6.1 Formation of planetary embryos and giant planet cores

A. Context and state of the art

In the classic model of planet accretion, dust particles set towards the midplane of the disk and collide with each other forming aggregates held together by electrostatic forces. Little by little these aggregates grow and get compacted by collisions, forming small planetesimals. Planetesims are objects with enough mass (>100m in size) that their gravity becomes important. For a given body, the collisional cross-section is enhanced relative to the geometric one ($\sigma=\pi R^2$, where R is the radius of the body) by the *gravitational focusing factor* $F_g=1+v_{esc}^2/v_{enc}^2$, where v_{esc} is the escape velocity from the body and v_{enc} is the encounter speed with the other planetesimals. As long as v_{enc} is small relative to v_{esc} this leads to a *runaway growth phase*: the planetesimals which are bigger grow at a faster pace, so that the mass ratios within the planetesimal population stretch with time [1]. A number of large bodies form this way. At the same time, the formation of large bodies excites the velocity dispersion of the planetesimal disk, so that v_{enc} becomes comparable to v_{esc}, the escape velocity from the largest bodies. When this happens, the runaway growth phase ends (F_g~1), and growth becomes oligarchic. That is, the largest bodies grow now at a comparable rate, while the small planetesimals collide with each other at too large velocity to accrete [2]. Thus, the mass distribution in the disk acquires a bimodal distribution. There is a set of large bodies with planetary masses, emerging from a disk of small, asteroidal-like planetesimals. These planetary bodies are called *planetary embryos* if they are not big enough to capture an atmosphere from the gas of the protoplanetary disk and *giant planet cores* if they do capture an atmosphere.

Today, we know that this classic picture of planet growth is totally flawed. When silicate grains grow to a size of about a millimeter, they start to bounce off each other, instead of accreting [3]. In the icy part of the disk, particles can grow up to a few decimeters in size. Then, they start to rapidly migrate in the disk towards the star due to gas drag. This radial drift produces large relative collision velocities and hence disruptive collisions. Even if collisions were not disruptive, these boulders would be rapidly lost by migration into the star [4]. And even if a planetesimal disk formed despite of all these difficulties, the runaway and oligarchic processes would stall when the largest embryos achieve a mass of about 1 Earth mass [5], way too small to qualify for the cores of the giant planets (which needed to be 10-20 Earth masses in order to accrete massive atmospheres such as those of Jupiter and Saturn).

Fortunately, over the past years new ideas have been proposed, which look very promising. First, it has been shown that small particles tend to clump due to turbulence in the disk [6][7]. If the disk is not turbulent per se, under some conditions the particle/gas interaction can generate turbulence (hence particle clumping) due to the Kelvin-Helmoltz instability [8] and the streaming instability [9]. If the clumps of particles are massive enough, the self-gravity of the clump can bind all the particles together, thus forming a large planetesimal (of a typical size of 100km)[10]. The size distributions in the asteroid belt and in the Kuiper belt indeed show a "bump" at this characteristic size, suggesting that this was indeed the preferential size at which planetesimals formed. Once formed, these planetesimals would remain embedded in the protoplanetary disk of gas and radially drifting particles. It has been shown that planetesimals are very effective in accreting the drifting particles, thanks to a combination of gravitational deflection and gas drag. The optimal particles are those with a gas-friction time comparable to the crossing-time of the gravitational sphere of influence of the planetesimal, i.e. pebble-size particles. For these particles, the capture cross section is orders of magnitude larger than the cross section for planetesimal-planetesimal collisions. This process is dubbed *pebble accretion*[11]. It has been shown that, provided the mass-flux in radially drifting pebbles is large enough (but within realistic limits) planetesimals initially the size of Ceres (the largest asteroid in the main belt) can grow to 10-20 Earth masses within the lifetime of the disk [11][12]. Thus, for the first time we have a credible scheme for the formation of giant planet cores.

Despite this new idea is much more promising than anything else proposed before, many issues still need to be explored in order to demonstrate that planets actually form this way. This is where our project at the Convergence Institute C4PO kicks in.

B. Current activity

An effective way to demonstrate that a process actually occurred in the formation of the Solar System is to show that it allows explaining features that are not explained by any other known process. This is the approach we have taken in order to gain confidence that the pebble accretion process is the dominant one in planet formation.

