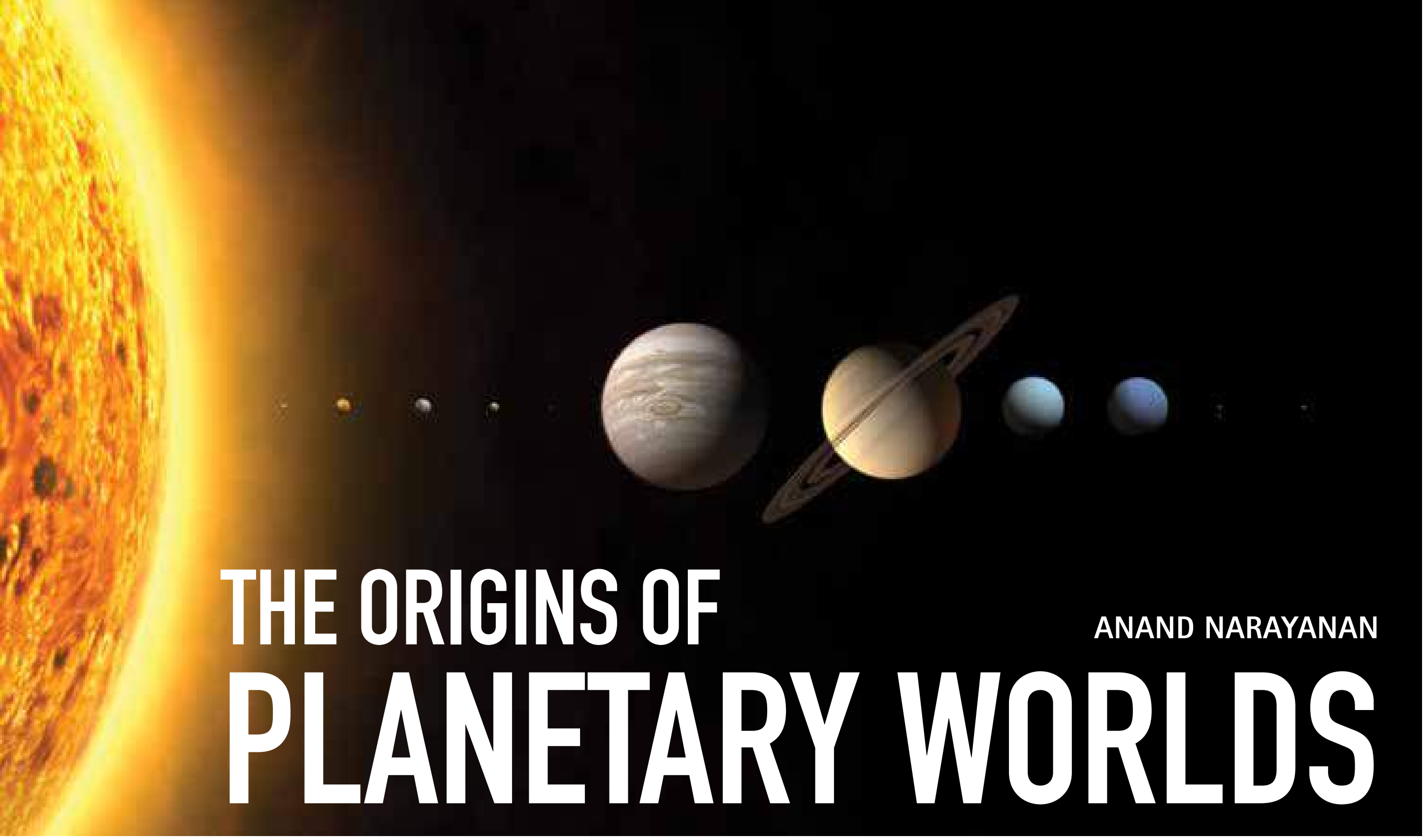

THE ORIGINS OF PLANETARY WORLDS

ANAND NARAYANAN

The solar system is the only place in the entire cosmos that we have surveyed directly using spacecrafts. Years of long and fascinating collaborative efforts between many different disciplines have helped us understand its origins and subsequent evolution. This article narrates this scientific story, discussing how our understanding of planetary systems has been altered by new findings from within and beyond the solar system.

Within the vastness of the universe, with its billions of galaxies and thousands of trillions of stars, there is only one place we can truly call home. The planet Earth is a tiny world compared to the astonishing scale of everything else in outer space. And yet, this rocky world is a special place. It is the only planet we know of that supports life.

Have you ever wondered how the Earth came to be? When and how it was formed? What was there before the birth of the solar system? Underlying such questions is a more fundamental and perennial urge – to know whether we are alone in this universe. We have always wondered about the possibility of life outside Earth. After all, the Earth is just one planet among many others orbiting the Sun, and the Sun a typical star in a universe of countless stars. What are the odds of finding another planet like the Earth circling another star? Is life is a one-time chance event, an extremely rare occurrence, or a ubiquitous phenomenon?

The Birth of the Solar System

The birth of the solar system is a thing of the past. We cannot go back in time and witness how it happened. Our best hope to understand the origins of the solar system lies in carefully formulating hypothesis on possible pathways through which planet formation could have happened. We can then corroborate our hypothesis against some hard scientific evidence. Fortunately, we do not have to do this entirely in the dark. The architecture of the solar system itself holds many crucial clues to its formation.

