Modern View on the Formation of the Solar System

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Our understanding of planet formation is being transformed thanks to the exoplanet detections and observations of circumstellar disks, but also the increasing precision of measurements of the Solar System meteorites. From all fronts, there is increasing evidence that planet formation starts already during the circumstellar disk buildup. Thus, the architecture of the Solar System as we know it today may be intimately connected to the earliest phases of the solar disk evolution. In this contribution, I describe the main developments that occurred in our understanding of the Solar System formation in the recent years.

1 Introduction

The planetary systems emerge out of disks surrounding young stars, called circumstellar or protoplanetary disks. These disks consist of mixture of hydrogen and helium gas with about 1% of heavier elements, which condense out as dust grains. These dust grains have sizes of up to 10 microns. The planet formation theory is needed to explain how these micron-sized grains grow into 1000 km and more-sized planets.

In recent years, planet formation theory has been undergoing revolutionary changes. These changes are motivated mostly by three arguments: the observed demographics of exoplanets, the high-resolution images of circumstellar disks, and the ultra-precise measurements of meteoritic compositions. The exoplanets turned out to be more common that we could have expected. The current estimates suggest that on average every star in our Galaxy is orbited by at least one planet (see, e.g., Cassan et al., 2012). Planet formation seems to be a frequent companion of the star formation process. What is more, planet formation produces very diverse outcomes. The most common type of planets detected so far are the so-called super-Earths and sub-Neptunes, a type of planet that falls in between the rocky terrestrial planets and gas giants and does not occur in the Solar System (see, e.g, Mulders et al., 2018).

A closer look into the birth places of planets, the disks surrounding young stars, was enabled by the Atacama Large Millimeter/submillimeter Array (ALMA) that has reached its final configuration in November 2014. The first circumstellar disk imaged with ALMA was this surrounding the star HL Tauri and it turned out to be full of so-called sub-structures: bright rings and dark gaps (ALMA Partnership et al., 2015). Since then, the sub-structures have been detected in many of the disks we have been able to image with the high-resolution (see, e.g., Andrews et al., 2018). This suggests that the planet formation process may not proceed the same way at every location in the disk. What is more, studies of mass budget of the circumstellar disks revealed that these disks do not seem to have enough solid material to produce planets at the abundance found in our Galaxy (Najita & Kenyon, 2014). A likely explanation for this corundrum is that planet formation starts very early, before the fully-fledged disks are formed (Tychoniec et al., 2020).

The last aspect contributing to the changes in our views on the formation of the Solar System is the improvement in measurements precision of the isotopic abundances in meteorites. This made it possible to detect differences in meteoritic composition down to one part per million. This kind of laboratory research has suggested that the Solar System material samples two distinct reservoirs, known as the carbonaceous chondrite (CC) and noncarbonaceous (NC) reservoirs, after their representative meteorite classes (Kruijer et al., 2020). The laboratory research made it possible to constrain the formation time of constituents found in meteorites, such as the calcium aluminum rich inclusions (CAIs) and chondrules (Connelly et al., 2012). At the same time, it was also possible to establish that some of the parent bodies of meteorites formed their iron cores within 1 Myr from the CAIs formation (Kruijer et al., 2014).

Taken together, these arguments forced the researchers to reconsider the classical theory of planet formation that has been established in the second half of the 20th century.

2 Classical theory of Solar System formation

The classical theory of planet formation, illustrated in Fig. 1, was based solely on explaining the architecture of the Solar System. The story of our planetary system started with planetesimals, the first gravitationally-bound building blocks of planets, the parent bodies of today's asteroids and comets. They were circumventing the Sun in a disk stretching from the orbit of Mercury to the Kuiper Belt. The largest planetesimals were growing the fastest in the process of so-called runaway growth and started to dominate their environment as so-called oligarchs (see, e.g., Wetherill & Stewart, 1989). As the oligarchs were stirring the leftover planetesimals, the runaway growth transitioned into slower, so-called oligarchic growth (Ida & Makino, 1993). The oligarchs that reached sufficient sizes during the lifetime of the hydrogen-helium gas disk started to accrete their gas atmospheres and became cores of gas-rich planets (Pollack et al., 1996). In this classical, in-situ formation scenario, this was only possible in the cold regions of the circumstellar disk, outwards of the water snow line, where the water exists in its solid form. The presence of water ice enhances the abundance of solids available for forming planetary cores. What is more, gas accretion is easier if the gas temperature is lower.

