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Exoplanets / *Exoplanètes*

Planetary formation and early phases

Formation planétaire et phases précoces

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Abstract. Planets form in proto-planetary disks. In this review, we describe the structure and properties of such disks, and the various phenomenons that lead to the final product: a planetary system. First, micrometre dust settles and coagulates. Then, a complex interplay between the gas and centimetre aggregates leads to efficient phenomenons such as the streaming instability and the pebble accretion. Finally, gas accretion proceeds on ten Earth mass solid cores.

Once the gas disk is dissipated, giant planets may form satellites from massive rings, the terrestrial planets assemble from smaller embryos, and global dynamical instabilities give the planetary systems their final architecture.

Résumé. Les planètes se forment dans des disques proto-planétaires. Dans cette revue, nous allons d'abord aborder la structure et les propriétés de ces disques, puis les phénomènes multiples qui permettent d'aboutir au produit final : un système planétaire. Premièrement viennent les processus de sédimentation et coagulation de la poussière micrométrique. Ensuite, les interactions complexes entre le gaz et des agrégats de poussière centimétrique entrainent des phénomènes très efficaces tels l'instabilité de flux et la « *pebble accretion* ». Enfin, l'accrétion du gaz se fait sur des cœurs solides d'une dizaine de masses terrestres.

Une fois le disque de gaz dissipé, les planètes géantes dotées d'anneaux massifs peuvent former des satellites, les planètes telluriques s'assemblent à partir d'embryons, et des instabilités dynamiques globales donnent aux systèmes planétaires leur architecture finale.

Keywords. Proto-planetary disks, formation of planets, formation of satellites, planetary migration, dynamics.

Mots-clés. Disques proto-planétaires, formation des planètes, formation des satellites, migration planétaire, dynamique.

Note. Follows up on a conference-debate of the French Academy of Sciences entitled “Exoplanets: the new challenges” held on 18 May 2021, visible via
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1. Introduction

"Where do we come from?" is one of the most fundamental and eager questions of humanity. It applies to civilisations, to the *homo sapiens* species, but more generally to our world, the Earth. How was it formed? When? Is it common or exceptional? All these questions have first been answered by myths and religions as soon as humans started to think. But as knowledge improved, more constraints have been identified, and a scientific approach could be applied to this problem. The first of these observations were made in the Greek antique times. It was noticed that seven objects visible to the naked eye[1] wander in time with respect to the stars, which are fixed in the sky[2].

More importantly, these so-called *planetes* (the Greek, for "wanderer") do not wander everywhere in the sky. They are limited to a narrow band, the ecliptic. This shows that the whole solar system – to which the Earth belongs – is flat, planar. Deducing from lunar eclipses that the Moon is about 4 times smaller than the Earth, from solar eclipses that the Moon and the Sun have the same angular diameter, and from geometric considerations at first quarter that the Sun is at least 20 times further from us than the Moon (it is actually 390 times further), Aristarchus of Samos found that the Sun is much bigger than the Earth (actually a million times in volume). From this, he correctly inferred that the Earth must be orbiting around the Sun and not the opposite. No knowledge of gravitation is needed to notice that a big stone is harder to move than a small gravel...

It seems therefore logical that the planets formed around the Sun from a flat structure: a disk. This idea emerged independently from Kant and Laplace more than two centuries ago. Their models were solely based on the above observations, and their disks lacked some modern physics. Nonetheless, they got the big picture right. The discovery of exoplanets in the late 1990s, and the almost five thousand now known exoplanets around about three thousand stars have only made the question of planets formation more acute. Indeed, observations have revealed planets of types unknown in our Solar System. Some are giant planets orbiting closer to their star than Mercury to the Sun while the giant planets in our Solar System are all in the outskirts, beyond 5 astronomical units. Some exoplanets have masses in a range between the terrestrial planets and the giant planets; are they terrestrial? Giant? Something else? Interestingly, some of the these planets lie in the *habitable zone* of their host star, that is the distance range at which the temperature at the surface of a solid body would allow liquid water to flow, if there is any water. Knowing whether or not water could have been delivered to these planets is key to assess the chances that these worlds may harbour life. Note that not only terrestrial planets are interesting in this matter, the satellites of giant planets could be very habitable worlds... Their formation is therefore another key question. By trying to find "where do we come from", we can provide insight to the other fundamental question: "are we alone"?

In this paper, we will review the processes that lead to planet formation as we understand them to date. In Section 2, we introduce the proto-planetary disks which are the context of the whole story, their formation, their structure, and the recent observations. Section 3 is devoted to the various processes that allow to move from micrometer dust grains to megameter planets inside a proto-planetary disk. In Section 4, the concept of planetary migration is presented, with its latest developments. Finally, Section 5 focuses on the step right after the dispersal of the proto-planetary disk, which shapes the final architecture of a planetary system.

