6.2 Planetary migration

A. Context and state of the art

What is planetary migration ?

Planets form in discs of gas and dust, called proto-planetary discs (see section 1). Although terrestrial planets finish their formation after the gas is dispersed (see section 6.3), the giant planets must grow from almost zero to their final mass within the disc, because they are mostly made of gas that they accrete from this disc (section 6.1). But the gravity field of a planet perturbs the gas. A wake forms, which is a one-armed spiral density wave, leading the planet in the disc inside its orbit, and trailing behind the planet in the outer disc. This density perturbation, in turn, exerts a force on the planet. This force leads the planet to change its orbit : it migrates. This phenomenon can't be neglected since the typical timescale of planetary migration is much shorter than the life time of the disc (a few million years). As a consequence, planets can be lost into their star, or at least end on an orbit which has nothing to do with the location where they formed.

Our understanding of planetary migration

The force from the wake is well understood since Ward (1997), and known to promote a too fast inwards migration, which would lead to the loss of planets into their star. Huge progress has been made in the past decade to solve this puzzling problem. A new contribution to the torque caused by the material librating in the horseshoe region, the so-called corotation torque, has been deeply investigated (see Baruteau et al., 2014, for a complete review). It has been shown that this torque can be positive, and overcome the classical, negative, wake torque when the disc is not isothermal. Typically, this is efficient for planets in the $5-30M_{\oplus}$ range, in the inner regions of the disc, where the radial gradient of entropy is steep (ex : at opacity transitions). An analytical formula for the torque felt by a planet in this type I migration has been found by Paardekooper et al. (2011). Combined with an accurate description of the temperature and density profiles of the protoplanetary disc and its evolution (see Theme 1), this allows to produce migration maps, where the torque felt by a planet is given as a function of its mass and position in the disc (Bitsch et al., 2013). In such maps, it appears possible to block a giant planet core at a zero-torque radius, where it can grow slowly.

Giant planets are massive enough to overcome the effects of viscosity and pressure of the gas, and manage to open a gap in the disc around their orbit, effectively splitting this disc in two. Then, they should stop drifting with respect to the gas, but they should follow the evolution of the gas disc, which is generally a viscous spreading towards the star, at a slow rate. This explains rather satisfactorily the distribution of giant exoplanets.

Open problems in planetary migration

The theoretical migration rate is a key ingredient in planet population synthesis models, and more generally in planet formation. But a recent publication (Fung et al. 2015) advocates in favor of a new torque, coming from 3D effects, acting on small mass planets, and large mass planets have been shown able to drift relative to the gas by Dürmann & Kley (2014). It could also be that gas accretion changes the picture. In other words, we have not yet reached the end of the story, in terms of the theoretical migration speed of planets in theoretical discs. However, more powerful numerical simulations, with 3D, radiative equation of state, and high resolution, should provide a definitive answer in the coming years. We have already contributed to the recent progresses on this topic, and want to stay part of the story.

On top of that, the migration speed depends critically on the disc parameters. Unfortunately, they are not understood with enough reliability and accuracy. The main source of uncertainty at the moment concerns what drives the evolution of the disc. Whether it is MRI turbulence, Hall effect, of disc winds, the disc structure is completely different, and so is the migration map, not to mention the role of dust and opacity in setting the temperature profile of the protoplanetary disc. In tight connection with the project presented in section 1, the disc structure should be better understood.

B. Current activity

Migration of accreting giant planets :
We are studying the migration of accreting planets, before and after they open a gap. Before a gap is open, the planets are in great danger of being lost, as the corotation torque mentioned above always saturate (becomes inefficient) beyond 20 to 30 Earth masses. Therefore, we perform high resolution, long term simulations, in an extended disc, in which planets are allowed to accrete gas and grow as they migrate. Using a recipe for the gas accretion given by previous works, we find that the competition between growth and migration is fair, in that the planets can reach a gap opening mass before having migrated all the way down to their central star. This result could be of crucial importance for our understanding of the formation and evolution of giant planets.
We are also working with the group of the university of Tübingen (Germany) on the migration of accreting giant planets who have opened a gap. In this case, it seems that gas accretion by the planet prevents gas to cross the gap, and locks the planet in the disc evolution again, in contrast to their recent results on non accreting planets (Dümann & Kley 2014). This is still under investigation, and the simulations are being improved by adding tracer particles, in order to follow the gas. If this result holds true, it is also fundamental for our understanding of the migration of giant planets, hence of the structure of planeteray systems.

