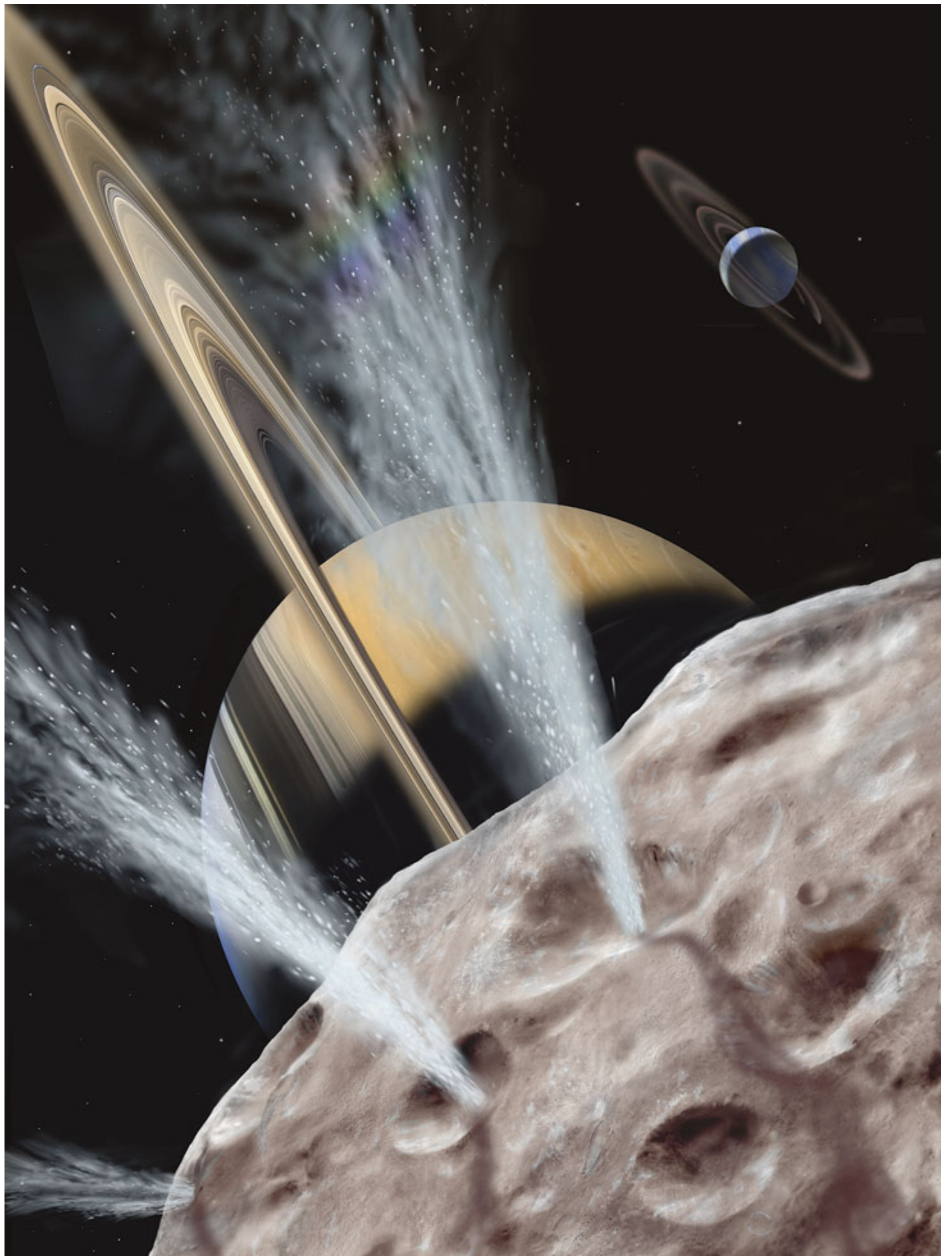

Fig. 2.1 Extended primordial rings encircle both Saturn and Neptune in this view of planetary migration in the early Solar System. According to the "Nice" theory, Neptune may have had several close encounters with Jupiter and/or Saturn. In the process, wandering asteroids such as Saturn's outer moon Phoebe may have been captured, or even exchanged, from one planet to another. These captures would have been violent, perhaps causing internal pressures leading to volcanic eruptions, differentiation and surface collapse (Painting © Michael Carroll, original iteration courtesy Astronomy magazine)

Chapter 2
How *They* Got Here

Even science has its fairy tales.