[1] These seven objects are well known since they gave the seven days of the week. It is obvious in English for Mo(o)nday, Satur(n)day, and Sunday, less obvious of the other four days, but they refer to the Nordic gods corresponding to the roman gods Mars (Tyr → Tuesday), Mercury (Odin → Wednesday), Jupiter (Thor → Thursday) and Venus (Frigg or Freya → Friday). In French, Lun(e)di, Mar(s)di, Merc(u)redi are most obvious, and one recognises "jovian" (associated to Jupiter) in Jeudi (remembering that the letters 'u' and 'v' were identical in latin) and "venerian" (from Venus) in Vendredi.

[2] This allows to draw constellations, which every civilisation did to get orientation in the night sky.

2. Proto-planetary disks

Stars form by the collapse of a gas cloud. But as a gas clump contracts, the conservation of angular momentum increases its rotation rate. Consider a gas parcel of specific angular momentum j falling onto a nascent star of mass M_*. Its angular velocity Ω is j/R^2 where R is the distance to the rotation axis of the cloud. Thus, in a frame rotating at the velocity Ω, it feels a centrifugal acceleration $R\Omega^2 = j^2/R^3$. But the gravitational acceleration from the star is centripetal and equal to GM_*/r^2 where r is the distance to the star. In a plane perpendicular to the rotation axis (where $R = r$), there is a equilibrium radius at which they balance, called the centrifugal radius :

$$R_{\text{centrif}} = \frac{j^2}{GM_*} \,. \tag{1}$$

Along the rotation axis of the cloud, nothing prevents the collapse, but perpendicularly to this direction, the gas should not be able to fall below R_{centrif}, which is of the order a hundred astronomical units for typical molecular clouds [1]. The physics of the collapse is actually much more complicated, and magnetic fields play a key role in redistributing angular momentum. The reader is referred to other papers for more details on this first phase [2, 3]. But the basic idea is that a gas disk of about a percent of the stellar mass is a natural outcome of stellar formation. If more massive, the disk would become gravitationaly unstable and accrete further onto the star, losing mass.

Note that gas clouds and proto-planetary disks are not only made of hydrogen and helium. They contain also heavy elements, which combine in molecules, and they later condense when the temperature is low enough into micrometer solids. These dust grains represent roughly a percent of the total mass. Thus they have been neglected above, but they are the key ingredients to form planets.

Below, we expand on the structure of such a proto-planetary disk, assuming as is usually done that the disk is isolated, in rotation around its star. However, there could be various episodes of gas accretion from the molecular cloud that perturb the density and temperature distribution of the disk, and this should be kept in mind.

2.1. *Hydrostatic equilibrium*

Above, we said that nothing prevents the collapse along the rotation axis of the gas cloud (which from now on we will refer to as the vertical direction, noted z). This is not absolutely true. Pressure inside the gas forbids it to become a razor thin disk. Our atmosphere has some thickness despite the Earth's gravity, because the pressure gradient balances exactly the gravity; this is the hydrostatic equilibrium. Similarly, a proto-planetary disk has some thickness and vertical structure, although the stellar gravity pulls it down towards the mid-plane. Expanding the vertical component of the stellar gravity to first order, neglecting the disk gravity, and writing the equation of vertical hydrostatic equilibrium, one gets the vertical distribution of the gas density ρ:

$$\rho(z) = \rho_0 \times \exp\left(-\frac{z^2}{2H^2}\right) \tag{2}$$

$$H = \sqrt{\gamma} c_s \Omega_K \tag{3}$$

$$\Omega_K(r) = \sqrt{GM_*/r^3} \tag{4}$$

where Ω_K is the Keplerian angular velocity (such that the centrifugal acceleration balances the stellar gravity) and c_s is the sound speed, which appears in the Equation of State $P = \gamma {c_s}^2 \rho$, with P the pressure and γ the adiabatic index. The typical scale height H is negligible compared to the distance to the star r, giving the disk an aspect ratio $h = H/r$ of a few percent.

The pressure gradient also has a radial component. Indeed, in general both ρ_0 and the temperature decrease with r. Hence, the pressure force pulls the gas away from the star. For the gas, this small reduction of the stellar gravity affects the equilibrium angular velocity, which is then given as :

$$\Omega_{\text{gas}} = \Omega_K \times (1-\eta) \tag{5}$$

where $\eta \ll 1$ is a coefficient proportional to h^2, depending on the local slopes of the density and temperature profiles. If the pressure is constant with radius, $\eta = 0$; if the pressure increases with r, $\eta < 0$ and the gas is slightly super-Keplerian. If the pressure decreases with r (the standard case), then $\eta > 0$ and the gas is slightly sub-Keplerian.