Patterns of a Common Origin

There are several lines of evidence that suggest that all the components of the solar system have a common origin. For example:

1. All planets orbit the Sun in the same direction. Seen from any point high above the Earth's North Pole, they all revolve around the Sun in counterclockwise direction.
2. The Sun rotates on its axis in the same direction as the planet's revolution around the Sun. This is called **prograde rotation.**
3. The orbits of all planets and a vast majority of minor bodies are nearly circular.
4. All planetary orbits lie along nearly the same plane.

Since, these would be unlikely to occur if individual components had come into existence independently, they seem to strongly suggest the origin of the entire solar system from a single event.

Age of the solar system

If the birth of the solar system was a single event in the history of the universe, how far back in time did it happen?

Scientists have attempted to answer this question by trying to estimate the age of very old rocks – not just here on Earth, but also from outer space. Age estimates of the oldest rocks on Earth done using a technique called radiometric dating, yield a value close to 4.5 billion years (see Figure 1). This is supported by the radiometric dating of several meteorite samples recovered from different locations on Earth, which also suggest an age close to 4.5 billion years. So that's when it must have all happened – about 4.5 billion years ago. To put that number in perspective, the first forms of life appeared about a billion years after the Earth formed, and early humans, according to some estimates, only around 600,000 years ago!

Fig. 1. Fragments of a meteorite collected on April 24, 2012, two days after they fell on Earth. Meteorites are chunks of rock, small and big, that fall onto Earth from outer space. As left-over rocks from the early days of the solar system, they are of great interest.

Credits: © NASA / Eric James.

4.5 billion years ago

What existed before the solar system? Astronomers have put together a more or less coherent model, in keeping with the known facts and theories. To understand this model, we need to shift our attention away from the stars, to the space between them.

When we gaze at the night sky with our naked eyes, we see the shimmering stars and the darkness of the empty space separating them. But the space between stars is far from empty! What our eyes fail to perceive are large columns of gas and dust that pervades most of the space between stars. This is called the **interstellar medium** or ISM for short. In long-exposure photographs, like the one in Figure 2, the ISM is visible as a thick dark lane.

The primary ingredients of the ISM are atoms of hydrogen and helium,

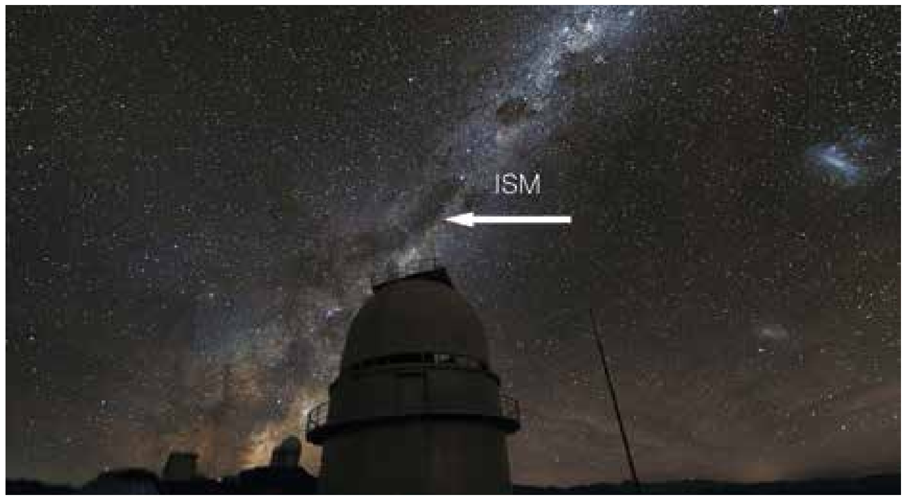

Fig. 2. A long-exposure photograph of the night sky, taken from a location in the Earth's Southern hemisphere. In the background, we see stars as tiny dots of light. Observing this image closely, one may also see dark patches or dark lanes that seem to hide the light from the stars. This is the interstellar medium (ISM), which is made up of gas and very tiny dust particles, spread over vast regions of our Galaxy, in between the stars. In the foreground is an astronomical observatory. Only from such very dark locations like this can the ISM be photographed from Earth with such clarity.

Credits: © European Southern Observatory/Z.Bardon. URL: http://phys.org/news/2016-11-magellanic-clouds.html.

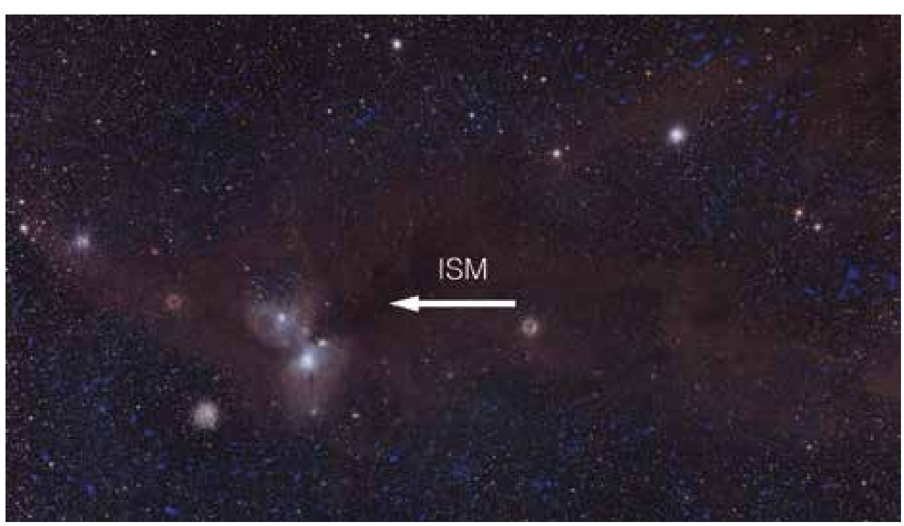

Fig. 3. A zoomed-in photograph of a region within our Galaxy. The diffuse dark cloud is the interstellar medium, which is a mixture of gas and dust grains. Such ISM clouds tend to dim the light coming from stars behind them.