A basic structure of the Solar System is the presence of low-mass terrestrial planets in its inner part and giant planets in its outer part. This is the result of the formation of a system of multiple embryos with approximately the mass of Mars in the inner disk and of a few multi-Earth-mass cores in the outer disk, within the lifetime of the gaseous component of the protoplanetary disk. In [13] we have shown that the process of pebble accretion can explain this dichotomy, provided that some assumptions hold true. We assumed that the mass-flow of pebbles is two-times lower and the characteristic size of the pebbles is approximately ten times smaller within the snowline than beyond the snowline (respectively at heliocentric distance $r < r_{ice}$ and $r > r_{ice}$, where r_{ice} is the snowline heliocentric distance), due to ice sublimation and the splitting of icy pebbles into a collection of chondrule-size silicate grains. In this case, objects of original sub-lunar mass would grow at drastically different rates in the two regions of the disk. Within the snowline these bodies would reach approximately the mass of Mars while beyond the snowline they would grow to ~20 Earth masses (Fig. 1). The results may change quantitatively with changes to the assumed parameters, but the establishment of a clear dichotomy in the mass distribution of protoplanets appears robust provided that there is enough turbulence in the disk to prevent the sedimentation of the silicate grains into a very thin layer.

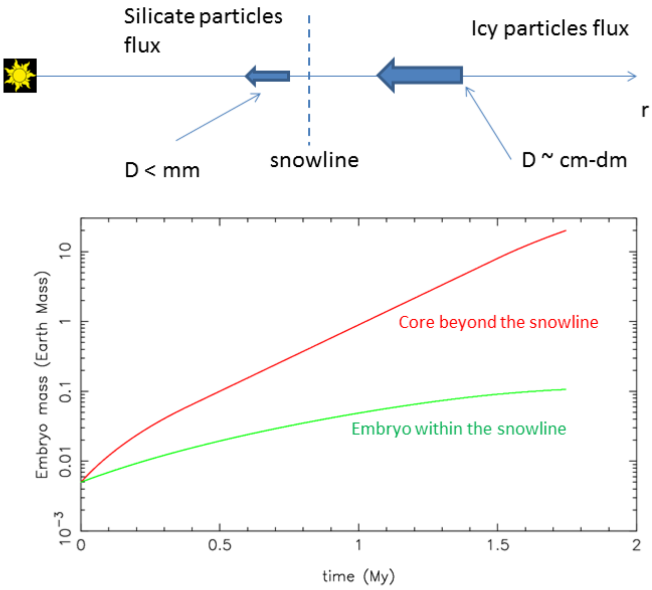

Fig.1. Top: scheme of the pebble flux, with particle size decreasing at the snowline as a result of ice sublimation. Bottom: the growth of two embryos, on either part of the snowline, starting from equal mass bodies. The outer embryo, because of the larger pebbles, grows much faster than the inner embryo. This explains the dichotomy of the mass distribution of proto-planets in the Solar System.

Another intriguing mystery of the Solar System is that the terrestrial planets and the asteroids dominant in the inner asteroid belt are water poor. This is surprising in view of the fact that in the protoplanetary disk the temperature should have decreased at 1 AU below water-condensation level well before the disk was photo-evaporated. Thus, the global water depletion of the inner Solar System is puzzling. In [14] we have shown that the process of pebble accretion can also explain this mystery. We first showed that, even if the inner disk becomes cold, there cannot be direct condensation of water. This is because the snowline moves towards the Sun more slowly than the gas itself. Thus the gas in the vicinity of the snowline always comes from farther out, where it should have already condensed, and therefore it should be dry. The appearance of ice in a range of heliocentric distances swept by the snowline can only be due to the radial drift of icy particles and pebbles from the outer disk. Then we showed that, if a planet with a mass larger than 20 Earth mass is present, the radial drift of particles is interrupted, because such a planet gives the disk a super-Keplerian rotation just outside of its own orbit [15]. From this result, we proposed that the precursor of Jupiter achieved this threshold mass when the snowline was still around 3 AU. This effectively fossilized the snowline at that location. In fact, even if it cooled later, the disk inside of Jupiter's orbit remained ice-depleted because the flow of icy particles from the outer system was intercepted by the planet (Fig. 2). This scenario predicts that planetary systems without giant planets should be much richer in water in their inner regions than our system.