2.2. *Viscosity and angular momentum transport*

Proto-planetary disks are estimated to have a mass around one percent of the mass of the central star (with a wide distribution around this average value), and a life time of a few million years [4]. Thus, they should accrete onto the star at a rate of the order of $10^{-8} M_*$/year. To fall onto the star, the gas must lose angular momentum. The Keplerian dynamics is such that the inner regions have a lower specific angular momentum but a higher angular velocity. The flow is sheared, and any type of friction between the inner and the outer regions tends to accelerate the outer regions and slow down the inner ones, transferring angular momentum outwards, and pushing the outer regions outwards and the inner regions inwards. The disk spreads and accretes onto the star.

The molecular viscosity of the gas is many orders of magnitude too weak to explain the observed accretion rates. But turbulent motion has exactly the same effect at the macroscopic scale as viscosity. Hence, the angular momentum transfer inside the proto-planetary disks has been modelled with a viscosity ν for decades, often parameterised by a coefficient α following $\nu = \alpha c_s H$ [5]. The underlying turbulence has been attributed to the Magneto-Rotational Instability (MRI) [6]. This phenomenon leads to values of α of a few 10^{-2}, which is enough to explain the observed accretion rates [7]. With such a viscosity, a proto-planetary disk smoothly spreads, with increasing size and decreasing density [8]. Meanwhile, the accretion rate onto the star also vanishes. When it drops below $10^{-9} M_\odot$/year (where $M_\odot$ is the mass of the Sun), stellar winds become non negligible and eventually blow the remaining gas quickly, leaving only solids and a so-called debris disk.

Recent results, however, question this model. It has long been suggested that in some regions of the disk, the ionisation rate could be too small for the MRI to be active, creating "*dead zones*" inside the proto-planetary disk, where the viscosity and the turbulence would be low. But the problem may be more global. The equations of Magneto-Hydro-Dynamics (MHD) are often taken as ideal, that is neglecting the Hall effect, the ambipolar diffusion, and the Ohmic dissipation. Modelling these three effects carefully, and tracking the ionisation rate, one finds a totally different type of angular momentum transport [9, 10]. In particular, the flow could be laminar instead of turbulent, and the angular momentum would not be transported within the proto-planetary disk, but vertically, to the magnetic field via disk winds. Obviously, this changes the conditions for planetary formation, as we will see below.

2.3. *Observations*

Observations of proto-planetary disks have made huge steps forward in the past decade. Instruments like SPHERE at the VLT allow for direct imaging of the light scattered by micrometer dust grains (which are well coupled to the gas) with amazing spatial resolution, thanks to extreme adaptive optics technique. They have revealed structures in proto-planetary disks, like cavities, rings, spirals... The Atacama Large Millimetre Array (ALMA) observes proto-planetary disks in the millimetre wavelength domain, and therefore sees the millimetre sized dust aggregates (which decouple from the gas, as we will see below). These aggregates too form structures in the disk, mostly axisymmetric rings and gaps. Uniform disks seem to be more the exception than the rule. These structures are often seen as the signposts of planets in formation, but it may not be as simple as that, since other processes may create these features, or a single planet could make multiple rings [11]. More interestingly, the millimetre sized dust seems to be very efficiently settled in the mid-plane, in a very thin layer. This implies that the gas turbulence is low (see Eq. (6) below), rather corresponding to $\alpha \approx 10^{-4}$ than 10^{-2}, supporting the most recent models of disk evolution.

Finally, planets have been observed inside proto-planetary disks, indirectly through their local kinematic effects on the gas [12] and also via direct imaging, the most recent example being PDS 70 [13], which hosts maybe two planets in resonance [14].

3. Building the planets : Growth of solids and gas accretion

3.1. *Dust: under the effects of gas friction*

Settling. When solids have a different velocity vector than the ambient gas, a friction force applies, opposite to the relative velocity, such that the latter is damped towards zero with a stopping time τ, which depends on the gas density and the particle size. Dust particles on an inclined orbit around the star have a vertical motion with a frequency equal to the orbital frequency Ω. With the friction force, this motion obeys the equations of the damped harmonic oscillator. Defining the Stokes number as $S_t = \tau\Omega$, if the friction is weak ($S_t \gg 1$, for bodies larger than a meter), the oscillations are slowly damped ; if the friction is strong ($S_t \ll 1$, for dust grains less than a millimetre), there are no oscillations, but an exponential damping of the altitude towards $z = 0$. The fastest damping occurs for the intermediate regime $S_t \sim 1$.