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(a) (b)

Fig. 4. Photographs of star-forming regions taken by the famous Hubble Space Telescope. (a) The famous Orion Nebula, one of the many current sites of star formation in our Galaxy (Milky Way or Akashganga). This particular nebula is very well studied by astronomers because of its relative proximity to us (approximately 1350 light years). It can be spotted in the sky as a faint glow if you look in the direction of the constellation Orion. The Orion Nebula contains enough gas to give birth to thousands of stars. The region that you see in this photograph is a few light years across. (b) The star-forming region in a nebula called NGC 346, within our Milky Way galaxy. The blue and dark coloured columns of gas are the dense ISM gas clouds. Most of the stars at the centre of this image are relatively young, born out of fragments in the gas cloud.

Credits: © NASA/ESA/HST.

with some trace amounts of heavier elements such as carbon, nitrogen, oxygen, and so on. In addition there are very tiny grains of dust. These dust grains, believe it or not, are very similar in composition and structure to the dust grains here on Earth.

Much of this ISM is wispy, with densities of 1 atom per cubic centimetre or even lesser. Although very diffuse, the ISM makes up about 15% of the total visible mass of our Galaxy. This is because there is a lot of space between stars, and the ISM occupies nearly all of it. Certain regions of the ISM are a 100 – 1000 times denser than the average. These denser clouds of gas are loosely referred to as **nebulae.** Very cold and dense nebulae, called **molecular clouds**, are the sites of birth of new stars (see Fig. 4).

Dense interstellar regions, like the Orion Nebula, are huge clouds of gas with enough mass to form hundreds or thousands of stars. The birth of an individual star happens through fragmentation. Studied with great interest in astronomy, fragmentation refers to a process where

Visible • WFPC2 **Infrared • NICMOS**

(a) **(b)**

Fig. 5. Two images of the same region, called the Trapezium cluster, within the Orion Nebula, showing a large column of interstellar gas. The two images of this cluster, which is roughly 1300 light years from us, were captured by two different cameras connected to the Hubble Space Telescope. (a) In this image taken at visible light (the same light that our eyes perceive), we can see the gas columns within the cluster. But, as photons of visible light are easily scattered by dust particles, this photo does not show us the inner regions of the nebula. (b) This is a photograph of the same region, taken with a different camera on Hubble that collects infrared photons. Since infrared photons are scattered much less by dust, we are able to peer through the diffuse gas clouds and see what is inside the nebula.

Credits: © NASA/ESA/HST.

Box 1. Sequential snapshots from a supercomputer simulation

Supercomputers help in simulating very slow but complex processes, like the birth of planetary systems, by allowing us to see the sequence of events at a very fast rate. This is very much like watching a movie in fast-forward.

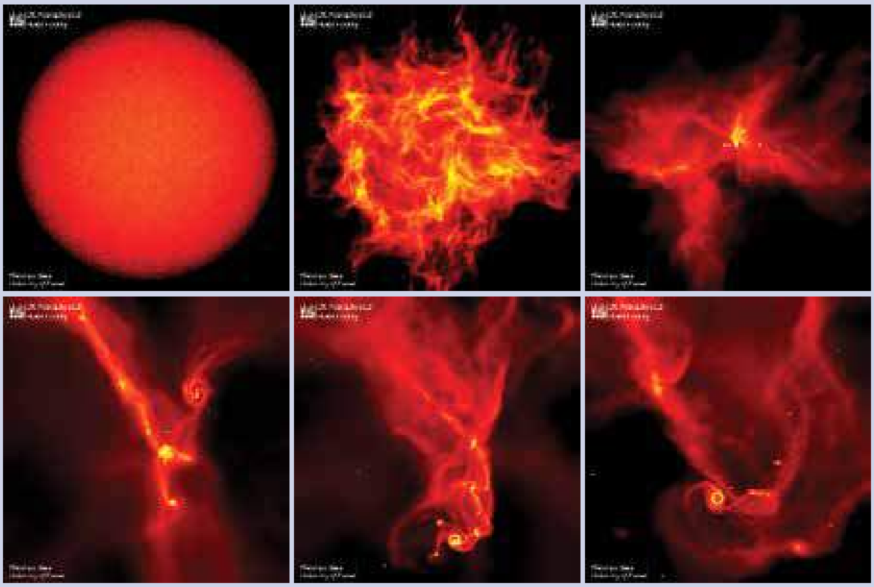

Fig. 6. A super-computer simulation of a star-forming nebula. This simulation begins with the visualization of a giant spherical nebula. It then adds some non-uniform turbulence to this gas cloud, causing parts of it to slowly fragment and collapse. The fragmentation process alters the shape of the nebula, giving it a more filamentary structure. The individual fragments continue to collapse, eventually forming stars. You can watch a full blown animation of this process here: https://www.youtube.com/watch?v=YbdwTwB8jtc.

Credits: © Mathew Batte, University of Exeter.

smaller segments break away from a bigger entity and begin to evolve independently. Many different processes – such as an external shock from an exploding star, a pressure wave propagating through a galaxy, or internal turbulence – can trigger the fragmentation process in an interstellar nebulae. These processes are extremely complex and can only be understood with the help of supercomputers.