The detection of the first exoplanet orbiting a solar-type star announced in 1995, which turned out to be so-called hot-Jupiter: gas-rich planet orbiting very close to their parent star (Mayor & Queloz, 1995), forced the researchers to consider the possibility of planet migration, which was already predicted theoretically as a possible consequence of the planet-disk interaction (Lin & Papaloizou, 1986). The explanation for existence of hot-Jupiters was that they were born outside of the water snow line but migrated inwards. However, this was only the beginning of challenges that were awaiting the classical theory.

In the classical theory, planetesimal formation was seen as an obvious first step. However, it was missing a convincing explanation. Thus, models of planet formation typically ignored the planetesimal formations stage and often used the power law function proposed by Weidenschilling (1977b), called the Minimum Mass Solar

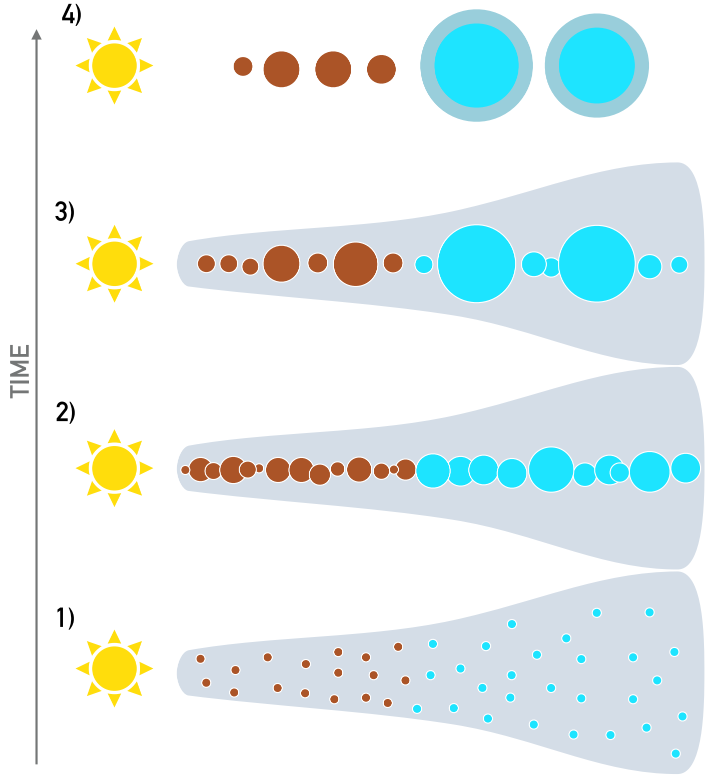

Fig. 1: Illustration of the classical paradigm for the Solar System formation. 1) Dust grains are ice-rich (blue) outside and dry (brown) inside of the water snow line. 2) Dust quickly sediments to the midplane and gravitationally-bound planetesimals are formed throughout the disk, recording the initial composition of dust. 3) Planetesimals grow by runway growth and a few oligarchs emerge that continue growing in the oligarchic growth regime. 4) Oligarchs outside of the water snow line form cores that are massive enough to accrete gas atmospheres. Oligarchs in the inner disk form the terrestrial planets in series of impacts.

Nebula (MMSN), as their initial condition. Goldreich & Ward (1973) proposed that the dust particles quickly settle to the midplane of the circumstellar disk and form a very thin sub-disk which is gravitationally unstable and fragments to form the first planetesimals. This scenario was quickly ousted as it was found that formation of sufficiently thin dust layer is not possible if the gas is even weakly turbulent (Weidenschilling, 1988). For many years then the dominant view was that planetesimals formed by continued growth of dust aggregates to ever larger sizes (Weidenschilling & Cuzzi, 1993).