Once upon a time, there lived a disk of dust and gas called the solar nebula. At the center of this pin-wheeling pancake cloud, laws of momentum and gravity dictated that material would fall in upon itself. As this central expanding mass grew heavier, its atoms could no longer hold themselves together, and nuclear fusion ignited the cloud into an incandescent orb. The Sun had arrived.

The fledgling starlet grew, pulling in more and more material with its increasing gravity. And just as an ice-skater pulls her arms in to spin more quickly, so the spinning of the disk began to increase. Irregular clumps of gas and dust grew into asteroids, comets, and ultimately planets. The rocky terrestrial planets established themselves near the Sun. Many of their volatiles burned away at the hands of furious solar winds gusting from the infant star. Out where it was colder and calmer, Jupiter and Saturn pulled hydrogen and helium to themselves from the solar nebula around them. Still further out, Uranus and Neptune were able to hold on to more water, becoming the ice giants we see today. In short, the planets formed where we see them now. This scenario is known as the Standard Model. It makes a nice story.

In science, however, models are meant to fall, and many researchers now believe that our planetary system's formative years were not so calm as we once thought. Dynamicists like Hal Levison of the Southwest Research Institute in Boulder, Colorado, have been studying the chinks in the armor of our beloved Solar System fairy tale.

The Standard Model faces two major problems. The first is what Levison calls the meter barrier. "Imagine these floating dust grains; these stick together and grow like dust bunnies. In objects 1–10 km size, if they hit gently enough they'll stick because of gravity. But you have this problem in between." Levison points to two coffee mugs on his desk. "If I bring these two cups together, no matter how gently, they aren't going to stick together. There is no good force to hold together things that are a meter to a decimeter size. Another problem is that there is aerodynamic drag on the particles. They are feeling the force of the gas they are moving through, feeling the headwind. That headwind will make them spiral into the Sun."

Very small particles can be suspended in the gas of the primordial solar nebula without settling. Large objects are unaffected by drag because of their mass. But those objects in between, in the meter range, should migrate into the Sun before they grow, effectively preventing any planets from forming. This puzzle has haunted dynamicists since it was introduced in the 1970s.

Some researchers propose that turbulence in the solar nebula may have concentrated meter-sized objects in eddies. The Sun's disk may have hosted swarms of these boulder-sized rocks, herded into vortices, gradually collapsing to form larger objects. Perhaps.

M. Carroll, *Living Among Giants: Exploring and Settling the Outer Solar System*,
DOI 10.1007/978-3-319-10674-8_2, © Springer International Publishing Switzerland 2015

A second substantial change in our view of planetary evolution – and one that is better established – is that the giant planets did not form where they are today. "You cannot make Uranus and Neptune where they are," Levison says. "They must be closer in. The problem we find is that if you put a bunch of Earth-sized objects out in that region, they don't hit each other. They gravitationally scatter one another into Jupiter-crossing orbits, and Jupiter throws them out of the Solar System. You simply cannot get these guys to accrete [in the current Uranus-Neptune region]."

Out at the edge of our planetary system, the icy Kuiper Belt poses another mystery. In the outer Solar System, objects such as the ice dwarf Pluto move with high inclinations and high eccentricities in resonances – orbital relationships – with Uranus and Neptune. But because of the way planets develop, these objects had to have formed in circular, low inclination,[1] low velocity orbits. That's the only way to get planets to accrete, and yet observers see quite a different picture in the Kuiper Belt. Kuiper Belt Objects (KBOs) sail along on inclined, high eccentricity orbits. Multiple populations of KBOs seem made of the wrong stuff, as if they came from different locations superimposed on each other. The planets in their current configuration could not have formed where they are. Something had to change in the structure of our planetary system. Many dynamicists now suspect that the giant planets began in a compact configuration and then migrated out. This scenario is the heart of the Nice Model, named after the coastal town in France where Levison and three other scientists first combined forces to craft it.