The damping of the vertical motion leads to the sedimentation of dust particles in the mid-plane, where they accumulate, at a rate depending on their Stokes number. This damping is balanced by stirring from turbulence, so that the thickness of the dust layer at equilibrium is given by:

$$H_{\text{dust}} = H\sqrt{\alpha / S_t}\,. \tag{6}$$

Growth. This settling of dust grains in the mid-plane allows them to have low velocity encounters, and to grow by sticking, forming aggregates that can reach centimetre size. These aggregates are held together by Van der Vaals forces. Gravity does not play a role here. Above this size the aggregates are too fragile and fragment during a collision. This represents a barrier in the growth of solids, that is hard to overcome [15], although a lucky winner among the billions of aggregates could make it and then proceed by accreting smaller dust [16, 17].

Drift. In the mid-plane, the solids tend to orbit the star at a Keplerian velocity Ω_K, while the gas is in general sub-Keplerian (see above) so that the solids feel a headwind. Therefore, they lose angular momentum, and as a consequence, they move to a smaller radius orbit : they drift. Again, the drift rate depends on the Stokes number. For $S_t \ll 1$, the grains are effectively dragged by the gas, which reduces the relative velocity and the friction force. For $S_t \gg 1$, the friction force is negligible and the drift is slow. For $S_t \sim 1$, the grains decouple efficiently from the gas (making the relative velocity close to the limit value $\eta\Omega_K$), but they are very sensitive to the friction, making the drift the fastest. In fact, the drift rate is such in this case that meter sized dust aggregates could be lost into the star in a thousand orbits [18].

Meter-sized barriers and pebbles ($\mathrm{s_t}$ones). Both aggregation and drift make the growth and survival of aggregates beyond about a meter most difficult [19]. This problem is called the *(centi)meter size barrier*.

As we have seen, the solids with $S_t \sim 1$ are the ones most sensitive to the effects of gas friction. Because with typical proto-planetary disk parameters, it corresponds to objects of a few centimetres, they are often called *pebbles*. I prefer to refer them as s_t*ones*, which evokes the same type of objects on Earth, and carries the notion that $S_t = one$.

Concentrating dust aggregates. Overcoming the meter size barriers requires to grow directly from less than a centimetre to objects large enough to be held together by their own gravity: *planetesimals*. This can be achieved if dust aggregates are concentrated enough to reach gravitational instability. It has been proposed that settling brings a gas to dust ratio in the mid-plane of the order of unity, so that the solids drag the gas to Keplerian velocity. In this case, the fluid is sheared vertically with a mid-plane layer orbiting faster than the rest of the gas disk. It leads to a Kelvin–Helmholtz instability, and vortices form, which concentrate dust at their centre. Under favourable conditions, gravity bound clusters of solids of masses of the order of that of Ceres can form [20–22].

Another type of instability is the so-called *streaming instability*. As aggregates drift, if a region has a larger density of solids, it has more capabilities of dragging the gas, reducing the relative velocity, the friction force, and the drift rate. Hence, zones of lower solids density catch up with the former, and increase even more the high concentration of solids. As this process runs away, the concentration of solids can reach large enough values to eventually form planetesimals [23].

3.2. *Planetesimals, proto-planets and cores*

Once gravity is the dominant force, planetesimals can grow by accreting one another when their trajectories cross each other's gravitational zone of influence. If the planetesimals are on circular orbits, the larger bodies grow faster because of their larger feeding zone, and growth proceeds while the mass ratios run away. The biggest planetesimals become proto-planets in a process called *runaway growth* [24].

Once the proto-planets are formed, though, they gravitationaly stir the planetesimal population in such a way that the relative velocities become equal to the escape velocities of the bodies. In this case, the mass ratios converge to unity, leading to the formation of a population of equal sized proto-planets that dominate the swarm of planetesimals. This process is called the *oligarchic growth* [25].

The runaway and oligarchic growths lead to the formation of objects of masses of the order of the mass of the Moon or Mars (1 to 10 percent of the Earth mass) called *embryos*.

However, the runaway and oligarchic growths neglect the effect of gas (which is legitimate for planetesimals whose Stokes number is very large). Pebbles (or $\mathrm{s_t}$ones, that is: objects which have a S_t about 1), if deflected by the gravity of an embryo, are significantly slowed down by the gas. As a consequence, they lose kinetic energy, and are eventually accreted by the embryo even if they were initially beyond the feeding zone of the embryo. In other words, gas friction increases dramatically the feeding zone of an embryo, for what concerns pebbles. This process, called *pebble accretion* [26, 27] is very efficient and can make embryos grow to several Earth masses within the lifetime of the proto-planetary disk. More specifically, the efficiency of pebble accretion increases a lot if the layer of pebbles is not thicker than the effective accretion radius of the embryo [28]. Thus, it is much more efficient beyond a typical mass, which depends strongly on how turbulent the gas disk is (Eq. (6) above). In laminar disks as evoked in Section 2.2, the $\mathrm{s_t}$ones are well settled, and pebble accretion can start earlier, or affect a wider range of pebble sizes.