3 Dust growth barriers

While dust growth is unquestionably the first step to planet formation, the direct growth from micron to kilometer sizes is a subject to many barriers. Laboratory experiments and models of dust coagulation in the protoplanetary environment show that the growth of dust is halted at millimeter to centimeter pebble-sizes (Dominik et al., 2007). While collision of the micron-sized dust grains happen at low speeds and lead to sticking, the collisions speeds increase with dust aggregate size and start to be destructive long before the aggregates reach the meter-sized boulder stage. This so-called fragmentation barrier is, however, not the only problem discovered in the dust evolution models. Solid particles are embedded in the gaseous disk that is rotating with a slightly sub-Keplerian velocity. Because of this, the dust aggregates are decelerated and spiral towards the central star (Weidenschilling, 1977a). In the outer parts of the protoplanetary disk, the radial drift removes dust aggregates even before they grow to sizes at which they would experience the high-velocity collisions (Brauer et al., 2008). This is called the radial drift barrier. Acting together, the fragmentation and drift barriers prevent growth past centimeter-sizes and, at the same time, lead to depletion of solids in the disk within 1 Myr, which is faster than the gas disk lifetime (see, e.g., Birnstiel et al., 2016).

4 Planetesimal formation

One way of overcoming the dust growth barriers is a collective collapse of gravitationally-bound pebble clumps directly to planetesimals. For this to happen, such dust-rich clumps must be formed. The background dust-to-gas ratio in a circumstellar disk is estimated to be on the order of 1%. In the clumps, this is enhanced by orders of magnitude. At this point, the most commonly accepted way of enhancing the dust-to-gas ratio is the streaming instability, a two-fluid hydrodynamic instability relying on the collective effects of dust drift (Youdin & Goodman, 2005; Johansen et al., 2007).

The streaming instability leads to formation of kilometer-sized planetesimals directly out of pebbles, thus omitting the problematic boulder sizes, at which the gas drag would lead to fastest radial drift and most energetic collisions. However, the production of planetesimals via the streaming instability is only effective when the pebbles managed to grow and their density is pre-enhanced from the initial 1% to about 100% (corresponding to local solids-to-gas ratio of unity, see, e.g., Bai & Stone 2010; Li & Youdin 2021). To create such density enhancements, models often invoke some perturbation to the smooth background disk structure, such as so-called zonal flows (see, e.g., Dittrich et al., 2013).

The collapse of pebble clumps caused through the streaming instability leads to planetesimals of particular properties. Numerical models showed that these planetesimals are mostly large, about 100-km (Simon et al., 2016), which is consistent with the size distribution observed in the asteroid belt (Morbidelli et al., 2009). What is more, the detailed structure of comet 67P/Churyumov-Gerasimenko investigated by the Rosetta mission: its porosity, homogeneity, and tensile strength, can be explained by the comet formation trough the gentle gravitational collapse of a bound pebble clump (Blum et al., 2017). The 67P consists of two distinct lobes. It turns out that the outskirts of the Solar System are full of such bilobed, as well as binary objects. One of the strongest arguments in favour of the streaming instability is the fact that it predicts that such binary planetesimals should form often and with approximately 80% of prograde binary orbits, which exactly matches the observations of trans-Neptunian binaries (Nesvorný et al., 2019).

5 Role of the water snow line

The water snow line was long seen a favourable location for planet formation. Stevenson & Lunine (1988) proposed that the outward diffusion of water vapor from inside of the snow line and its re-condensation on solid material outside of the snow line, which is called the cold finger effect, may be the cause for fast formation of Jupiter core in the Solar System. Birnstiel et al. (2010) showed that the dust evolution may lead to pile-up of material inside of the water snow line, enhancing the solids-to-gas ratio in the inner part of the disk. However, these result was based on laboratory experiments which found that water ice grains are significantly more sticky than silicates and thus their fragmentation velocity was assumed to be ten times higher (Aumatell & Wurm, 2014; Gundlach & Blum, 2015). It is important to note that more recent laboratory experiments, performed with better control of temperature, revealed that the increased stickiness of water ice only holds when an aggregate is close to its melting temperature. In a colder environment, consistent with the temperatures in the outer parts of protoplanetary disks, water ice aggregates have no advantage over silicate aggregates and they can even be less sticky (Gundlach et al., 2018; Musiolik & Wurm, 2019; Steinpilz et al., 2019).