The Nice Model proposes two extreme alternatives to the Standard Model. One scenario describes a smooth migration where Uranus and Neptune slowly spiral out through the solar nebula. The other idea has the four giant planets (and possibly a fifth that was later ejected from our Solar System) huddling close together until a global instability causes Uranus and Neptune to migrate wildly (see Fig. 2.2). Models show that their orbits cross each other, and even cross orbits of Jupiter and Saturn. Gravity from the two gas giants sends Uranus and Neptune packing, where they settle into a disk of planetesimals – a sort of distant asteroid belt – that no longer exists. This population of outer asteroids and comets, which would eventually give rise to the Kuiper Belt, was, in Levison's words, "a place where thousands of earth-like masses allowed things like Pluto to grow." It was the migration of the giant planets that destroyed it. But the disk's mass and its interaction with the worlds closer to the Sun essentially saved the planets, preventing them from being ejected from the Solar System.

The Nice Model's concepts are bolstered not only by observations of our own Solar System but also by studies of exoplanets, says Principal Scientist Dan Durda of the Southwest Research Institute in Boulder, Colorado. "A lot of what's advanced our thinking is seeing these hot Jupiters around other stars. It forced people into thinking, 'Oh, wait a minute, our simple picture of forming planets in a disk doesn't fit because how do you get a Jupiter in that close?' It forced people into thinking about what

1. Inclination refers to how tipped an orbit is to the "equator" of the Solar System, where most planets orbit around the Sun.

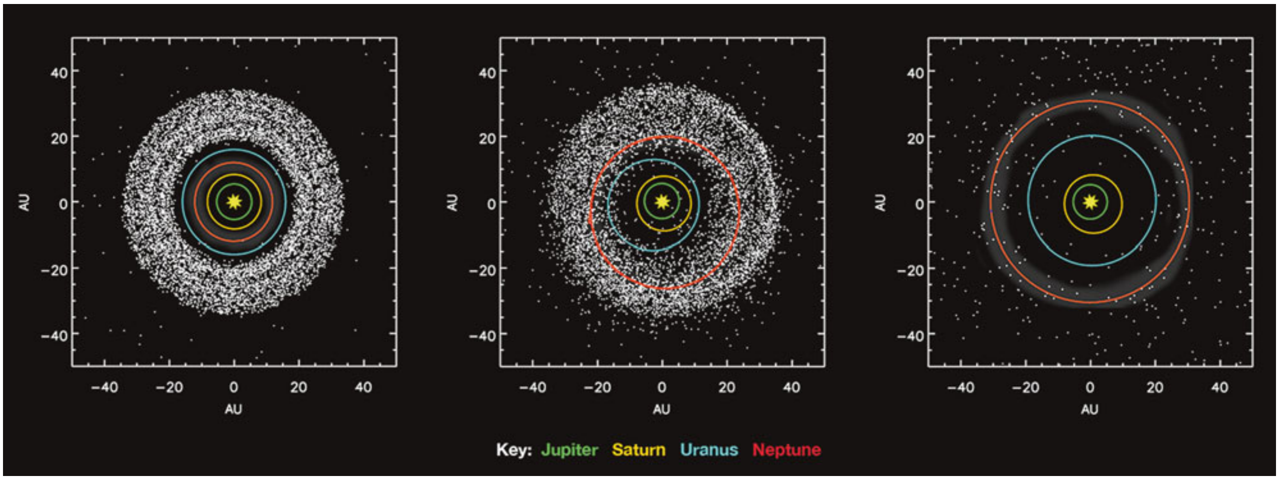

Fig. 2.2 The Nice Model. Left: The outer planets and planetesimal belt before Jupiter and Saturn reach a 2:1 resonance. Center: As Neptune (dark blue) and Uranus (blue-green) swap places, they scatter planetesimals into the inner Solar System. Right: Planets in their current orbits, after they have ejected the planetesimals from the Solar System (From R. Gomes, H. F. Levison, K. Tsiganis, A. Morbidelli, 2005)