In the inner regions of the proto-planetary disk, the increase of temperature makes water ice evaporate, and the pebbles fragment as they drift inwards. Their Stokes number then drops, which reduces the efficiency of pebble accretion. This may explain the dichotomy of the Solar System, where solids grew to the size of the cores of the giant planets beyond the iceline at a few astronomical units, while they remained smaller than Mars in the terrestrial planets region [28, 29]. The terrestrial planets of the Solar System then assembled from collisions among emrbyos and planetesimals after the gas disk dissipated [30]. However, the possibility that the four terrestrial planets of the Solar System completed their formation by pebble accretion is not completely ruled out [31].

Eventually, if the core becomes massive enough to start perturbing the gas density profile, a pressure maximum builds outside its orbit. At this location, the gas orbits exactly at Keplerian velocity, which stops the drift of $s_t$ones, and terminates the growth by pebble accretion. The critical mass is called the isolation mass, and is of the order of a dozen Earth masses, depending on the local disk parameters [32].

3.3. *Gas accretion and final mass of giant planets*

Once a 10 Earth mass core of solids is formed inside the proto-planetary disk, its surface gravity is large enough to capture gas. As gas falls in the potential well of the planet, it contracts and heats. It then cools by radiation, thus contracts further and leaves room for more gas. One can solve the hydrostatic equilibrium equations for a sphere of gas around a solid core of a given mass and luminosity (to account for the the heat liberated by the accretion of solids). For any core mass below a threshold M_c, a solution exists for the envelope structure. This allows the planet to grow smoothly, at equilibrium [33]. At this phase, the planet is very much alike Uranus and Neptune; the ice giants may well have never reached the next phase and the threshold mass before the Solar nebula dissipated. The threshold mass depends on the luminosity, but does not exceed 20 Earth masses. When the core mass exceeds M_c, or when the luminosity vanishes because the accretion of solids is terminated because the planet has reached the isolation mass for pebble accretion [34], the gas envelope collapses, and the gas accretion runs away [35]. The origin of the end of the runaway accretion is not clear today.

These classical 1D models have been extended recently to 3D thanks to numerical simulations with high resolution. In these simulations which follow the gas dynamics in the proto-planetary disk, the gas flow into the Hill sphere of the growing giant planet is not pure inflow. Most of the gas leaves the neighbourhood of the planet after having approached the core. This slows down the cooling and the accretion rate of small mass planets, offering an explanation for the existence (and even the predominance) of super-Earths among exoplanets [36]. Moreover, beyond the threshold mass, the gas circulation is also more complex than expected, and the accretion rates are not as dramatic as previously thought [37]. In fact, there seems to be no threshold mass anymore, but rather a smooth increase of the accretion rate with the planetary mass as $\mathrm{d}M/\mathrm{d}t \propto M^{1.9}$. This still makes the evolution of mass as a function of time look like a sharp increase after a slow phase, with a divergence towards infinite mass at some finite time. So, the reason why growing giant planets do not accrete all the gas of the disk and reach about ten Jupiter masses remains unclear. One can only imagine that they reach a runaway gas accretion phase at the moment where the proto-planetary disk is about to dissipate, but this fine tuning is not fully satisfactory.

Assuming that the disk dissipates at a random time during the growth of the giant planets, though, it seems natural that lighter planets are more common since the planets spend more time at lower masses. In fact, with $\mathrm{d}M/\mathrm{d}t \propto M^{1.9}$, the final distribution of their masses should be in the form $\mathrm{d}N/\mathrm{d}M \propto M^{-1.9}$. It turns out that statistics of exoplanetary systems detected with micro-lensing events provide a planet to star mass ratio q in $\mathrm{d}N/\mathrm{d}q \propto q^{-1.93\pm0.1}$ for $q > 1.7\times10^{-4}$ (that is: about 3.2 Neptune masses or 0.6 Saturn mass for a solar mass star) [38]. Although this nice agreement should be taken with care given all the hypotheses behind the numerical simulations, it seems robust that the frequency of exoplanets detected by micro-lensing decreases smoothly above $q = 1.7\times10^{-4}$. This contrasts with what was expected from the 1D models described in the first paragraph, who predict a desert just above the critical mass for runaway gas accretion [39].

One should keep in mind, though, that the 3D numerical simulations presented above were performed in standard disks with a viscosity corresponding to $\alpha \approx 0.6\times10^{-2}$. The new paradigm for proto-planetary disks presented in Section 2.2 may change the picture by making it harder for the gas to reach the planet, but this remains to be checked.