It's likely that our Sun, like the newly born stars in the Orion Nebula (see Fig. 7), was also formed from a small fragment within a big nebula about 5 billion years ago. Let's call this fragmented bit the **presolar nebula.** Once fragmented, the presolar nebula started collapsing under its own gravity, shrinking in size every step of the way.

Fig. 7. Fragments within the Orion nebula collapsing under their own gravity. This image, taken by the Hubble Space Telescope, shows several fragments embedded within a cloud in the Orion Nebula. Each fragment has started collapsing under its own gravity and is well on its way to becoming one or more stars. It is possible that our own solar system was formed out of a fragment similar to this.

Credits: © STScI/NASA and ESA.

As it continued to collapse, the temperature of the presolar nebula started rising. This is because the gravitational energy in the collapsing star gets converted first to kinetic energy, and then to thermal energy (which is heat). The collapsing nebula was hottest at its center where most of its mass was concentrated into a big ball of gas (see Fig 8).

Fig. 8. An artist's impression of what a young Sun must have looked like, soon after it formed. In its early phase, the glow of the Sun would have come from the conversion of gravitational energy into thermal energy. Nuclear fusion reactions would have started only after a million years or so, when the density and temperature at the centre of the Sun had reached high values.

Credits: © NASA Goddard Media Studios.

This ball of gas was destined to become the Sun, but not immediately, because conditions were not conducive for the onset of nuclear fusion reactions at its core. Astronomers call such blossoming stars **protostars.** Although nuclear fusion had not yet begun, the conversion of gravitational energy would have been enough to set the proto-Sun ablaze.

Protoplanetary disks – A key milestone in planet formation

According to the current model of planet formation, as the proto-Sun was born, something very interesting took shape around it. A part of the collapsing nebula flattened out, forming a thick disk of material around the proto-Sun. This disk of material is called the **circumstellar disk**

Fig. 9. An artist's impression of a protoplanetary disk around a nascent star.

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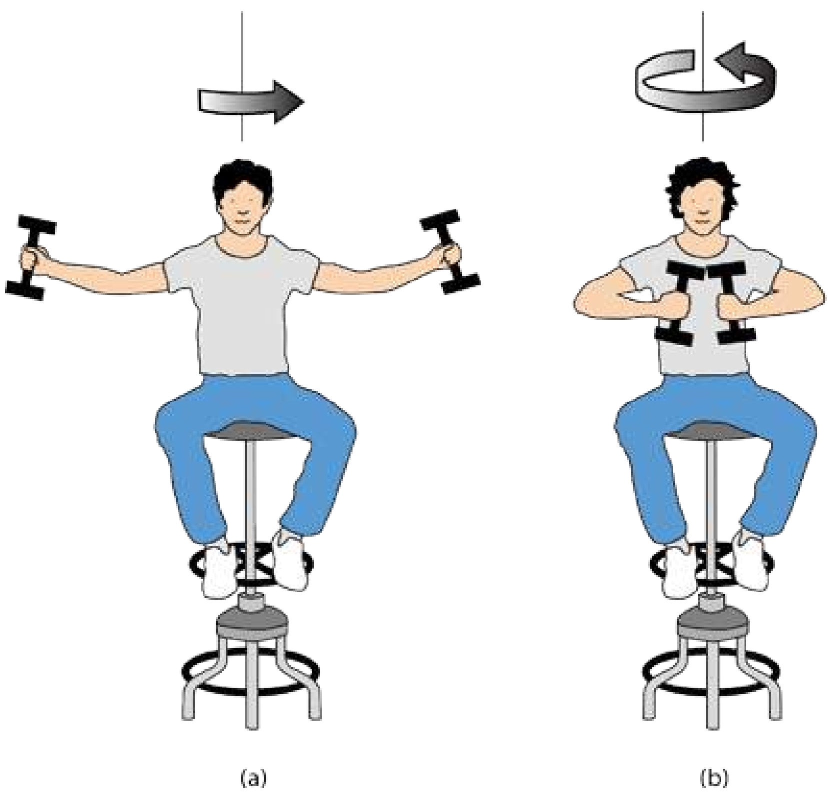

Fig. 10. Spinning on a swirling chair – an example of the principle of conservation of angular momentum. You will notice that when your weight is spread out, you tend to rotate slower. As you shrink by pulling hands and legs inwards, your speed of rotation automatically increases. The principle of cconservation of angular momentum tells us that the angular momentum of a system, which is the product of how mass is distributed within that system and its spin velocity (also called angular velocity), will remain a constant. Thus, if the mass of the system is more concentrated, then the system will spin faster. If the mass gets more distributed, the spin will slow down. Here is a nice video that demonstrates this concept: https://www.youtube.com/watch?v=_eMH07Tghs0.

(meaning, a disk circling the star), or the **protoplanetary disk** (meaning, a disk that is a precursor to planet formation).

This disk forms as a result of the need to conserve the angular momentum of the system. The principle of conservation of angular momentum is rather simple. We regularly experience it in our lives. Have you ever sat on a swirling chair? Next time you do so, ask your friends to spin you around. Extend your arms outwards (see Fig. 10). If you want, you can also spread your legs apart. After a few spins, pull both hands and legs inwards. Repeat this and see what happens to your spin speed.

When the pre-solar nebula shrank in size, it started rotating faster. This increase in velocity of rotation ensured that the entire cloud did not collapse into the central proto-sun. Instead some of it formed a circumstellar disk. Estimates suggest that about 99% of the mass of the collapsing nebula must have gone into the Sun, and only 1% settled into the disk. This 1% mass lead to the formation of the planets, their moons, asteroids and everything else that we see in the solar system.