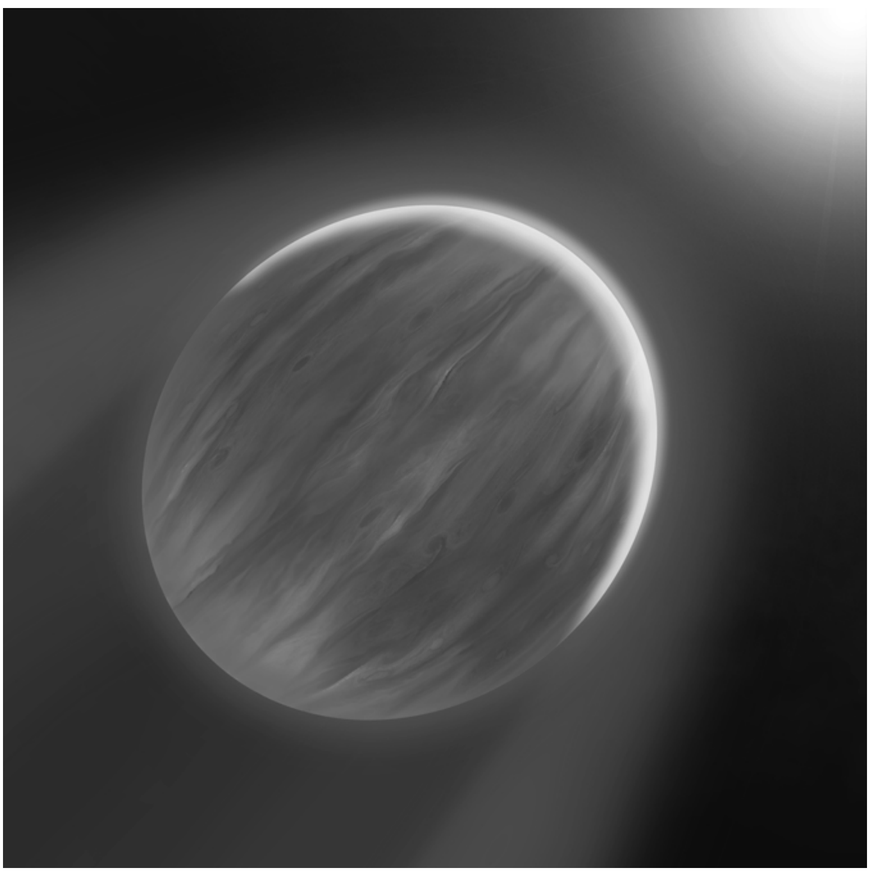

Fig. 2.3 The discovery of "hot Jupiters," exoplanets orbiting near their stars, has played a key role in our understanding of how planetary formation occurs (Painting by the author)

happens in the disk as a big Jupiter is forming, and people like Bill Ward and others started realizing that there are all these interactions between the planet itself and the disk."

As a planet forms within a disk, researchers suspect that it sets up gaps and waves, and those density waves and gaps create torques on the planet itself.