3.4. *Satellites formation*

Giant planets, as they accrete gas, get surrounded by a circum-planetary disk (CPD), like stars are surrounded by a proto-planetary disk. This occurs when the planetary gravity dominates the pressure of the gas, that is above masses of the order of that of Saturn. For Uranus and Neptune, the formation of a circum-planetary disk would require an extreme, unrealistic cooling of the gas. In the CPD, processes similar to the ones described above can take place, leading to the formation of a miniature planetary system: the satellites. In more details, the CPD is constantly fed in gas and solids from the proto-planetary disk, so that the whole dynamics of the growth, drift, and migration of solids differs. Several models have been elaborated [40–44]. It seems that the MRI has difficulty to maintain due to an expected low ionisation rate [45]. New models with low turbulence and angular momentum transport [46] also reproduce more or less satisfactorily the Galilean moons of Jupiter and the presence of Titan around Saturn.

These models are difficult to apply to Uranus and Neptune which may never have had a CPD. Also, they hardly address the less massive moons of Saturn, notably. Another model of satellite formation takes place after the dissipation of the gas disk, from the spreading of a massive ring of solids beyond the Roche radius [47]. Such a ring could be the leftover of the formation and inwards migration of satellites inside the CPD [48]. This model explains the peculiar mass-distance distribution of the Saturnian satellites inside the orbit of Titan, which turns out to be similar to the one of the satellites of Uranus and Neptune; it suggests that the ice giants used to have massive rings, now almost fully gone, which gave birth to their satellites [49]. This model gained further momentum with the recent discovery of the fast outwards migration of Titan [50], which suggests that even this large moon may be coming from the rings.

It applies also to the formation of the Moon after a giant impact hit the Earth and created a huge ring of silicates [49], and to the satellites of Mars [51]. If generic in the Solar System, this mechanism could well apply to exoplanets, and series of satellites of increasing mass with distance to the Roche radius may be expected around giant exoplanets.

Finally, the accretion of solid bodies from the spreading of a ring of debris beyond the Roche radius of a central body could also apply to the case of white dwarfs who are polluted by incoming asteroids or first generation planets destabilised by the death of the central star, and give rise to a second generation of planets [52].

4. Planetary migration and architecture of planetary systems

It is now well established that planets embedded in their proto-planetary disk perturb the disk gravitationaly and feel a back reaction from the density perturbations. In contrast to the drift of the solids seen in Section 3.1, this phenomenon has nothing to do with friction (the Stokes number of a planet is extremely high), not even dynamical friction[3], but is purely gravitational.

As the global tendency is to reduce the relative velocity between the planet and the gas, this results in damping efficiently the eccentricity and inclination of any planet orbiting in the gas disk. As a consequence, the planetary orbits should all be circular and co-planar. Another consequence, which we develop below, is a change in the orbital radius of the planet: *planetary migration*. More details on planet-disk interactions can be found in this review [53].

4.1. *Small mass planets: type I migration*

The density perturbation of the gas disk by a planet is a pressure supported wave, with the shape of a one-armed spiral called the *wake*, leading the planet in the inner disk, and trailing behind the planet outside its orbit. The two arms are not exactly symmetric, and the resulting force exerted on the planet has a constant direction in the frame corotating with the planet. It thus exerts a torque on the planet, changing its orbital angular momentum. As a consequence, the orbital radius changes too, and the planet migrates.

The torque due to the wake is called the differential Lindblad torque [54–56]. It scales linearly with the disk surface density Σ, and more precisely is proportional to the reference torque:

$$\Gamma_0 = q^2 \Sigma r^4 \Omega^2 h^{-2} \,, \tag{7}$$

where again q is the planet to star mass ratio and h the disk aspect ratio.

An other torque applies to the planet, originating from the region around its orbit, where the gas is on average in corotation with the planet, having orbits in the shape of horseshoes in the frame corotating with the planet. This so-called corotation torque scale also with Γ_0. While the Lindblad torque is generally negative, the corotation torque can be positive, especially in regions where the density radial gradient is positive. This leads to the formation of planet traps, which are equilibrium radii in the disk where the migration converges [57]. This corotation torque can be further enhanced by thermal effects when the proto-planetary disk has a radial entropy gradient [58, 59]. But it can not be sustained in the limit of vanishing viscosity, because the corotation region is closed and only has a limited amount of angular momentum to provide. It must exchange angular momentum with the rest of the disk, and this is done by viscous friction at the separatrix between the horseshoe region and the inner or outer disk [60]. In the non-viscous case, the static corotation torque mentioned before can not be sustained, but the corotation region tends to keep its angular momentum and therefore acts as a ball-and-chain for the migrating planet. This *dynamical corotation torque* can slow down migration significantly (unless the disk has a peculiar density profile with zero vortensity gradient) if α is less than a few 10^{-4} [61].