From Disks to Planets – The Pivotal Few Millions Years

Imagine constructing a whole planet as big as the Earth or Jupiter by piecing together particles the size of sand. As absurd and as far-fetched as it may seem, this is exactly what seems to have happened in the case of our solar system. The formation of planets from the swirling gas and dust around the young Sun was an unhurried process that took several million years to complete. These years are likely to have been very dramatic as there were many ways things could have gone differently, retarding the formation of planets and their long-term stability in the solar system.

In the sequence of events that unfolded, the first was the slow condensation of material in the rotating proto-planetary disk to form small lumps of the order

Box 2. Activity zone: Order out of Chaos. The formation of a proto-star with a circumstellar disk is a slow process, lasting several million years. What is interesting, and perhaps counter-intuitive, is that irrespective of the size or shape of a gas fragment in a nebula, after a few million years into its collapse, it will change shape. Its new shape will consist of central spinning big blob of gas, with a disk of matter rotating around it in the same direction. This is an example of order emerging out of chaos.

To see a similar phenomenon in action, try out this simple experiment. Quickly stir in a pinch of coloured powder or turmeric into a bowl of water in a random manner. Leave it for a few seconds and watch what happens. No matter how randomly you stir the water, the powder will almost always settle into a slow rotation, in one direction or the other.

Fig. 11. The formation of dust balls (also called dust bunnies) in our houses is an example of accretion in action.

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of size of a few centimetres. When they encountered each other, these lumps got glued together due to electrostatic force (see Box 3). Once the lumps grew to rocks that were a few centimetres in size, gravitational forces became central to the story. Through gravitational attraction, smaller rocks gathered more matter and gradually grew bigger. This process of smaller objects acting under some force to collate together and grow bigger is called **accretion.** You can find an example of accretion in your own house. You may have noticed that when corners and edges of furniture or walls are not cleaned regularly, the dust in these places tends to gather into balls (see Fig. 11). This is an example of **accretion** – smaller objects acting under some force to collate together and grow bigger.

The rocks formed through accretion are called **planetesimals** (meaning very tiny planets). Planetesimals are not planets. We can think of them as flakes of condensed material that can gradually acquire more mass, and in the very distant future become planets. The kind of chemical compounds that would condense to solid planetesimals depended largely on the temperature in the protoplanetary disk. The temperature in any region of the protoplanetary disk was dictated by its distance from the central proto-Sun. While the temperature of the protoplanetary disc was highest near its centre, due to the Sun's fierce heat, it eased out in a slow manner from the centre of the protoplanetary disk to its outskirts (see Fig. 12).

Astronomers who study the formation and evolution of proto-planetary disks often talk about the **frost-line,** a boundary beyond which easily volatile compounds, like water, can exist as solids. At distances closer than the frost line, these volatile compounds will only exist in their vapour forms. For water and several other hydrogen based compounds, like methane and ammonia, a temperature of about 200 K is a good approximation for transition from solid to vapour form. Given that different volatile compounds have different melting points, the frost line is more likely to be a zone rather than a sharp line. The frost line in today's solar system lies between the orbits of Mars and Jupiter. In the distant past, when the Sun was not so bright, the frost line must have been closer.

In the high temperature regions (500 K – 1500K) inner to the frost line, non-volatile materials, like silicates, and metallic compounds made of iron, nickel, and aluminium, condensed into hard grains. These hard grains first grew into rocky planetesimals, and then to the rocky planets of the inner solar system (i.e., Mercury, Venus, Earth and Mars). Beyond the frost line, hydrogen compounds condensed into grainy ices. Silicates and metals were also still present in the outer solar system, but they were outnumbered by the hydrogen compounds. Thus, the planetesimals that grew in the outer regions of the solar system were primarily icy rocks made of hydrogen compounds with trace amounts of silicate grains and metals engrained in them.

The lightest elements, hydrogen and helium, initially remained as gases, dispersed everywhere in the collapsed

Box 3. What force would have initiated the growth of planets from grains of dust? Gravity would be the common guess. While gravity did play a major role in the formation of the solar system, it was not the first and the most decisive force to seed the growth of planets. The small dust particles in the protoplanetary disk were too small and too light for gravity to be significant between them. Have you ever seen how a balloon that is rubbed on a woollen or cotton material sometimes sticks to the wall? Or how your hair stands up when you bring a ruler that is rubbed on some surface close to it. The main attractive force acting in these cases is electrostatic force, the force between charged particles. The same electrostatic force caused small grains and lumps in the protoplanetary disk to stick together and grow bigger in size.