Schoonenberg & Ormel (2017) and Drążkowska & Alibert (2017) independently showed that the coaction of the cold finger and traffic jam effects leads to a pebble pile-up and local burst of planetesimal formation just outside of the water snow line. This makes the water snow line an advantageous location for the formation of first planetesimals. However, the location of these snow line depends strongly on the underlying circumstellar disk conditions. Since the observational capabilities of resolving the signatures of water snow lines are at the moment limited to outbursting stars, where the snow line is pushed to larger distances (see, e.g., Cieza et al., 2016), we must rely on numerical disk models.

6 Planetesimal formation during circumstellar disk buildup

Hueso & Guillot (2005) presented a one-dimensional model of the formation of protoplanetary disk as the result of the gravitational collapse of a spherical, rotating molecular cloud. Despite its simplicity, this model satisfyingly reproduces the observed properties of circumstellar disks. Drążkowska & Dullemond (2018) investigated the possibility of forming planetesimals at the water snow line (see above) in such disk model. The disk formation follows inside-out pattern. The initial disk is compact and light, the water snow line falls close to the young star. As the disk becomes more massive, it heats up and the snow line moves outward. During the further, viscous evolution in the so-called Class II, the disk spreads cools down and the snow line gradually moves inward. Drążkowska & Dullemond (2018) found that if the midplane turbulence level is sufficiently low, some planetesimals may already form during the disk buildup stage, along the outward-moving snow line. This early burst of planetesimal formation is driven by the cold finger effect, which is fast but not as efficient in enhancing solid density as the traffic jam effect (see above). The joint action of the traffic jam and cold finger effects drives much more massive burst of planetesimal formation during the Class II stage.

7 Planetesimal evolution

The planetesimals formed outside of the snow line are rich in water ice. However, some planetesimals may lose water because of their internal heating caused by decay of short-lived radioisotopes, mostly Aluminum-26 (Grimm & McSween, 1993). The Aluminum-26 has half life of 0.7 Myr, comparable to the duration of circumstellar disk buildup. Thus, assuming that enrichment of the disk material takes place shortly before or during the molecular cloud infall, only the planetesimals that form very early will experience the full consequences of the radiogenic heating.

Lichtenberg et al. (2021) studied the internal evolution of planetesimals formed in the models presented by Drążkowska & Dullemond (2018) and found that most of planetesimals formed during the disk buildup stage lose the water and form iron cores as a consequence of the radiogenic heating. Planetesimals formed later, in the second burst, experience much less of such processing. The proprieties of planetesimals formed in the first burst: their aqueous alteration and iron core formation times, are consistent with the meteorites from the non-carbonaceous reservoir (see Sect. 1). Analogically, the planetesimals formed during the disk evolution are consistent with the carbonaceous meteorites. Thus it is not the initial formation location inside or outside of the water snow line but the timing of planetesimal formation that explains the composition dichotomy of the Solar System planets (see Fig. 2). In this picture, the isotopic dichotomy can also be explained if the material infalling from the molecular cloud onto the disk gradually changes composition with time (see, e.g., Nanne et al., 2019). Because there is a period when planetesimals do not form at all, the isotopic composition the planetesimals sample is not continuous.

8 Planetary growth by planetesimal and pebble accretion

One of the recent developments in the planet formation theory was the introduction of the pebble accretion concept. The pebbles which are necessary to form planetesimals by the streaming instability can also contribute to fast growth of planetary cores. Growing planetary cores by accretion of pebbles may be faster than planetesimal accretion because it is aided by the gas drag, which helps the pebbles to settle on the planet (Ormel & Klahr, 2010; Lambrechts & Johansen, 2012). Pebble accretion is now the preferred pathway to forming the cores of gas-rich and ice-rich planets in the Solar System (Lambrechts & Johansen, 2014). It was also proposed that the terrestrial planets may be an outcome of pebble accretion (Johansen et al., 2021). Nevertheless, pebble accretion is only faster than planetesimal accretion if the planetary core is already large (the models typically start with Moon-mass embryos) and the pebble flux is sufficiently high (see, e.g., Ormel, 2017).