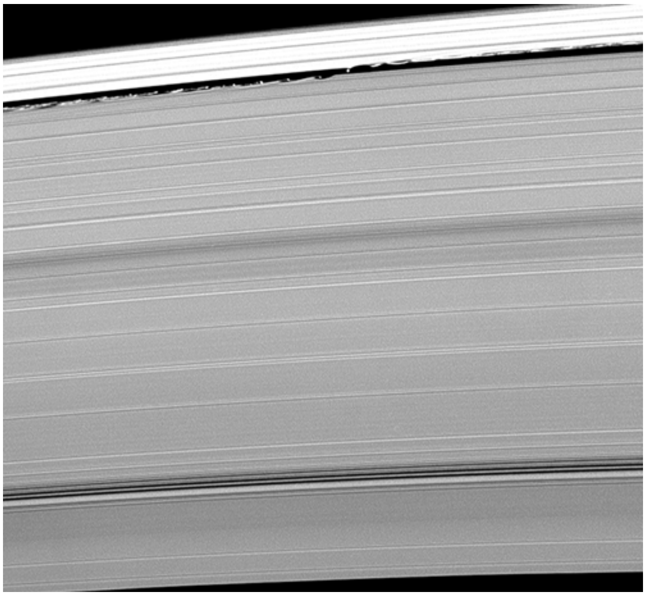

Fig. 2.4 Saturn's rings provide insight into the dynamics of protoplanetary disks. In this Cassini spacecraft view, the tiny moon Daphnis orbits within the Keeler Gap, disturbing ring material in front and behind into waves and curls (Image courtesy of NASA/JPL/Space Science Institute)

When the planet forms and clears a gap, that gap can force the planet to move inward, Durda says. "It caused a whole decade of rethinking and re-understanding and learning about these processes that happen within the disks. It caused us to go back and look at a lot of the things that happened in our own Solar System, and that's what led to a lot of these gas/disk/planet interaction ideas. It's really been a paradigm shift from the idea that things have to form where we see them today to this idea of a whole lot of mechanisms that cause migrations and restructuring. It really is a huge shift in our understanding, and exoplanets have certainly played a key role."

Another contributor to our understanding of these processes has been the study of the structure of Saturn's rings. The Cassini mission has provided unprecedented detail of this complex, vast plain of material, offering scientists a real-life analog of a protoplanetary disk. Within the rings, gaps form at locations where particles are in gravitational resonances with large moons. Spiral density waves move throughout the system like the grooves on an old LP. Smaller moons, often embedded within the rings themselves, induce elegant ripples undulating for thousands of miles along the racetrack-like bands of icy ring particles, while two-mile-high chevrons of material rear up at the edge of the B ring. "The Saturn ring system is probably one of the best natural laboratories for seeing the dynamics of a disk," Durda says.

Not everybody accepts the Nice Model. Its predictions seem at odds with some observations. Critics point out that the Nice Model is not confirmed by the number of craters and impact basins on Earth's Moon (which has less than what Nice calls for). The composition of fragments in the lunar samples points to asteroid impactors, while Nice suggests there should have been more comets falling on its surface. The Nice Model also suggests that when the planets migrated, their gravity would scatter asteroids into certain types of families that are not seen in the asteroids. This scattering would also have pounded the icy satellites of the outer planets to such an extent that they would have lost most of their icy crusts. This has not happened.

Computer studies demonstrate that a migration of Jupiter and Saturn would increase the eccentricities of the terrestrial planet orbits beyond their current values, leaving the Asteroid Belt with an excessive ratio of high to low inclination objects after the migration. In the case of the original Nice Model the slow approach of Jupiter and Saturn to their mutual 2:1 resonance, necessary to match the timing of the Late Heavy

Bombardment, can result in the ejection of Mars and the destabilization of the inner Solar System.

The separation of Jupiter's and Saturn's orbits caused by close encounters with one of the ice giants, called the "Jumping Jupiter Scenario," avoids these issues, but often results in the ejection of an ice giant. This has led some to propose an early Solar System with five giant planets, one of which was ejected during the period of instability.

Researchers continue to revise models that tweak the parameters of the Nice scenario and incorporate new findings. SwRI's Levison asserts, "No one has developed a model that is even close to being an alternative."

BEFORE THE NICE TIMES – A DIGRESSION

Scientists of the eighteenth century had two clues about the formation of planets. The first was that stars spin (as could be seen by sunspots on our own Sun and the regular changes in light from distant stars). The second clue was that all the planets travel in nearly circular orbits – and in the same direction – around their parent star. This led to the early conclusion that the Sun and planets issued from a disk of material that was spinning. We now call this disk the solar nebula.