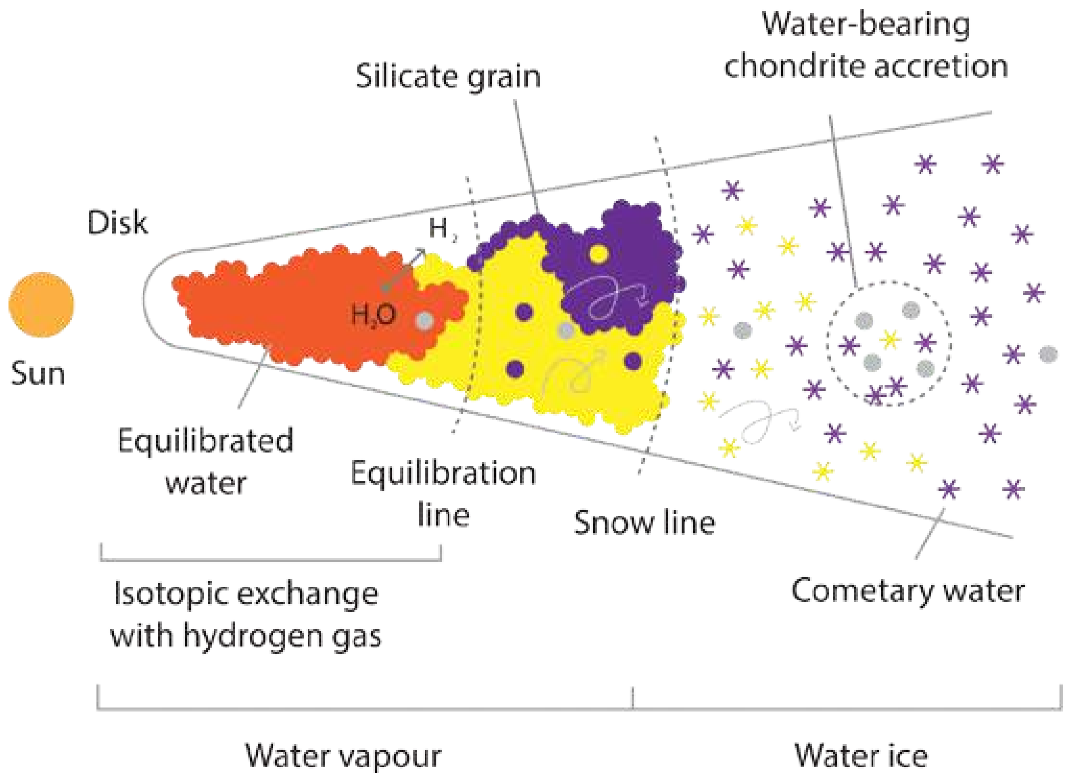

Fig. 12. The temperatures in the protoplanetary disk decide which chemical elements condense at a given location. Close to the newly formed Sun, grains made of heavier metals, with their very high melting points, could remain as solids. Icy materials were easily vaporized because of these high temperatures. They would condense as solids only at a distance from the Sun. The pressure from the Sun's radiation would also sweep the gases into the outer regions of the solar system, mostly beyond the orbit of Mars. This sorting of material in the protoplanetary disk eventually led to the diversity that we come across between the inner terrestrial planets and the outer gas giants of the solar system.

solar nebula without ever condensing into solids. These gases were slowly pushed from the inner to the outer regions of the protoplanetary disk by the pressure of the light radiated by the newly-born Sun, in much the same way as wind steers the sails of a boat. Scientists call this pressure from light – **radiation pressure.** Most of the hydrogen and helium gas thus settled in the outer regions of the solar system. There the icy planetesimals accrued them in large measures, growing gradually in size to become gas-giants, like Jupiter or Saturn. According to this scenario, we expect the cores of these gas-giant planets to be icy, but as of now, these claims remain speculative. For planetary scientists, finding out what the inner regions of a big planet like Jupiter or Saturn is made of from spacecraft observations has been very tricky. Some of the hydrogen and helium gas was also drawn in by terrestrial

	Examples	Typical Condensation Temperature	Relative Abundance (by mass)
Metals	Iron, Nickel, Aluminium	1000-1600 K	0.2 %
Rock	Various minerals	500-1300 K	0.4 %
Hydrogen Compounds	Water (H_2O), Methane (CH_4), Ammonia (NH_3)	<150 K	1.4 %
Hydrogen and Helium Gas	Hydrogen, Helium	Do not condense in nebula	98 %

Fig. 13. Materials in the solar nebula. A summary of the four types of materials found in the solar nebula – with examples of each type and their typical condensation temperatures. The squares represent the relative proportions of each type (by mass).