Finally, when the gas disk is not exactly adiabatic nor isothermal, its close encounter with the planet changes its entropy. It loses internal energy as it radiates away when it is compressed and heated near the planet, but it can also gain internal energy if the planet is luminous. In a sheared disk, this leads to two fingers of different temperature (hence density) than the ambient gas. They are not exactly symmetric if the gas is not exactly Keplerian, leading to a so-called heating torque [62].

All in all, these torques make planets more massive than the Earth migrate on timescales smaller than the lifetime of a proto-planetary disk. The direction of the migration depends on the disk structure and on the planet mass and luminosity. One can then make migration

[3]Dynamical fiction is a phenomenon which applies when a massive body moves with respect to a swarm of particles. In the frame of the massive body, all the particles have bent trajectories which converge behind it, creating a mass concentration that pulls the body in the direction opposite to the relative motion.

maps, where the torque is given as a function of orbital radius and planet mass, for a given disk structure [63–65].

4.2. *Gap opening planets: type II migration*

Giant planets perturb the density profile of the proto-planetary disk and open gaps, separating the inner and the outer disk, depleting the corotation region [66–68]. Gas accretion by the planet itself can further help opening the gap, especially in low viscosity disks where the density profiles take longer to be smoothed by the viscous torques [69]. Their migration is then drastically different than small mass planets embedded in the disk. While the gross idea is that the planets are locked inside their gap and follow the disk accretion onto the star [70], recent results suggest a more complex picture [71]. In any case, the migration rate scales with the disk viscosity [72]. This so-called type II migration may explain nicely the presence of giant planets, most likely formed at several au from their host star, on close-in orbits: the famous hot Jupiters [73]. Even though about half hot Jupiters are on orbits inclined with respect to the stellar equator, this could be due to an inclination of the proto-planetary disk itself [74].

However, most giant exoplanets are not hot Jupiters. Their late formation, together with helping for the problem of their final mass, could also help reducing their time spent in type II migration and the amplitude of the later. One may also imagine that giant planets form far, beyond 20 au [75], but this seems unrealistic. An interesting alternative is that in disks with low viscosity, type II migration may be of very limited amplitude [76, 77]. The fact that most giant exoplanets are located close to the region where they seem most likely to form may then be seen as another observational constraint in favour of these new proto-planetary disk models [78].

4.3. *Application to multiple planets*

In presence of multiple planets in the system, things get more complicated. First, low mass planets in type I migration may have different migrations rates if they have different masses, or are located in different regions of the disk. Hence, convergent migration is expected to happen in many cases. This may lead to the merger of the two proto-planets [79], but also to their capture in mean motion resonance [80]. In particular, if one planet in stopped at the inner edge of the disk (which acts as a very efficient planet trap), a chain of Super-Earths in resonance may be built. Conversely, if a planet grows fast enough to reach an outwards migration regime [81], it may swallow all the solid bodies on its way and become a giant planet core [82].

Giant planets are more easily caught in mean motion resonance and generally end up in a single gap. Their behaviour is then different from that of a single planet, since the inner and the outer disks interact with two planets of different masses. The pair of planets can then feel a total positive torque and migrate outwards [83–85]. It has even been proposed that Jupiter migrated inwards in the Solar System until ~ 1.5 au, and then tacked under the influence of Saturn to get back to its present position [86]. This *Grand Tack* scenario explains the small mass of Mars and the structure of the main asteroid belt, but requires some fine tuning for Jupiter to tack at the right time [87]. Besides, it relies on viscous disks. The dynamics of the Jupiter-Saturn pair in low viscosity disks appears slightly different, with no possibility for a tack [88].

5. After gas dispersal

5.1. *Terrestrial planet formation*

In the case of the Solar System, it is expected that planetary embryos of masses of the order one to ten percent of the Earth mass are the outcome of the runaway and oligarchic growth. Dozens if not a hundred of such bodies are supposed to orbit in the terrestrial planets region, surrounded by planetesimals left over from planet formation. While the gas disk tended to circularise the orbits of all these bodies, and prevent them from colliding, the system is too densely packed to be stable when the gas is gone. Due to close encounters, the eccentricities rise, the orbits cross, and mergers occur[4]. The system stabilises once all the mass is concentrated in three to five planets: the actual terrestrial planets [89]. During this process, which lasts about a hundred million years, the region is shaken, so that bodies from different distance to the Sun may merge, delivering volatiles (like water) to the Earth [90].

In this process, giant impacts among embryos are expected. The last one the Earth experiences is probably the moon-forming impact, which expelled mantle material into a huge ring of molten silicates, from which the Moon formed [49, 91]. Chemical and isotopic constraints allow to date this impact to at least 40 million years after the disk dispersed [92].