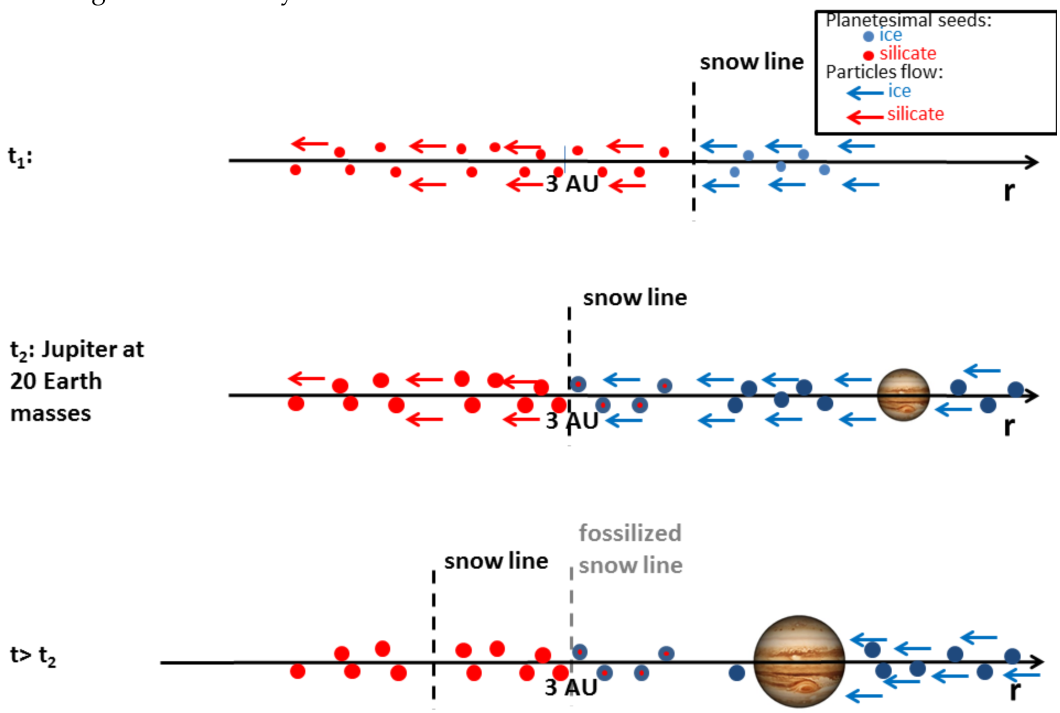

Fig. 2: Sketch of how the inner Solar System could remain water-poor despite the cooling of the propotplanetary disk. The top panel shows the disk at an early time, before the formation of Jupiter. The central panel shows the situation at the time when snowline remains fossilized. The bottom panel sketches the situation after the fossilization of the snowline.

C. Future steps

The future long term goal of this research is to build a coherent scenario of the formation of planetesimals, planetary embryos and giant planet cores, based on the pebble-accretion process.

The first step is to obtain a coherent set of formulae describing the efficiency at which bodies accrete pebbles depending on the various parameters that characterize the dynamics: the effective radius of gravitational influence of the body (the Bondi radius or the Hill radius depending on the body's mass and differential velocity relative to the gas), the eccentricity and inclination of the object, the scale height of the pebble's layer, the Stokes number of the pebbles. These formulae need to be calibrated on hydrodynamical simulations and have to have no discontinuities when growth passes from one regime to the other as the body's mass increases or the disk evolves. This work is ongoing.