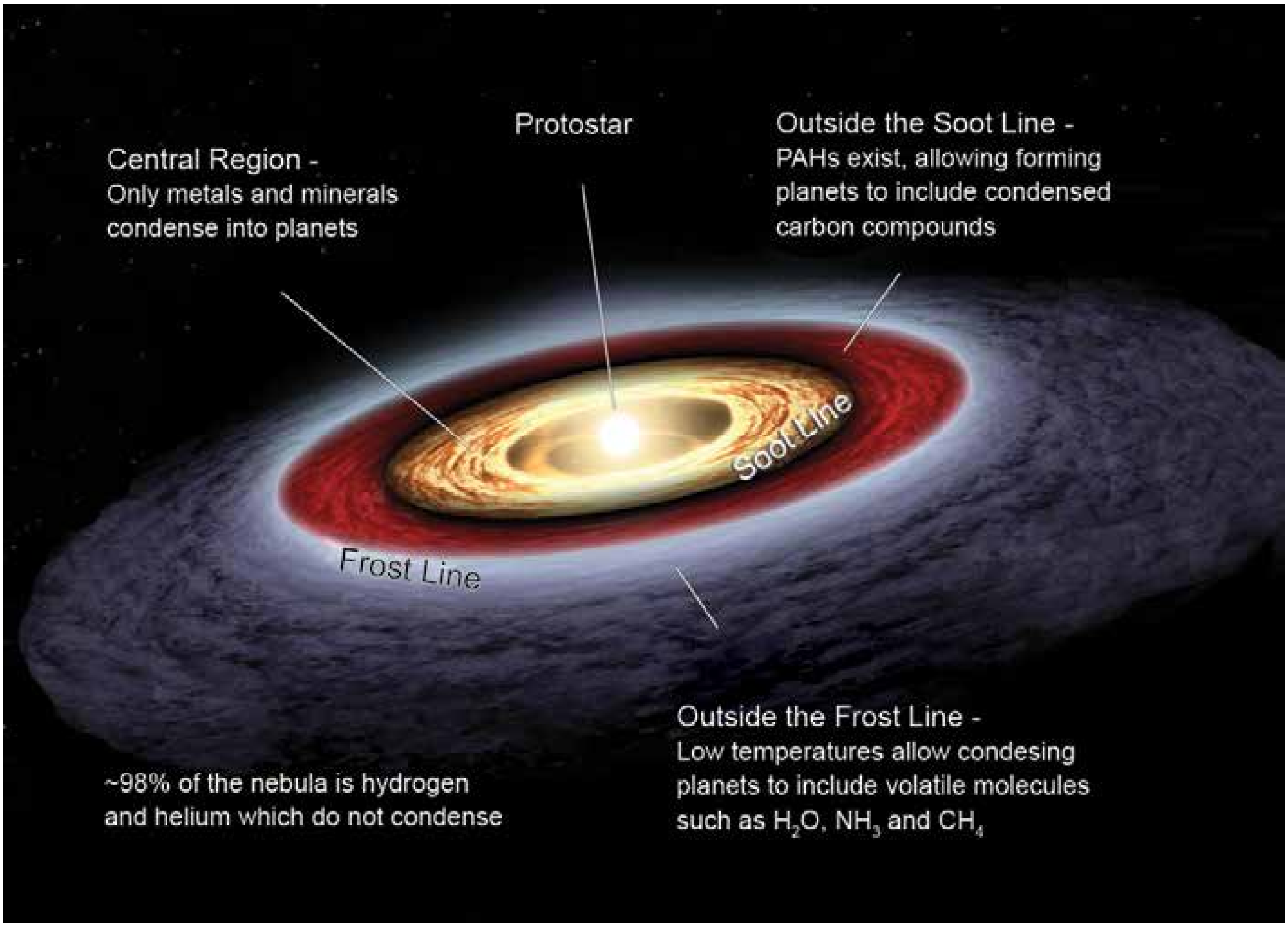

Fig. 14. An artist's impression of the proto-Sun and the disk around it. Metals and minerals with high melting points condensed in the inner regions of the solar system to form the terrestrial planets. In contrast, it was only beyond the frost line that easily volatile compounds could become solid. The temperature gradient across the protoplanetary disk is the key reason for the differing chemical compositions of terrestrial planets and gas giants.

Credits: © NASA/JPL-Caltech.

planets, and formed their early atmosphere.

As this process neared its end, many planetesimals remained scattered between the newly formed planets. These leftovers became comets and asteroids. Their material compositions were similar to the planets: i.e., asteroids made of hard rock and metal in the inner solar system, and icy fragile comets in the outer solar system. The leftovers must have had nearly circular orbits in the same plane as the orbits of planets. But in due course of time, as these planetesimals moved close to large planets, gravitational forces must have toppled their orbits into arbitrary directions, like a pellet released from a sling shot. A good number of these planetesimals must have escaped the confines of the solar system through this process. Many others ended up in much-elongated orbits that took them in and out of the solar system. The planets on the other hand, with their significantly higher mass, remained unperturbed by such encounters, eventually settling into dynamical stable orbits.

Evidence from Afar

This account of the formation of the solar system (planetary systems in general) goes by the name **Nebular Hypothesis.** A hypothesis is a suggested explanation for something based on reason. It is not a theory, because all aspects of it are not fully proven. But it is not a wild guess either. First proposed in a very crude form in the late 18th century, the Nebular Hypothesis has been refined and reworked from time to time, based on fresh insights into the process of planet formation.

One may wonder how much of the Nebular Hypothesis is backed by evidence. As already mentioned, the birth of the solar system is an event from a past that we have no direct access to. But it is only reasonable to assume that the same forces that drove the formation of our solar system might be acting elsewhere in the universe. In fact, there must be some planetary systems taking shape around other newly born stars at this very moment! Through very high resolution photography of star forming regions within the Milky Way, astronomers have found several instances of the birth of planetary systems. The Orion nebula, described earlier (see Fig. 4a), contains many examples of this. Nestled within its vast columns of gas, are several thousands of newly born stars. Such observations strongly affirm the view that stars are born out of the gravitational collapse of dense fragments within gas clouds in interstellar space. Today we know of hundreds of such sites of star formation, or stellar nurseries, within the Milky Way.

Through its high resolution cameras, the Hubble Space Telescope has also found that quite a few of the infant stars in the Orion nebula have extended disks around them (see Fig. 15 and 16). These proto-planetary disks stretch out to radii of more than 100 astronomical units (an astronomical unit, or AU, is the distance between the Sun and Earth ~ approximately 150 million kilometres). If we could roll back time to a period somewhere between 4 – 5 billion years ago, our solar system, from a distance of a few hundred light years, would have looked like any one of these.

An important aspect in the validation of the Nebular Hypothesis is to discover fully formed planets around other stars. From the 1990s onwards, astronomers have been routinely discovering planetary systems around other stars. These extrasolar planet (**exoplanets**, for short) discoveries have been made using several different techniques. The most successful of these techniques, at present, is biased towards finding big planets, of the size of Jupiter and Saturn, circling their host stars. Only very recently have these techniques reached the level of sophistication required to discover planets that are smaller, but still a few times the mass of the Earth. Astronomers call such planets the **super-Earths**. The Holy Grail, no doubt, is to find a planet of the size and mass of the Earth around a Sun-like star, at a distance where the heat from the Sun is just right enough to ensure the presence of liquid water – a prerequisite for life as we know it. If such a planet exists, we may not have to wait too long for its discovery, given the very rapid pace at which the field of extrasolar planet research is evolving.