Models of planet formation typically make assumptions about the underlying planetesimal and pebble population. In the model analyzed by Lichtenberg et al. (2021), the dominant mode of planetary growth changes with location in the disk and time. Since the ice-rich pebbles are larger then the dry pebbles inside of the snow line, and the pebble flux in the inner disk is significantly restricted by the

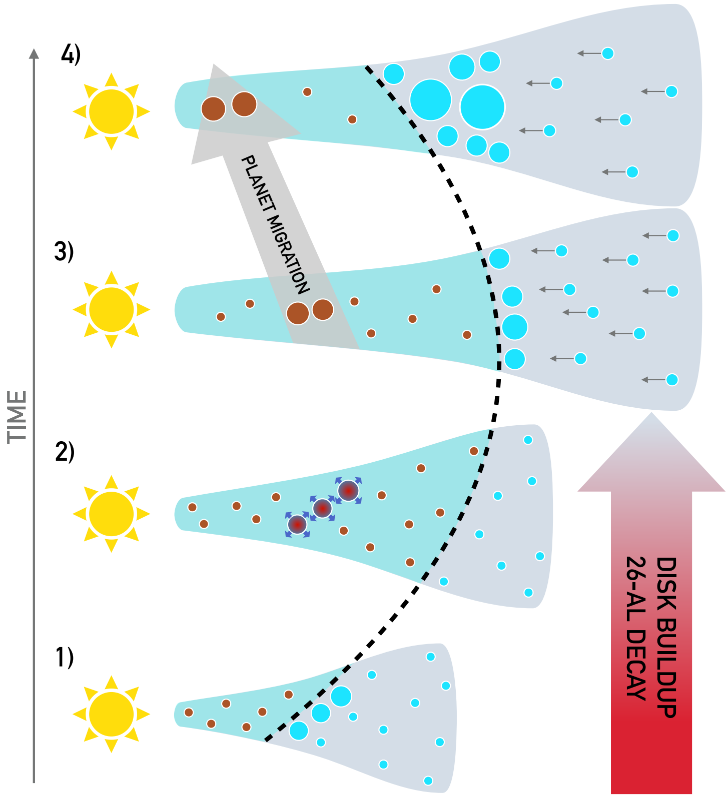

Fig. 2: Illustration of the emerging new paradigm for Solar System formation. 1) The first planetesimals form outside of the water snow line (black dashed-line) thanks to the cold finger effect already during the circumstellar disk buildup stage. 2) The early-formed planetesimals dehydrate and form iron cores due to 26-Al radioactive decay. They grow by planetesimal and pebble accretion. At the same time, the snow line moves out as the disk becomes more massive and hotter. 3) When the disk is fully-formed, more planetesimals keep forming outside of the water snow line as a result of the interplay between the cold finger and traffic jam effects. The ongoing planetesimal formation stops the pebble flux arriving to the inner disk. 4) Massive planetary cores form outside of the water snow line, which is now gradually moving inward as the disk cools down. The rocky planets stay inside of the water snow line due to planet migration.

ongoing planetesimal formation, planetesimal accretion remains the dominant mode of terrestrial planet formation while the pebble accretion is responsible for forming the cores of outer planets. The fact that the pebble flux to the inner disk is blocked by the massive second burst of planetesimal formation helps to preserve the primordial isotopic dichotomy. At the same time, planet migration keeps the cores growing in the inner disk from becoming water rich when the snow line is moving inward (see Fig. 2).

9 Summary

In this contribution, I described how the classical model of Solar System formation has been evolving in recent years. Contrasting Fig. 1 and Fig. 2 reveals the major conceptual changes to the planet formation paradigm. Planetesimal formation is not treated anymore as a single burst and the timing of planetesimal formation is decisive in shaping the composition and architecture of the planetary system. As both the planetesimal formation via the streaming instability and the planetary growth by pebble accretion are sensitive to the underlying disk conditions, the emerging planet formation theory should be able to explain the diversity of planetary systems observed in our Galaxy.

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