5.2. *The fate of resonant chains of Super-Earths*

While the natural outcome of planet migration simulations is the formation of chains of planets in resonance, such planetary systems are famous (e.g. TRAPPIST-1) but rare. An analysis of the orbital period ratios suggests that several exoplanet pairs are indeed in mean motion resonance [93], but the overall distribution shows no predominance for resonances.

In fact, resonant chains may be unstable in the absence of the gas disk. Secondary resonances between the synodic frequency and the frequency of libration of the resonant angle may appear and destabilise the system. The libration frequency decreases with increasing order of the resonance, number of planets in the chain, and planetary mass. Therefore, the critical mass for destabilising a resonant chain decreases with the number of planets and the compactness of the chain [94]. Most chains of resonant Super Earths should be broken this way, a short time after the disk has dissipated.

The destabilisation of the system leads to its dynamical excitation, possible collisions or ejections, and eventually a system of more separated, more eccentric and inclined planets. The overall distribution of Super Earths is in good agreement with ~ 95% chains being broken [95,96]. In addition, the instability brings some mutual inclination to the planetary orbits (forced to be co-planar by the gas disk), which makes multi-transiting planetary systems rare. This explains the apparent *Kepler dichotomy*: the Kepler satellite has detected an excess of single-transiting systems relative to what might be expected based on the number of systems with multiple transiting planets detected. Actually, even the single Super Earths detected by Kepler are probably multiple, in a system with non zero mutual inclinations [96].

5.3. *Global instability of giant planets*

As for giant planets, we know very well of one system whose final architecture was sculpted by a global instability from a resonant configuration: our own Solar System. According to the so-called *Nice model*, Jupiter, Saturn, Uranus and Neptune (and maybe a third ice giant [97,98]) were, after their formation and migration in the proto-solar nebula, in a compact configuration, probably resonant [99]. Some possible resonant configurations are unstable and break in a few tens of million years at most. Some are stable on the long term, but can be slowly perturbed to reach instability, by interactions with a massive disk of planetesimals left over from planet formation, beyond the orbit of Neptune [100]. In any case, an instability occurred, and brought the giant planets on their present orbits [101].

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[4] Mergers may not be perfect during a collision, but the debris being on object-crossing orbits, they fall back on the new object in long term.

This global instability also explains many features of the Solar System, like the distribution of Jupiter's Trojan asteroids [102], the Late Heavy Bombardment (even though its "late" aspect is questioned) [103], the structure of the Kuiper Belt [104], the capture of irregular satellites [105]... It also allows for the formation of the terrestrial planets to take place with Jupiter and Saturn on circular orbits, before the instability occurs, which eases the reproduction of some dynamical aspects of the inner Solar System.

Besides, in many simulations of the Nice model, the outcome is not exactly like the Solar System, and more dramatic instabilities leading to the ejection of a giant planet are common (hence the possibility of having a fifth giant planet initialy). The remaining giant planet(s) then often have large eccentricities, which are not expected from the formation inside a gaseous proto-planetary disk. The observed distribution of the eccentricities of giant exoplanets suggests that such episodes of violent instability among planets may be common, and responsible for the final architecture of planetary systems.

6. Conclusion

Planetary formation is a fundamental, but very complex question. How to gain 12 orders of magnitude in size from a dust grain to an Earth sized body necessarily implies many different physical laws and successive processes. Shall one of these fail, or be too long, the growth of planets will terminate. However, statistics of exoplanets show that these processes must be rather efficient, since most stars have planets. But in contrast with what was expected, most stars don't have terrestrial planets around 1 au and giant planets between 5 and 30 au. And planetary systems are very different from one another.

In this story, many bifurcation points have been identified. Whether a proto-planetary disk is turbulent or not changes the behaviour of the dust (thus the timescale and typical masses of planetesimals and embryos), but also of migrating planets. Whether a planet can reach the critical mass to become a gas giant or not influences the whole system. Whether a massive planet migrates significantly or not affects the growth and distribution of all other planets. Whether a resonant chain is stable or not determines the final architecture of the planetary system. All of these events allow for totally different outcomes of planet formation. In the end, it is no surprise that the exoplanets come in such a diversity. The challenge now is to understand the rate of each outcome, and to compare theory with observations. This is the goal of planet population synthesis [106]. In this field, researchers model all the above ingredients with (not so) simple equations, input initial conditions, and get a population of planets. The comparison with the actual distribution of exoplanets may reveal problems in the model, errors in the initial conditions, or missing ingredients in the theory. However, there are so many parameters to tune that these models are often degenerate, and their predictive power is limited. All in all, the gross agreement between planet population synthesis and observations suggests that the models described in this paper work quite well, even though many details remain to be understood.

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