Migration of small mass planets in 3D radiative discs:
Our group has developed a 3D version of the famous FARGO code, the code FARGOCA, which includes a radiative transfer package. We are working on a way to refine the grid close to a planet, in order to study with great details the flow around terrestrial planets. We want to investigate the new torque mentioned above (Fung et al. 2015) in the more realistic case of a fully radiative disc. First results seem to indicate that this torque vanishes in simulations where non isothermal effects are taken into account. This should be checked very carefully, as such a strong torque could have a very important impact on planetary migration.

C. Future steps

The "cold finger effect":
Using the latest 3D, high resolution of FARGOCA, we will also investigate in more details the "cold finger" effect that we had identified in a previous work (Lega et al. 2014). This is an other possible source of torque felt by a small mass planet. We didn't have time to perform a thorough study of this phenomenon yet, but it should not be forgotten.

Once this cold finger and the Fung et al. (2015) torque have been exhaustively investigated, we will probably have reached an almost final answer about the torque felt by a small mass planet in a disc. With our present research on type II migration, we hope to get in the future years on comprehensive understanding of planet migration for all masses. Then, the next steps are the application of these results to understand the evolution of planetary systems. Two aspects are crucial: the disc structure and evolution (which determines the migration map) and the planet-planet interactions during the migration (which perturb this picture and lead to more complex phenomena.

Take the dust evolution into account :
The capability of producing realistic migration maps depends both on the more precise comprehension of the torque exerted on a planet and on the accuracy of the description of the disc profiles. The improvement in the computation of the thermal structure of the discs (see Theme 1) that

will be obtained by including the evolution of the gas to dust ratio will be of crucial importance for this part of the project.
On top of that, the ability of the gas to cool is a key parameter for the efficiency of the corotation torque. The evolution of the dust (thus of the opacity) in the corotation region is not a priori obvious, and should be investigated. For all these reasons, including the dust evolution in our code is a major step forward. We will probably not change the torque that a planet should feel in given conditions of density, temperature, and opacity, but we may find that the set of parameters which is relevant is not the one previously thought. This could change the migration maps, which are the tool of choice to understand how planets migrate.

Long term evolution of systems :
A promising scenario of the early evolution of the Solar System has been published recently, led by Nice authors, called the Grand Tack (Walsh et al. 2011). In this model, Jupiter and Saturn migrate first inwards, but then approach each other, enter in resonance, and migrate together outwards. This in-then-out migration of Jupiter could explain many aspects of the architecture of the terrestrial planets and main asteroid belt of the Solar System (see section 6.3). However, this model relies on migration of fixed mass planets, and on some fine tuning of the parameters of the disc and the sequence of the formation of Jupiter and Saturn. Our better understanding of gas accretion of giant planets, and of the migration of accreting planets should allow us, on long term, to test and refine the Grand Tack model.

Another question we want to address is the formation of chains of Super Earth – mini Neptunes planets. Many stars have such planets of intermediate masses, unknown in our solar System, and migration studies show that they should be in chains of mean motion resonances. This is not observed. It could be that such chains are unstable, but then, what are the consequences of breaking such a chain on the system ?
In order to understand the observed systems, analytic and numerical studies of the migration of SENs and their multi-resonant dynamics should be undertaken. A Ph.D. subject on this problem has been proposed, for a start in the fall 2016.
Super-Earths seem to be the most abundant planets in the universe, so it is crucial to understand their formation process. This work is related to that described in chapter A6.1 on the pebble accretion of proto-planets.

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D. International collaborations

We collaborate actively with :
- Bertram Bitsch (University of Lund, Sweden)
- Pr. Wilhelm Kley and Christoph Dürmann (University of Tübingen, Germany)

- Frédéric Masset (UNAM, Mexico)
We collaborate regularly with :
- Pr. Richard Nelson (Queen Mary University of London, UK)
- Masahiro Ogihara (Tokyo, Japan)
- Takeru Suzuki (Nagoya University, Japan)

E. List of people involved in the project

Permanent researchers : A. Crida, A. Morbidelli, H. Méheut
Software Engineer : E. Lega
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F. Most significant publications of the team

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Short CV of participants

A. Crida, 36, Maître de Conférences (associate professor). Expert of planet migration and planet-disc interactions. Co-author of 37 articles in peer-reviewed journals, 2 book chapters, and 2 News&Views papers. Recipient of the French Society for Astronomy and Astrophysics award for young Associate Professor. Member of the Institut Universitaire de France.

E. Lega, 49, Research Engineer. Expert in software development and management of massive simulations. Main developer of the code FARGOCA: a 3D version of the FARGO code which includes a radiative transfer package. Main developer of the software for data analysis and visualization. Co-author of 85 articles in peer-reviewed journals, co-editor of 4 books, co-organizer of 15 schools (Formation Permanente CNRS) and 2 international conferences.