Thus, our best hope of finding answers to the origins of our solar system lie not only in investigating objects within the confines of the Sun's gravity, but also those worlds that are far away from us. By looking into the far reaches of space, we are in a way searching for answers to our own origins.

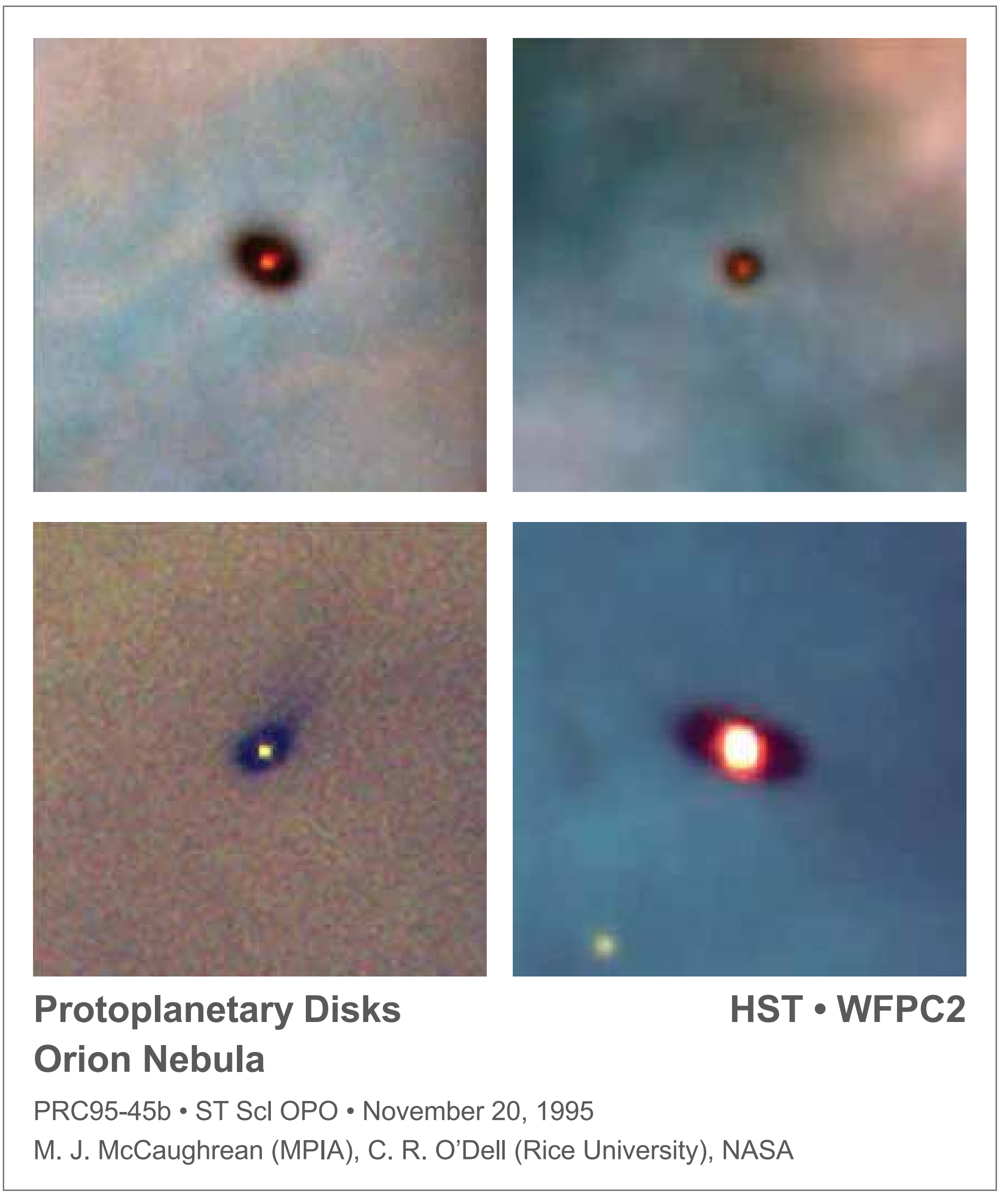

Fig. 15. Four examples of protoplanetary disks around young stars in the Orion Nebula. The bright object in the centre of each image is a newly born star (a protostar), surrounding which is an extended disk of material that may eventually give birth to planets, asteroids and comets.

Credits: © STScI / NASA and ESA.

Fig. 16. An assortment of newly born stars in the Orion Nebula. There are thousands of examples of on-going star and planet formation within the Orion Nebula. Look closely and you will notice the presence of protoplanetary disks around some of these young stars.
Credits: © NASA/ESA and L.Ricci (ESO).

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Resources

1. A Lunar and Planetary Institute designed activity for the classroom to help students understand the sequence of events in the formation of the solar system- http://www.lpi.usra.edu/education/timeline/activity/.
2. A short video that takes one through the formation of the solar system - https://www.stem.org.uk/elibrary/resource/26893.
3. This page from the Big History Project has a wonderful timeline on the formation of the solar system - https://www.bighistoryproject.com/home. Look under the link "Earth &The Solar System".
4. This page from the University of Colorado has several activities, appropriate for students from classes 4 – 8, to help understand the solar system - http://lasp.colorado.edu/education/outerplanets/solsys_planets.php.

Anand Narayanan teaches astrophysics at the Indian Institute of Space Science and Technology. His research is on understanding how baryonic matter is distributed outside of galaxies at large scales. He regularly contributes to astronomy related educational and public outreach activities. Every so often he likes to travel, exploring the cultural history of south India.