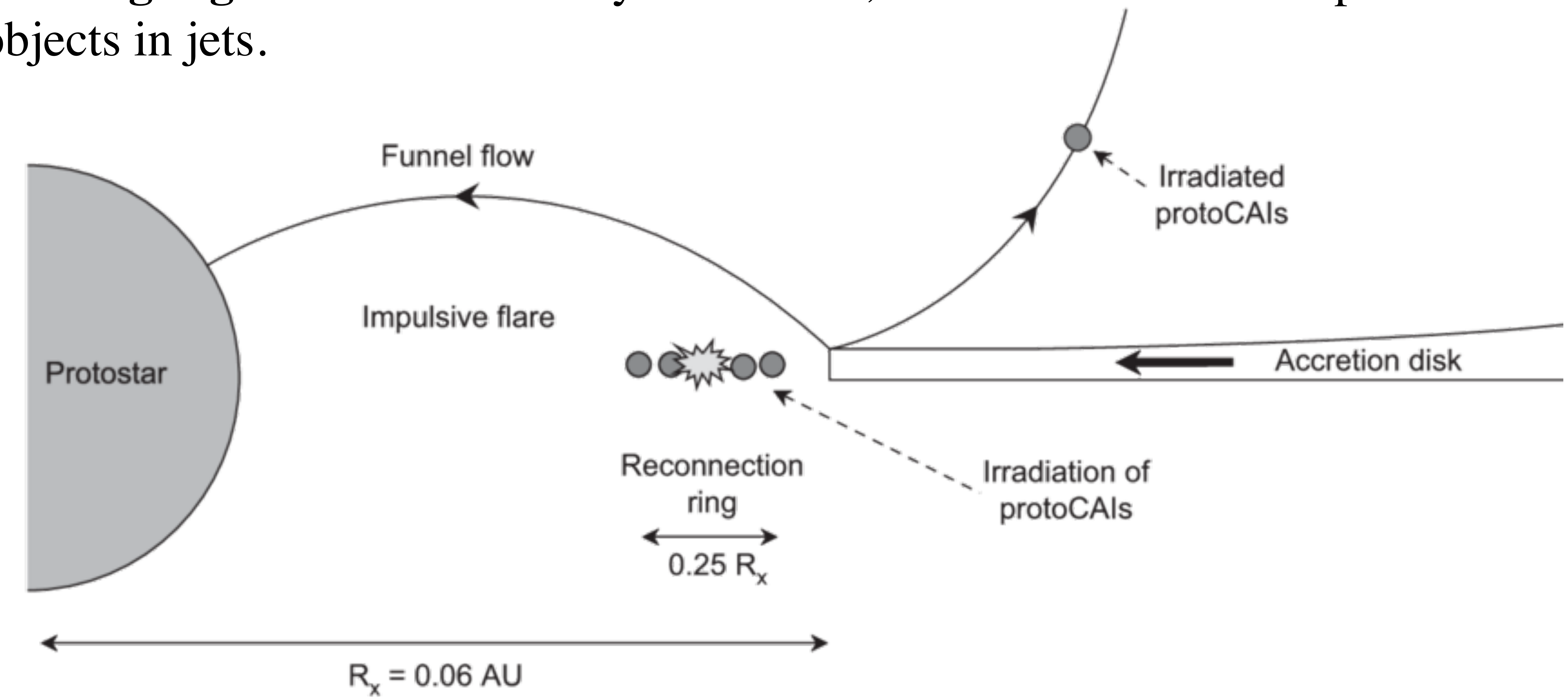
- As a consequence of **Neptune's outward migration,** Neptune swept up some of the remaining **planetesimals, trapping them in 3-to-2 orbital resonances** with the planet as it moved outward.
- It may be that **Pluto** and the other Plutinos were caught up in this outward migration. The **orbits of the scattered Kuiper belt objects (KBOs)** were also likely to have been perturbed by the migration of Neptune.
- The classical KBOs were probably far enough from Neptune not to be as drastically affected by its migration.
- The Kuiper belt may be the Solar System's analog to debris disks seen around other stars.
- Similarly, the **Oort cloud cometary nuclei** are likely to be planetesimals that were **scattered more severely by Uranus and Neptune**.
- Once sufficiently far from the Sun, scattered cometary nuclei had their orbits randomized by passing stars and interstellar clouds.

The Formation of CAIs and chondoles

- A particularly challenging problem with the model of Solar System formation described above is the **presence of chondrules mixed in with CAIs in a matrix** of hydrated and carbon- bearing minerals in chondritic **meteorites**.
- Both the chondrules and the CAIs have certainly been **exposed to intense heat, but the matrix has clearly never been heated** to temperatures greater than a few hundred kevins. Because silicates require lower temperatures to condense out of the solar nebula, **the chondrules probably formed after the CAIs.**
- Silicate dust grains likely formed out of the nebula, coalescing into small clumps through repeated collisions.
- However, they could not have formed initially as molten droplets but, instead, were melted after formation.
- Currently, the most plausible scenario suggests that powerful flares during FU Orionis events may be responsible for the melting or partial melting of chondrules and CAIs.