The second step will be the incorporation of these formulae in the code *Boulder*, developed in [16]. This code treats in a statistical manner the evolution of a population of planetesimals. It evolves their velocity dispersion following self-stirring, dynamical friction, gas-drag and collisional damping formulae, as well as their size-frequency distribution (SFD) according to mutual collisions (which can be accretional, erosional or disruptive). By including the pebble accretion formulae, *Boulder* will be able to incorporate this new growth process in the context of the collisional evolution of planetesimal populations. The goal in using this new version of the Boulder code is to understand how a planetesimal population evolves and grows until it produces a set of planetary embryos and giant planet cores, which will eventually lead to the formation of terrestrial planets and giant planets respectively. Because the *Boulder* code is multi-ring, we can study how this process depends on heliocentric distance. Each radial ring will receive a flux of pebbles that is reduced according to the fraction of pebbles that the outer rings have already accreted. The time dependent source of pebbles in the outer disk will be modeled using a drift-limited pebble coagulation model as in [12]. The properties of the disk will also evolve with time. This project will therefore interact heavily with that described in Theme 1. Different possible disk evolutions, outcome of the project in Theme 1, will be implemented to see which ones lead to a result consistent with the Solar System structure. Another free parameter will be the characteristic size of the first planetesimals, formed by the turbulent clumping of solids, although we will restrict the range of possibilities according to the results that our collaborators abroad will obtain on this process. Several benchmarks will be considered as a measure of "success". First of all, the size distributions observed in the asteroid belt and in the Kuiper belt will need to be reproduced, with their characteristic "knee" and "foot" (places where the slope of the SFD changes from shallow to steep, then to shallow again, from small to large object sizes).. Second, a set of planetary embryos have to be produced in the inner part of the protoplanetary disk, consistent with those required in terrestrial planet formation models (see Theme 6.3). In the outer part of the disk, giant planet cores need to be produced, sufficiently massive to acquire massive atmosphere and become giant planets. Additional constraints to be matched come from the analysis of meteorites (see Themes 5.4., 5.5). Meteorites show that most asteroids are made of chondrules, and that they accreted relatively late in the history of the disk. The origin of chondrules is elusive, but will be the object of specific research in Theme 5.1. A serious hypothesis is that chondrules are the outcome of high-energy collisions among a pre-existing first generation of planetesimals. If confirmed, our models have to show how a first generation of bodies could have formed early in the disk and how a second generation could have formed from the debris of the first generation. Needless to say, the interaction between this project and that conducted in Theme 5.1 will be strong and continuous over the timeframe of the Institute. Among the outcomes of this project, there will be information on masses, formation timescales and location of the emerging protoplanets (embryos and cores) in the disk, which will be inputs for the planet migration models in Theme 6.2.

A third step in this research will be to incorporate the pebble accretion formulae in N-body codes. In fact, a statistical code like *Boulder* cannot treat the dynamical evolution properly when the system becomes dominated by a set of proto-planets. Thus, the plan is that, once a set of proto-planets is identified in the *Boulder* simulations, their subsequent dynamical evolution and further growth will be followed via N-body simulations, also incorporating the pebble-accretion process. This combination of *Boulder* simulations and N-body simulations will allow us to follow the entire process of planet formation, up to the ultimate planets. The forces exerted by the gaseous component of the planetary disk, responsible for the eccentricity and inclination damping of the orbits of the proto-planets as well as their radial migration (see Theme 6.2) will also be incorporated. This approach will be followed in order to study not just the formation of the planets in the Solar System, but also of extrasolar systems: specifically, the systems of super-Earths. Super-Earths are the most abundant planets in the galaxy, (orbiting about 50% of the stars) but they are totally absent in our Solar System, which is highly puzzling. It is not clear yet whether the formation process of super-Earth is more related to that of terrestrial planets or to that of the cores of the giant planets. Preliminary results suggest that super-Earths had to form very quickly before the dispersal of the gas from the proto-planetary disk, and hence migrated towards short-period orbits. If this is true, then they are more similar to the cores of the giant planets than to our terrestrial planets, because the latter instead formed on a ~100My timescale from mutual collisions of planetary embryos, in a gas-free environment. Our research will address this question with specific end-to-end simulations of the planet formation process, for disks of various initial masses in solids.

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D. International collaborations

On this topic we have a strong collaboration with the Observatory of Lund (Sweden), more specifically with the group of A. Johansen, who is the initiator of the idea of formation of planetesimals by self-gravitating clumps of pebbles and of the subsequent growth of proto-planets by pebble accretion. We also have a collaboration with Prof. S. Ida at ELSI in Japan.
We also have a strong collaboration with the group of S. Raymond at the Observatory of Brodeaux.

E. List of people involved in the project

Alessandro Morbidelli (50% ETP), Aurelien Crida (30%) and Tristan Guillot (30%) with post docs Michiel Lambrechts and Seth Jacobson and Ph.D. student Gabriele Pichierri.
Contact: morby@oca.eu

F. Most significant publications of the team

[13] Morbidelli, A., Lambrechts, M., Jacobson, S., Bitsch, B. 2015. The great dichotomy of the Solar System: Small terrestrial embryos and massive giant planet cores. Icarus 258, 418-429.
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Short CV of participants

A Morbidelli, is CNRS research director. He is an expert of planet formation and dynamical evolution. He is the current Director of the French National Planetary Science Program. Author of ~200 reviewed publications, with over 10,000 citations and an H-index of 54 (source ADS), he has been the recipient of the bronze medal of CNRS, of the Urey Prize of the Division for Planetary Sciences of the AAS, of the Mergier-Bourdeix prize of the French Academy of Science and of the Lepine prize from the city of Nice. He has been recently elected Associate member of the Royal Academy of Belgium and the French Academy of Science.