Immanuel Kant, a Prussian philosopher and writer, first put forth the concept of a solar nebula in 1755[2] (and independently, in 1796, it was put forward by French astronomer Pierre Simon Laplace). Kant proposed that clouds of gas floating through the universe would be unstable and would tend to clump together gravitationally. As these cosmic clouds collapsed, Kant suggested, they rotated. This rotation would spin the clouds into flattened pancakes, leading ultimately to planets circling a central star.

Others have put forth other ideas. In 1905, geologist Thomas Chamberlin and astronomer Forest Moulton proposed that a star had passed close to the young Sun, pulling material away into a spiral arm. This arm coalesced into the planets. The advantage to their theory was that the thickest part of the arm would have been in the center, where the gas and ice giants are, with the thin parts leaving small terrestrial planets on one end and comets and distant asteroids on the far end. At the time, spiral galaxies were thought to be stars with arms of material pin-wheeling out from the center, and these were seen as evidence for their theory. Three decades later, Soviet astronomer Otto Schmidt suggested that the Sun drifted through a dense cloud of interstellar gas, trailing debris from which the Solar System eventually formed.

Other theories came along, too. It turns out that Immanuel Kant was right, but no one actually saw disks around stars until the advent of radio telescopes, which could peer into visually opaque dark clouds. More recently, the Hubble Space Telescope (HST) and Spitzer telescope have discovered dozens of planet-forming disks around stars, confirming Kant's original scenario.

2. Kant may have been influenced by the earlier work of Emanuel Swedenborg.

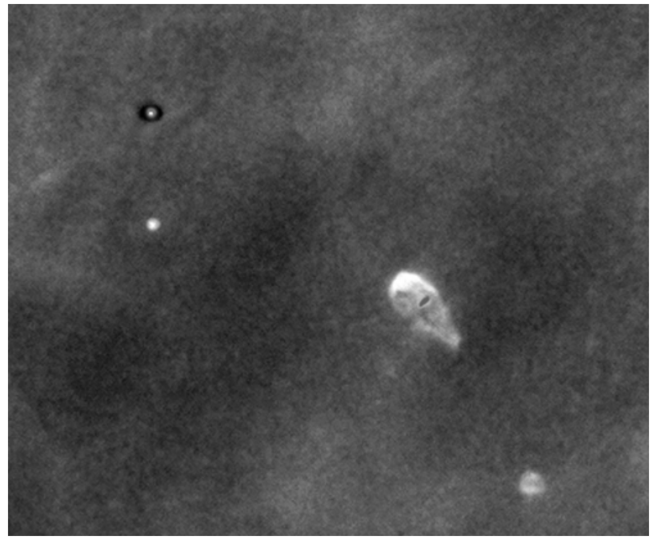

Fig. 2.5 Protoplanetary disks in the Orion Nebula, called proplyds, provide confirmation of Immanuel Kant's theory of Solar System formation (HST image courtesy of STScI)

BEYOND THE SNOW LINE

The regions nearest the Sun were far too hot for water or gas to condense out as ice. Planets there pooled into silicate, rocky bodies. The hot inner Solar System was adrift in a fog of tiny igneous spheres called chondrules. Chondrules have been found in many ancient meteorites, primordial flotsam born in very high temperatures (1,500–1,900 K). These chondrules stuck together, becoming the terrestrial planets. Farther out from the great

Fig. 2.6 Spherical chondrules are composed primarily of silicate minerals such as olivine and pyroxene. Found in many kinds of meteorites, they lend clues to the early Solar System's development (Photo courtesy of Dan Durda. Used with permission)

disk of the solar nebula, temperatures were cold enough to form ice. The line between the two regions is called the "snow line." Beyond that line, smaller bodies assembled themselves into balls of ice and rock. The gas giants, with their immense gravity, pulled hydrogen and helium directly from the nebula around them. They may have grown steadily as their gravity increased, or they may have benefitted from waves of material cast toward them through gravitational instabilities in the cloud. Either way, the gas giants ended up as massive globes of hydrogen, helium and ammonia with metallic cores.