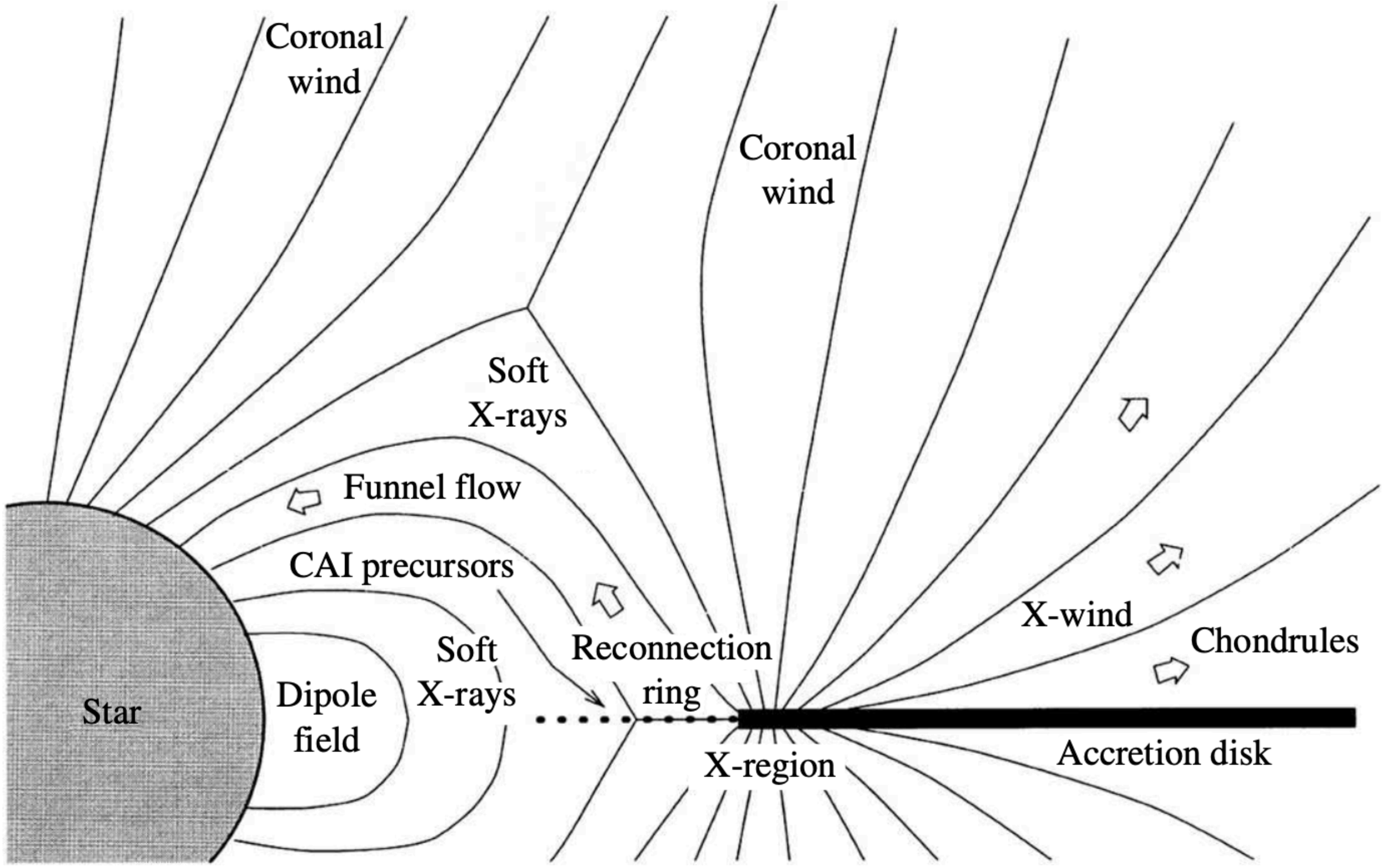
The Formation of CAIs and chondoles

- As the inner edge of the accretion disk moves in and out on timescales of 30 years or so (perhaps associated with magnetic field activity), the **silicate grains are exposed to flash heating by flares** resulting from reconnection events.
- In the rarefied environment at the interior edge of the nebula, the **droplets are able to cool rather quickly,** perhaps between 100 and 2000 K per hour. It has been suggested that the metamorphosed chondrules may be **launched back into the planet-forming region** of the nebula by an X-wind, similar to the wind responsible for the ejection of Herbig–Haro objects in jets.



The Formation of CAIs and chondoles

- In the planet-forming region of the nebula, the chondrules and CAIs are **incorporated into the matrix**. This model of chondrule formation implies that the solar nebula was a very dynamic system indeed.
- Planet formation models are under active research.
- The newly discovered exoplanets and new the research with new telescopes (e.g. James Webb telescope, LOFAR) are advancing the field rapidly.



A schematic diagram of the X-wind model.

Shu et al., 2001.)

Condrites

- A chondrite is a stony (non-metallic) meteorite that has not been modified, by either melting or differentiation of the parent body. They are formed when various types of dust and small grains in the early Solar System accreted to form primitive asteroids.