Whether the Nice Model is correct or not, we know that Uranus and Neptune formed beyond the snow line, too. Although Jupiter and Saturn were able to collect massive amounts of hydrogen and helium, the ice giants have ended up with less of those gases and more gases associated with frozen water and organics: oxygen, nitrogen, methane and carbon.

While they were at it, all those spinning gas and ice giants cocooned themselves within their own disk-shaped clouds. Like the infant Sun's inner system, the central cloud that led to the gas giants was warm, heated by the energy of accretion.

As Jupiter and Saturn cooled, they shrank, leaving behind a cooling cloud of gas, ice and dust. Within these mini accretion disks, ring systems formed and, farther out, moons coalesced. Jupiter's four major moons, the Galilean satellites, provide the perfect example of the result. Close in to Jupiter, Io and Europa collapsed into spheres with dense, large rocky cores and, in the case of Europa, a relatively thin water-ice crust. These are Jupiter's version of the terrestrial planets. In Jupiter's outer cloud, where there was more water, Ganymede and Callisto formed as larger, less dense worlds with small stony centers and deep ice crusts. Icy giants. (Oddly, moons of the ice giant Neptune do not seem to follow this organized pattern of decreasing density with increasing distance, perhaps because of the large interloper Triton, which came from outside of the system.)

As the formation of a gas or ice giant comes to an end, the planet will continue to accumulate gas, rock and ice from the solar nebula – the cloud of dust and gas around the Sun. The disk of material, orbiting the giant planets in their equatorial planes, begins to ebb and flow with the same kinds of eddies that initially cause the planets in the Sun's own cloud. According to new studies,[3] as the protosatellite cloud coalesces around its parent planet and moons form within, the gravity of the newborn moons disrupts the cloud, triggering spiral waves. As the satellites grow, the effect becomes more marked, so that the moons' orbits begin to spiral in toward the planet. As more material flows into the cloud, the inner satellites move in toward the planet while new ones are born toward the outside of the gaseous disk.

Dan Durda describes the early evolution of the vast satellite system at Jupiter: "The implications are that the four Galilean satellites we see are the last of a whole conveyor belt of satellites that formed and got gobbled up

3. For more, see www.swri.org/9what/releases/2006/canup.htm.

by the planet as they migrated in through this disk." As the young Sun matures, Durda, explains, it endures the T-tauri phase, an energetic stage in which its solar wind blows most of the dust and gas from the planetary system. "What shuts off that disk and shuts off that conveyor belt is the T-tauri phase when the Sun really does turn up and clears the disks – not only the protoplanetary disks but the protosatellite disk around Jupiter as well. It gets rid of those gas disks and shuts off that process."

This conveyor-belt mix of satellite birth and destruction keeps the mass of the moons at a constant total. The satellite systems of Jupiter, Saturn and Uranus are quite different from each other. Jupiter's four Galileans are nearly alike in size, whereas Saturn has one giant moon along with many mid-sized ones. The satellites of Uranus are somewhat comparable in arrangement to those of Jupiter's. Even so, researchers point out that Jupiter, Saturn and Uranus do, in fact, have a similar ratio between the mass of the planet and the overall mass of the satellite system, with the satellites making up roughly one hundredth of 1 % (0.0001) of the mass of their parent planet.

The outer Solar System eventually settled into the arrangement we see today. It is a realm of bitter cold, mind-numbing isolation, and lonely darkness. But the Solar System's outermost planetary regions play host to some of the most spectacular formations, beautiful landscapes and bizarre phenomena ever witnessed by humankind. It is waiting for us, but before the humans set foot on those cold and remarkable shores, the robots must go forth. Some already have.

http://www.springer.com/978-3-319-10673-1

Living Among Giants
Exploring and Settling the Outer Solar System
Carroll, M.
2015, XIX, 225 p. 151 illus., 109 illus. in color.,
Hardcover
ISBN: 978-3-319-10673-1